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Adams, J.E. 1944. "Upper Permian Ochoa Series of the Delaware Basin, West Texas and Southeastern New Mexico." American Association of Petroleum Geologists Bulletin, Vol. 28, No. 11, 1596-1625. WPO 37940.

p 1612, para 4, line 4;

" It seems probable, however, that the uppermost Castile salts were dissolved to form a shallow solution valley along the original margin of these salts. This and the tilting of the Delaware basin northward probably mark a time break between the two formations. The unconformity between the Salado and the overlying Rustler formation is marked by extensive erosion and solution.

It is probable that the Salado should be correlated with the Tessey formation of the Glass Mountains. The Tessey is made up of practically pure, almost non-fossiliferous dolomites and probably reprssents the back-reef facies of a post-Capitan reef, into which the limed-up section of the southern Salado appears to grade.[18]

RUSTLER FORMATION

Deposition of the Rustler, the third formation of the Ochoa series, was preceded by a period of uplift and erosion in the area along the west edge of the Delaware basin. This erosion stripped off all the western Salado and may have truncated the entire Castile formation as well. The lowest Rustler outcrops observed are about 100 feet above the top of the Delaware Mountain group. As a result of uplifts beyond the limits of the Delaware basin, the oldest deposit of the Rustler formation, in its western outcrops, is a clastic member. Included are coarse, siliceous conglomerates with well rounded pebbles up to 2 or 3 inches in diameter, coarse gray sandstones, traces of red and yellow shale, coarse dolomite conglomerates, and bedded gray and buff dolomite. Many of the siliceous pebbles are etched in a peculiar manner with all the broken crystals of the original surface spalled out, leaving well rounded pebbles covered with unmarred crystal faces. The bedding in all these deposits seems to be distorted. Toward the east the conglomerates grade into sandstones."

p 1614, para 3;

" The first five members in the foregoing section belong to the upper Rustler, the others to the lower part of the formation. The 30-foot gypsiferous dolomite, No. 2 in the sequence, is a persistent marker in the north half of the Delaware basin. For this stringer Lang favors the name Magenta member of the Rustler formation, after Magenta Point north of the Laguna Grande salt lake, and this name is used on the stratigraphic sections. For the 35-foot dolomite, No. 6 in the section, he favors the name Culebra member of the Rustler formation, from Culebra Bluff on the east side of the Pecos River where the member is well exposed. Because this member is a good marker in the subsurface, the name Culebra is also used in the cross sections."

p. 1614, para 5;

" Local features include a zone of euhedral quartz crystals in the anhydrite between the magenta and Culebra dolomites, and oölites in one or the other of the two main dolomite members. The oölites are most common in that part of the Rustler overlying the Capitan reef and the back-reef areas."

Algermissen, S.T., and Perkins, D.M. 1976. A Probabilistic Estimate of Maximum Ground Acceleration in the Contiguous United States. Open-file Report 76-416, pp. 1-45. U.S. Geological Survey.

INTRODUCTION, p 1;

" This paper presents a probabilistic estimate of the maximum ground acceleration to be expected from earthquakes occurring in the contiguous United States. It is based primarily upon the historic seismic record which ranges from very incomplete before 1930 to moderately complete after 1960. Geologic data, primarily distribution of faults, have been employed only to a minor extent, because such data have not been interpreted yet with earthquake hazard evaluation in mind.

The map provides a preliminary estimate of the relative hazard in various parts of the country. The report provides a method for evaluating the relative importance of the many parameters and assumptions in hazard analysis. The map and methods of evaluation described reflect the current state of understanding and are intended to be useful for engineering purposes in reducing the effects of earthquakes on buildings and other structures.

Studies are underway on improved methods for evaluating the relative earthquakes hazard of different regions. Comments on this paper are invited to help guide future research and revisions of the accompanying map.

The earthquake hazard in the United States has been estimated in a variety of ways since the initial effort by Ulrich (see Roberts and Ulrich, 1950). In general, the earlier maps provided an estimate of the severity of ground shaking or damage but the frequency of occurrence of the shaking or damage was not given. Ulrich's map showed the distribution of expected damage in terms of no damage (zone 0), minor damage (zone 1), moderate damage (zone 2), and major damage (zone 3). The zones were not defined further and the frequency of occurrence of damage was not suggested. Richter (1959) and Algermissen (1969) estimated the ground motion in terms of maximum Modified Mercalli intensity. Richter used the terms 'occasional' and 'frequent' to characterize intensity IX shaking and Algermissen included recurrence curves for various parts of the country in the paper accompanying his map.

The first probabilistic hazard maps covering portions of the United States were by Milne and Davenport (1969a). Recently, Wiggins, Hirshberg and Bronowicki (1974) prepared a probabilistic map of maximum particle velocity and Modified Mercalli intensity for the entire United States. The maps are based on an analysis of the historical seismicity. In general, geological data were not incorporated into the development of the maps."

Anderson, R.Y., 1978. Deep Dissolution of Salt, Northern Delaware Basin, New Mexico. Report to Sandia National Laboratories, Albuquerque, NM. WPO 29527 - WPO 29530.

Abstract, p v:

" Deep-seated dissolution in the Delaware basin has developed in association with the Capitan (reef) and the underlying Bell Canyon (Delaware) aquifers and at a more permeable horizon between the Castile and Salado formations. The uplift, erosion, and exposure of the reef in the Guadalupe and Glass mountains has channeled meteoric waters through the reef aquifer. These waters gained access to the salt through fractures around the reef margin, and dissolved overlying and superjacent salt by means of brine density flow. This type of deep dissolution moved into the salt beds laterally at a horizon of increased permeability between the Castile and Salado formations and dissolved a wedge that undercut the overlying evaporites. The deep-seated dissolution also produced a number of large-scale collapse structures along the basin margin and along the western edge of salt. This wedge-like effect, combined with surface dissolution, has removed 50 percent of the original salt from the basin and removed 70 percent of the original salt at the lower Salado horizon.

The water in the aquifers, by gaining access to overlying chambers though fractures, have also dissolved smaller scale localized chambers in overlying salt beds that subsequently collapse to form breccia pipes, deep-seated sinks, and other collapse structures. These features have been exhumed to different stratigraphic levels in the tilted and eroded basin, resulting in surface expression as limestone buttes (Castiles), collapsed outliers, domal structures with collapsed centers (breccia pipes), and deep-seated sinks. Many of the deep-seated sinks are associated with salt anticlines which probably formed as a result of differential stress from unloading related to dissolution. Localized collapse, as well as regional dissolution, is an ongoing process.

The W.I.P.P. site lies in a corner of the Delaware basin that has been relatively protected from regional but not localized effects of deep dissolution. Deep seated, wedge-like dissolution, however, has progressed from north to south in the basin and salt in the northern part of the Delaware basin will eventually be dissolved at the lower Salado horizons before overlying salt has been removed from the basin by processes of near-surface dissolution (suberosion)."

Introduction, p 1, para 1;

" Two types of salt dissolution, deep and shallow, can be recognized in the Delaware Basin. The more familiar shallow type is the result of the subsurface movement of undersaturated ground water across the upper surface of salt. Near-surface dissolution has left a residue at the top of the salt body of the Salado Formation referred to by Vine (1963) as the leached zone. Estimates of the rate of dissolution and surface lowering (suberosion) for this process can be obtained from ground water flow data or, indirectly, from the rate of retreat of the dissolving edge of the salt (Bachman and Johnson, 1973, p. 41; Jones, 1973, p 4; Bachman, 1974, p. 68; Piper, 1973).

A second type of salt dissolution can be recognized as having dissolved salt from somewhere within the body of evaporites, generally resulting in the collapse and lowering of the overlying stratigraphic units. This type of salt dissolution was recognized by Anderson and others (1972) as a blanket dissolution breccia which occurs to the west of the present salt edge in the basin. In addition, abundant evidence exists that deep-seated dissolution within the evaporites has resulted in more localized collapse features around the margin of the basin and within the basin. The origin of these deep dissolution features and breccias is more problematical than the origin of surface dissolution and the rates of dissolution more difficult to assess. This report summarizes investigations to recognize and delineate the effects of deep dissolution in the northern Delaware basin. It relates observed patterns of deep dissolution to probable hydrologic and tectonic factors and offers some explanations concerning the origin of the dissolution features. Finally, the report briefly summarizes the implications of the findings for the stability of the W.I.P.P. site."

POTENTIAL GEOLOGIC HAZARDS FROM DEEP-SEATED DISSOLUTION (Implications for the W.I.P.P. Site), p. 76;

" <u>Long-term Hazards</u>:

The northern part of the Delaware basin has been relatively protected from the effects of advancing deep dissolution from the west and from the development of large dissolution depressions and a wedge along the reef margin. The area selected for the site is about equidistant from large-scale dissolution features to the southwest, southeast, and northwest. Of the possible locations in the basin, the present site is probably the best available from the standpoint of large-scale features of deep dissolution.

The Delaware basin itself, however, has been extensively affected by deep dissolution and the disposal horizons selected are the ones most susceptible to the process. I hesitate to make estimates of long-term site stability on the basis of what little information is available concerning the timing of the uplift and the age of the dissolution-related deposits. A general idea can be obtained by a slightly different approach than using the rate of advance of a dissolution edge as was done by Bachman and Johnson (1973). About 50 percent of the original volume of salt from the salt beds of the Castile and Salado formations has been dissolved from the basin. The removal of salt from the beds below the middle Salado probably did not begin until the western edge of the basin was well exposed and until a considerable volume of salt had already been removed from the upper Salado units. If we assume as Bachman and Johnson (1973, p. 39) did, that the stripping of the protective Ogallala Formation began about 4 m.y. ago, we can use this figure as a starting point for the beginning of deep dissolution. If we also assume a linear relationship (probably not a valid assumption) and that 73 percent of the lower Salado salt has been dissolved since that time, then the salt from that unit will be gone from the basin in about another million years.

For the site area, this would probably be a minimum estimate of the time until total dissolution of the lower Salado unit because of the protection afforded by the northeast corner of the basin, unless, of course, the 4 m.y. assumption is incorrect or if the dissolution rate should be nonlinear and faster during later stages."

Anderson, R.Y., and Kirkland, D.W. 1980. Dissolution of Salt Deposits by Brine Density Flow. Geology, Vol. 8, No. 2, pp. 66–69.

ABSTRACT, P 66;

" The origin of collapse structures and breccias that vertically penetrate or occur within impermeable evaporites has never really been understood. The density of the brine that develops as salt deposits are dissolved can generate continuous gravitational brine movement. If the source of the dissolving water is artesian, or continuous, a flow cycle is developed in which the salt itself supplies the density gradient that becomes the vehicle of its own dissolution. The Delaware Basin in western Texas and southeastern New Mexico provides a particularly good example of how brine density flow can produce dissolution chambers that collapse to form breccias. The potential for dissolution by brine flow is an inherent property of partly exhumed evaporites and may constitute a risk factor in the storage of radioactive waste in evaporite deposits."

Anderson, R.Y., 1981. "Deep-Seated Salt Dissolution in the Delaware Basin, Texas and New Mexico." In Environmental Geology and Hydrology in New Mexico, S.G. Wells and W. Lambert, eds., Special Publication No. 10., pp. 133-145. New Mexico Geological Society.

ABSTRACT, p 133, col 1;

"   Patterns of salt dissolution in the Delaware Basin are related to the bedrock geometry and hydrology that developed following uplift, tilting, and erosion in the late Cenozoic, and the greatest volume of salt has been removed since that time. During the Permian, some salt was dissolved from the top of the Castile Formation before deposition of the Salado Formation and from the top of the Salado before deposition of the Rustler Formation. In addition, some salt dissolution occurred after the Permian and before the Cretaceous. Post-uplift surface dissolution has progressed across the Delaware Basin from south to north and from west to east and generally down the regional dip. Deep-seated dissolution has occurred around the margin of the basin where the Capitan Limestone aquifer is in contact with the Permian evaporites and within the basin where selective dissolution in the lower Salado has undercut the overlying salt beds of the middle and upper Salado. Dissolution has not advanced down regional dip uniformly but has left outliers of salt and has progressed selectively into structurally predisposed areas. This selective advance has significance for the stability of the U. S. Department of Energy's Waste Isolation Pilot Plant (WIPP) site."

Reef and Reef-Margin Dissolution, p 137, col 2;

"   The inner margin of the reef, where buried around the northern and eastern sides of the basin, is the locus of a number of deep-seated dissolution features. Some of the small isolated domes in the northern part of the basin described by Vine (1960) (fig. 2) have recently been cored as part of the WIPP exploration, and Dome A exhibits collapse and brecciation to a depth equivalent to the top of the reef (D. Powers, personal commun.). The eastern chain of large dissolution depressions of Maley and Huffington (1953) occupy an equivalent position with respect to the reef margin. The absence of Salado salt in the deeper part of these depressions indicates that they 'root' in or above the Capitan reef aquifer. A depression occupying the same position with respect to the reef appears to have controlled the western edge of Salado salt where it crosses the reef in the northern part of the basin (fig. 2 and illustrated by Brokaw and others, 1972). Both San Simon Sink and its surrounding depression, San Simon Swale (fig. 2), have developed relatively recently along the inner reef margin in the northeastern corner of the basin. A new sink developed in June, 1980 between Kermit and Wink, Texas (fig. 2)(Baumgardner and others, 1980) on the edge of one of the depressions defined by Maley and Huffington (1953)."

STAGE AND RATE OF DISSOLUTION, p. 144, col. 1, para. 4;

"   Compared to some other evaporite basins on the continental platform containing even older salt beds, such as the Michigan Basin or the evaporites in Saskatchewan, the Delaware Basin with 50 percent of the salt removed has reached a rather mature stage of dissolution.

This is reflected in the size, abundance, and distribution of dissolution features.

. . .

This schedule of uplift and exhumation agrees quite well with the age of the stratigraphic and geomorphic units associated with dissolution in the basin for which some age information is available. Substantial dissolution is associated with Gatuna Formation which is probably early Pleistocene and pre-Kansan in age (Bachman, 1974, P. 28). The Mescalero surface, which is developed on top of Gatuna sediments and which developed after the formation of the major features in the central part of the basin (i.e., Big Sinks depression) has been dated indirectly with an ash bed at about 600,000 years (Bachman, 1980). Deposits associated with the recent development of Nash Draw was placed in the Wisconsin. San Simon Swale and Sink sediments are no older than about 50,000 years."

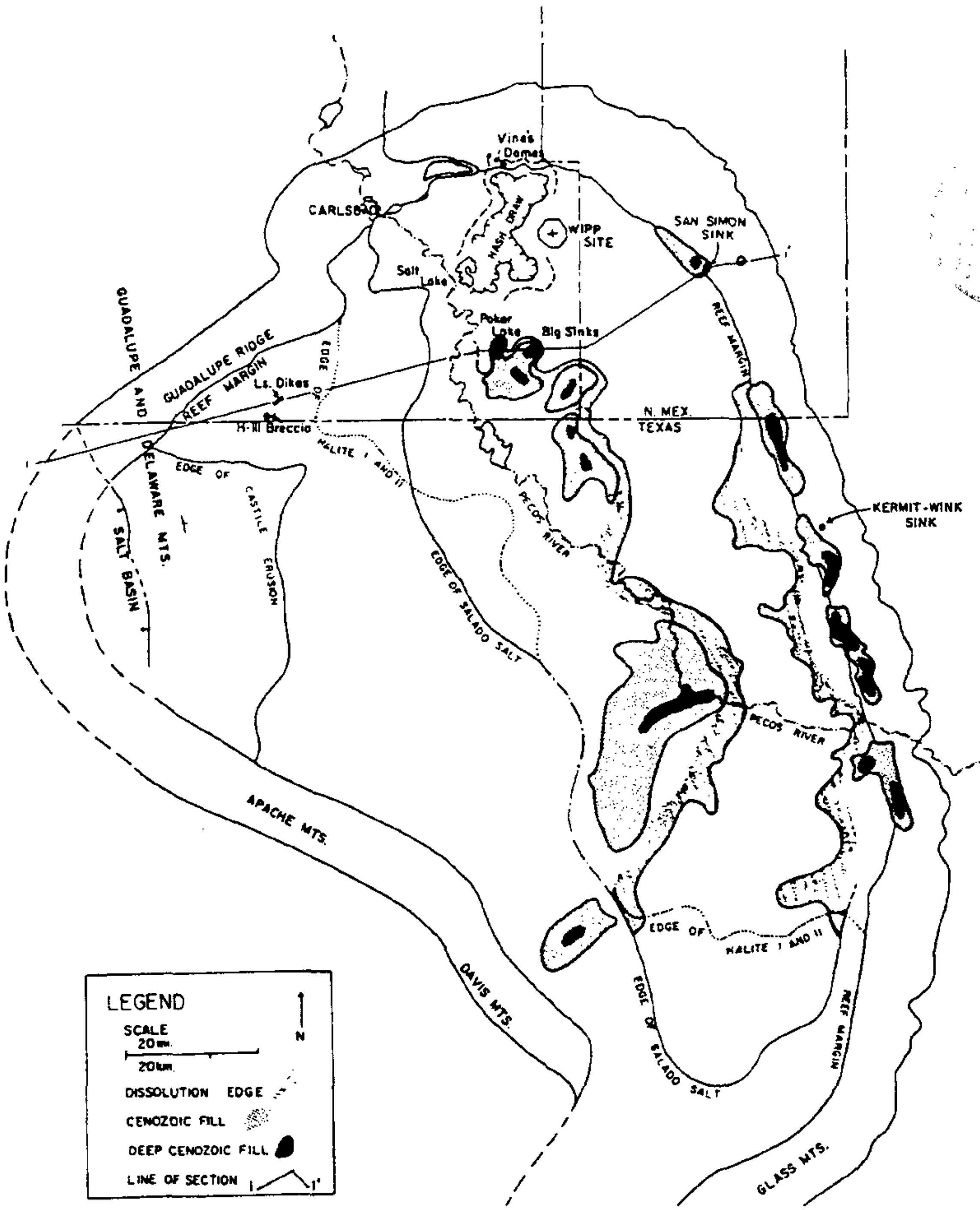


Figure 2. Map of Delaware Basin showing location of Capitan reef, major dissolution depressions, and western dissolution edge of evaporites and of major salt units.

Anderson, R.Y. 1993. "The Castile as a 'Nonmarine' Evaporite." In Carlsbad Region, New Mexico and Texas, New Mexico Geological Society, Forty-Fourth Annual Field Conference, Carlsbad, NM, October 6-9, 1993, D.W. Love et al., eds., pp. 12-13. New Mexico Geological Society, Socorro, NM.

p 12, col 2;

" After King (1947) showed that the low proportion of halite to anhydrite in the Castile evaporite could be explained by the reflux of brine from the Delaware Basin, the Castile became the classical example of a marine, 'deep water' evaporite. Anderson and Dean (in press) have reexamined the distribution of evaporites units, as well as geochemical evidence and they suggest that reflux is not the only way to explain the compositional and stratigraphic relationships of the Castile. According to the alternate explanation, the brine was not a residual of sea water flowing directly into the basin. Rather, it is suggested that chloride recharge was from ground water seeping into the basin from the south, especially during lowstands (Fig. 1.12a), with the brine derived from a partly marine source or from previously deposited evaporites. In this model, the Delaware Basin was a hydrologically closed basin with water level subject to extreme highstands (Fig. 1.12b) and lowstands, a type of response similar to that observed in existing closed basins in western North America.

Support for a closed-basin model can be found in the record of climatic variability that is preserved in the Castile. For example, millennial oscillations in climate and lake level are strongly expressed in the closed hydrologic basins in western North America during the late Pleistocene. Millennial cycles also are dominant in the Castile and determine the incidence and duration of halite accumulation (lowstands). Cycles of precession and eccentricity also are well defined in the Castile and in the record of the ocean and cryosphere over the past million years. The occurrence of climate cycles recognized in the Pleistocene and Holocene does not address the question of marine recharge for the Castile. However, strong expression of the same climatic periodicities within the Castile is consistent with a closed-basin hydrologic setting and meteoric recharge.

More direct evidence for meteoric recharge can be seen in the depletion of ^{18}O in limestone beds along the western margin of the basin (Magaritz et al., 1983) and in rapid, synchronous changes in the seasonal rate of accumulation of calcium sulfate (freshening events) that resulted in beds of laminated limestone. Such events can be traced from the western margin to the center of the basin, suggesting that a significant volume of meteoric recharge entered the basin from the west during those times when water level was at or near a highstand (Fig. 1.12b). Other evidence for meteoric contributions can be found in the low bromine concentrations in halite, which give the Castile an affinity with other nonmarine evaporites. Ground-water recharge of ions derived from preexisting evaporites provides an alternate mechanism to account for the low ratio of halite to sulfate.

The geometrical relationships of stratigraphic units provides indirect evidence for ground-water recharge and for large changes in water level within the Delaware Basin. For example, as the basin filled with sediment there was a southward shift in the locus of thick accumulation of halite (Fig 1.12c) that can best be explained if water level was initially drawn down to a minimum pool several hundred meters below the basin rim (Fig 1.12a). Reflux during such lowstands seems unlikely. Also, beds of laminated halite are thicker to the north, implying that seasonal accumulation of halite was less continuous in the south, even during lowstands, as would be expected if chloride entered the basin in ground water.

Although no single line of evidence eliminated direct marine inflow as a source for the brine, the strong response to climate forcing, combined with evidence for drawdown and meteoric contributions, leaves the clear possibility that the Delaware Basin was isolated from the sea."

Figures are not included. Unable to scan into document without breaking backing of original document. This document is otherwise totally included.

Anderson, R.Y., Dean, W.E., Jr., Kirkland, D.W., and Snider, H. I. 1972. "Permian Castile Varved Evaporite Sequence, West Texas and New Mexico." Geological Society of America Bulletin, Vol. 83, No. 1, pp. 59-85.

ABSTRACT; p 59, col 1;

" Laminations in the Upper Permian evaporite sequence in the Delaware Basin appear in the preevaporite phase of the uppermost Bell Canyon Formation as alternation of siltstone and organic layers. The laminations then change character and composition upward to organically laminated claystone, organically laminated calcite, the calcite-laminated anhydrite typical of the Castile Formation, and finally to the anhydrite-laminated halite of the Castile and Salado.

Laminae are correlative for distances up to 111 km (70.2 mi) and probably throughout most of the basin. Each laminae is synchronous, and each couplet of two laminated components is interpreted as representing an annual layer of sedimentation--a varve.

The thickness of each couplet in the 260,000-varve sequence (a total thickness of 447.2 m, (1465 ft) has been measured individually and recorded and provides the basis for subdividing and correlating major stratigraphic units within the basin. The uppermost 9.2 m (30.3 ft) of the Bell Canyon Formation contains about 50,850 varve couplets; the Basal Limestone Member of the Castile about 600; the lowermost anhydrite member of the Castile (Anhydrite I) contains 38,397; Halite I, 1,063;Anhydrite II, ??,414; Halite II, 1,758; Anhydrite III, 46,592; Halite III, 17,879; and Anhydrite IV, 54,187. The part of the Salado collected (126.6 m) contains 35,422 varve couplets. The Bell Canyon-Castile sequence in the cores studies is apparently continuous, with no recognizable unconformities.

The dominant petrologic oscillation in the Castile and Salado, other than the laminations, is a change from thinner undisturbed anhydrite laminae to thicker anhydrite laminae that generally show a secondary or penecontemporaneous nodular character, with about 1,000 to 3,000 units between major oscillations or nodular beds. These nodular zones are correlative throughout the area of study and underly halite when it is present. The halite layers alternate with anhydrite laminae, are generally recrystallized, and have an average thickness of about 3 cm. The halite beds were once west of their present occurrence in the basin but were dissolved, leaving beds of anhydrite breccia. The onset and cessation of halite deposition in the basin was nearly synchronous.

The Anhydrite I and II Members thicken gradually across the basin from west to east, whereas the Halite I, II, and III Members are thickest in the eastern and northeastern part of the basin and thicken from southeast to northwest. This distribution and the synchroneity indicate a departure from the classical model of evaporite zonation."

SUBDIVISION AND DISTRIBUTION OF THE CASTILE AND UPPERMOST BELL CANYON FORMATION, p. 73, col. 1, para. 3;

" The Castile Formation has been subdivided here into eight members which permit examination of the present areal distribution patterns of halite and anhydrite."

TABLE 2. SUBDIVISIONS OF THE UPPER BELL CANYON-CASTILE SEQUENCE, DELAWARE BASIN, TEXAS AND NEW MEXICO.

UNM-Phillips #1			
Formation	Number of varve couplets	Thickness	Average thickness of calcite-anhydrite varve couplets
Salado Formation (partial section, undifferentiated)	35,422	12,660 cm	0.36 cm
Members			
Castile Formation			
Anhydrite IV	54,187	9,842 cm	0.18 cm
Halite III (including anhydrite beds)	*17,879	2,748 cm	0.16 cm
Anhydrite III	46,592	9,554 cm	0.21 cm
Halite II (including anhydrite beds)	+ 1,758	801 cm	0.45 cm
Anhydrite II	14,414	2,738 cm	0.19 cm
Halite I	+ 1,063	330 cm	0.31 cm
Anhydrite I	38,397	5,092 cm	0.13 cm
Basal Limestone	600	28 cm	0.04 cm
Estimated totals (Castile Formation)	174,890	31,133 cm	
Units			Average thickness of clastic-organic varve couplets
Bell Canyon Formation			
Claystone III	5,800	78 cm	0.01 cm
Siltstone III	24,814	551 cm	0.02 cm
Claystone II	15,650	166 cm	0.01 cm
Siltstone II	1,086	44 cm	0.04 cm
Claystone I	++ca 2,000	24 cm	ca. 0.01 cm
Siltstone I	++ca 1,500	61 cm	ca. 0.04 cm
Estimated totals (Bell Canyon Formation)	50,850	924 cm	
Combined totals	261,162	44,717 cm	

• Number of layers i halite fraction determined by extrapolation.
\+ Number of layers determined in Union-University "37" #4 core; thickness of calcite-anhydrite fractions only.
++ Number of layers in UNM-Cowden #4 core.

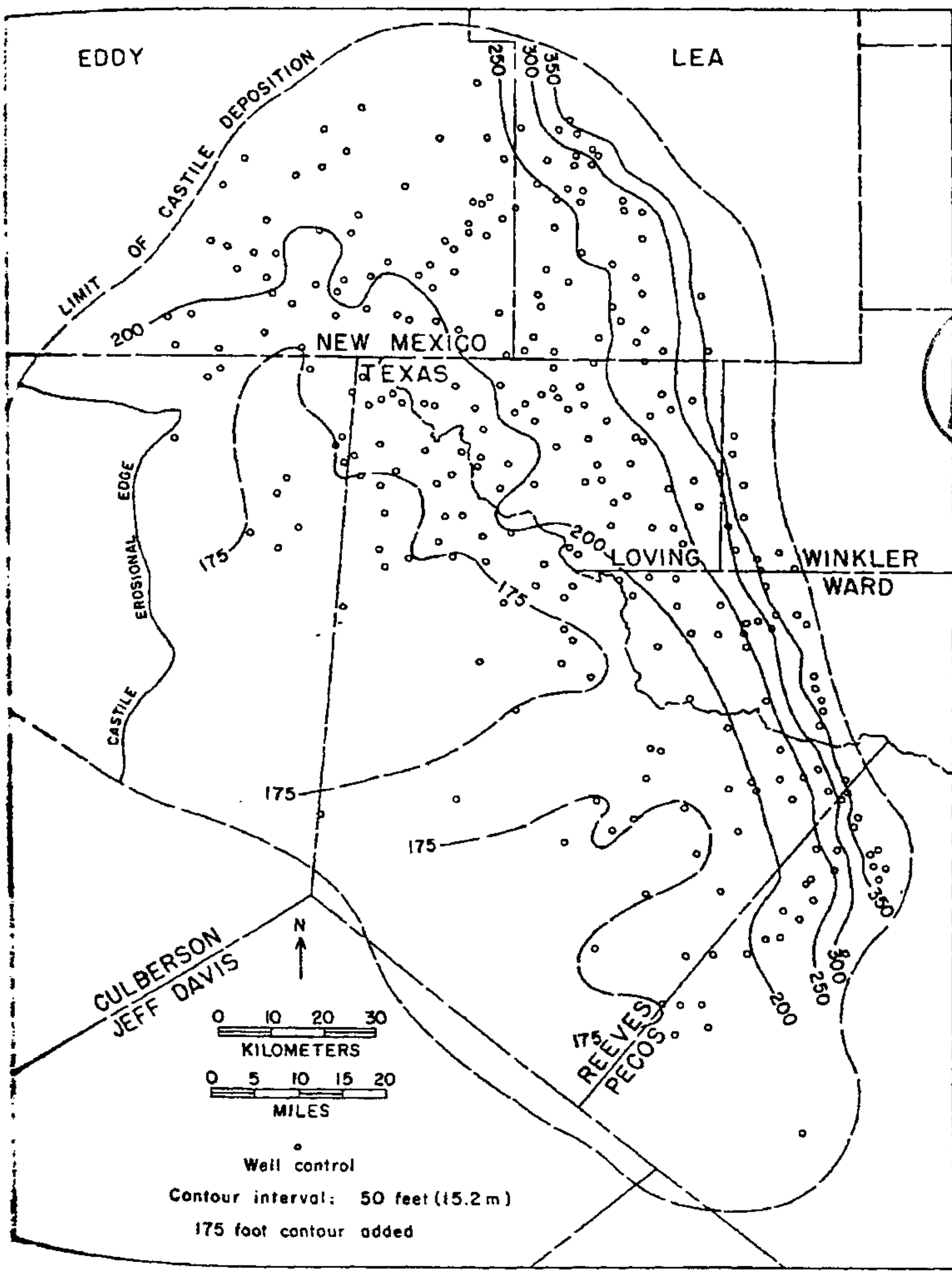


Figure 10. Thickness distribution of Anhydrite I Member, Castile Formation.

EFFECTS OF SOLUTION, p 81, col 1;

" The interpretation that breccia beds in the University of New Mexico-Phillips no. 1 core represented halite beds in the eastern part of the basin had been made on the basis of sonic log correlations prior to the availability of the Union-University '37' halite core. The Winkler County core, however, revealed that thin anhydrite beds of only a few decimeters thick within more massive halite units maintained their position and character after halite solution. This fact, and the observation that single anhydrite laminae, once separated by several centimeters of halite, were sometimes little disturbed upon solution, showed that the withdrawal of halite was a very gentle process.

With the exception of one halite bed in Anhydrite IV, every halite bed observed in the Winkler County core from the eastern part of the basin has an equivalent breccia bed in the University of New Mexico-Phillips no. 1 core. Inasmuch as this core locality is only about 32 km (20 mi) from the western edge of the basin, there is every reason to suppose that halite deposition once extended to, or nearly to, the western margin. The present western solution margin of halite units within the Castile shifts progressively eastward, with Halite II more areally restricted than Halite I. The halite in the Salado, however, extends farther westward than the present western solution limit of Castile halite (fig. 8). This suggests that an episode of solution might have taken place prior to Salado deposition. The isopach map of the halite beds within Anhydrite IV (Fig. 17) shows a very irregular distribution of halite in the east-central and northeastern part of the basin that is not present in any of the lower Castile halites and could also represent solution prior to Salado deposition.

It seems more likely, however, that all of the solution took place after Salado time and that the irregular distribution pattern in Anhydrite IV developed later. A comparison of the Anhydrite IV isopach for halite and the published map of Tertiary basin fill of Maley and Huffington (1953) shows a very close agreement between the locus of Cenozoic basin fill in the Delaware Basin and the areas of thin or missing halite in Anhydrite IV. Similarly, there is also a correlation between the Cenozoic basins and thin areas in the Salado."

Anderson, R.Y., and Powers, D.W. 1978. "Salt Anticlines in the Castile-Salado Evaporite Sequence, Northern Delaware Basin, New Mexico." In Geology and Mineral Deposits of Ochoan Rocks in Delaware Basin and Adjacent Areas, G.S. Austin, ed., Circular 159. pp. 79-83. New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.

ABSTRACT, p 79, col 1, para 1;

" A number of structures have been encountered within the body of the Castile-Salado evaporites that can reasonably be interpreted as salt anticlines. One such structure, associated with brine, H_2S, and dissolution effects, was found during exploratory coring for the proposed nuclear waste disposal site near Carlsbad, New Mexico. Correlation of stratigraphic units in the recovered core with cores and logs from nearby boreholes shows that the middle anhydrite unit (A-II) of the Castile Formation, which attains dips of as much as 70°, has been displaced vertically by as much as 950 ft (290 m). Extension fractures in the A-II unit suggest that it has been stretched over a pod of exceptionally thick salt of the lower halite unit (H-I) of the Castile Formation that moved into the axis of the anticlinal structure. Exceptionally thick and thin units of lower salt (H-I) occur in other nearby boreholes in a zone of deformation marginal to the reef. Suspected salt anticlines also occur at scattered localities in the northern part of the Delaware Basin. The association of extension fracturing to microfolding in the middle anhydrite unit (A-II) suggests that salt deformation accompanied or followed Cenozoic uplift and tilting of the basin."

p 83, col 1, para 1, line 7;

" . . . It is even conceivable that original dissolution, particularly around the margin of the basin, may have developed the differential loading required to initiate salt movement."

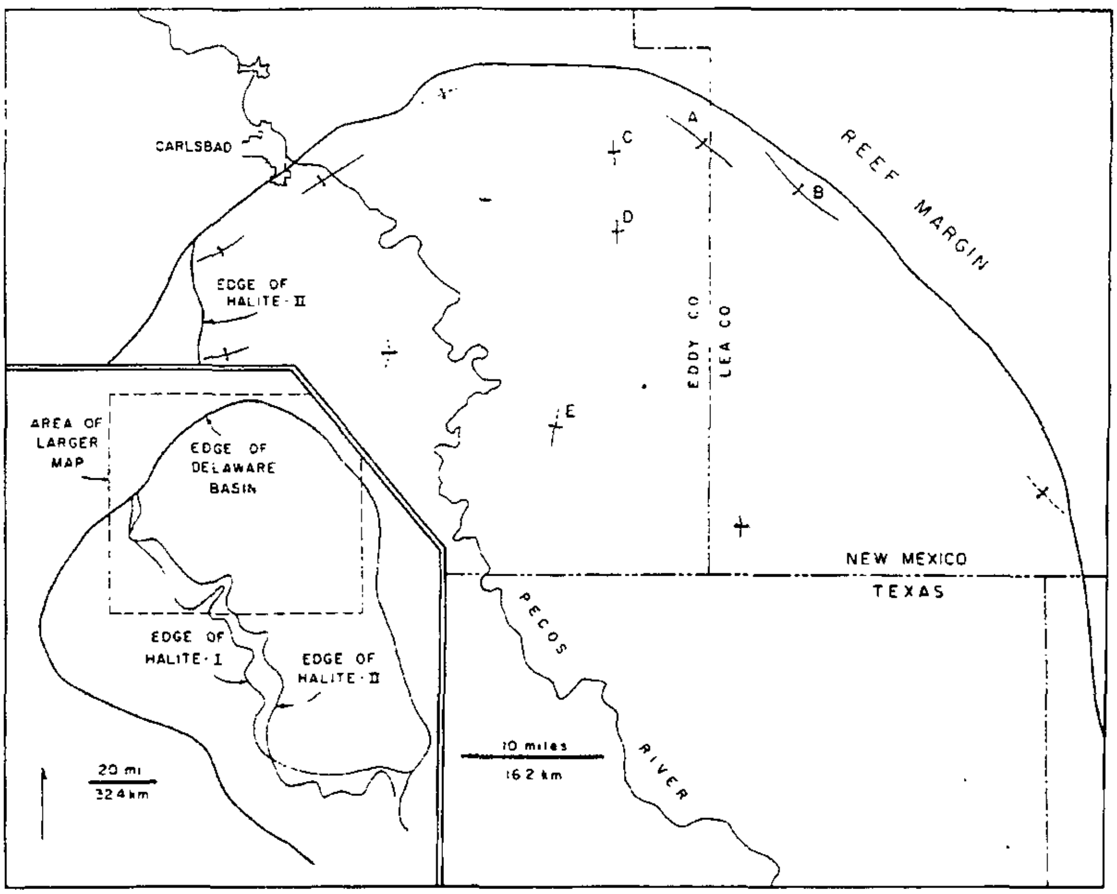


FIGURE 1—Index map showing the distribution of the lower two halite beds (I and II) of the Castile Formation and the location of anticlinal structures developed within those salts. Structures with dashed pattern were located with only one data point. ERDA No. 6, AEC No. 7, and AEC No. 8 are wells drilled on top and on the flanks of structure A.

FIGURE 3—SLABBED AND POLISHED SECTION FROM THE UPPER ANHYDRITE SHOWN IN FIG. 2. a indicates calcium sulfate filling "pull-apart" structures; b indicates zone of cross-hatched fracture pattern.

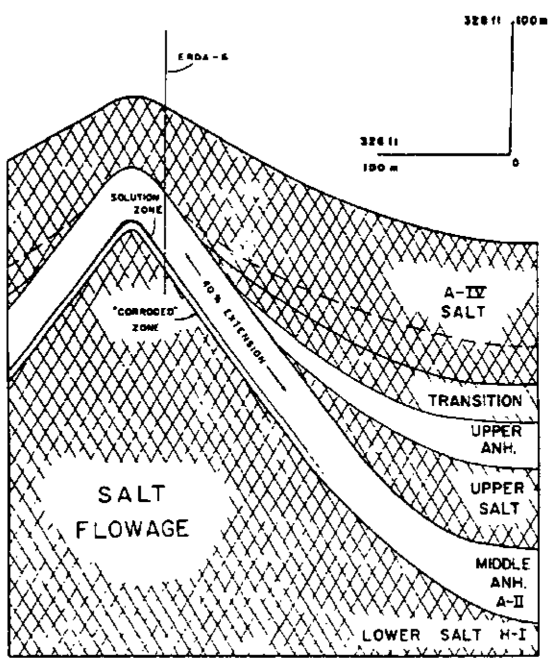


FIGURE 4—DIAGRAMMATIC CROSS SECTION OF STRUCTURE AT ERDA No. 6, ILLUSTRATING LOSS OF STRATIGRAPHIC SECTION AND FLOWAGE IN HALITE I OF CASTILE FORMATION. The middle anhydrite was encountered at a depth of 2,550 ft.

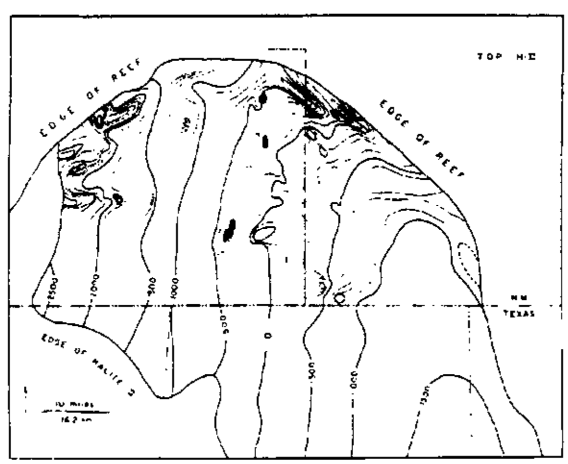


FIGURE 5—STRUCTURE CONTOUR MAP ON THE TOP OF SECOND HALITE OF CASTILE FORMATION (HALITE II). General N-S strike of the bed and gentle (1°) eastward dip is also reflected very well by the Bell Canyon Formation underlying the Castile Formation, but the Bell Canyon Formation does not have the smaller anticline and syncline pattern. Structures with dashed pattern were located with only one data point.

Anderson, R.Y., Kietzke, K.K., and Rhodes, D.J. 1978. "Development of Dissolution Breccias, Northern Delaware Basin, New Mexico and Texas." In Geology and Mineral Deposits of Ochoan Rocks in Delaware Basin and Adjacent Areas, G.S. Austin, ed., Circular 159. New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.

ABSTRACT, p. 47;

" Beds of dissolution breccia are persistent in Castile-Salado evaporites in the western part of the Delaware Basin. Dissolution breccia consists of subangular to somewhat rounded and elongate fragments of individual laminae of calcite-laminated anhydrite set in an anhydrite matrix. Collapse breccias consisting of angular fragments of laminated anhydrite with little or no matrix often overlie dissolution breccias or may occur separately within the anhydrite some distance above dissolution horizons. Correlation of individual calcite-laminated anhydrite laminae associated with dissolution breccias with the same laminae associated with halite beds shows that dissolution breccias are equivalent to halite beds. Even the thinnest halite beds in the eastern part of the basin once extended west of their present distribution, probably to near the western margin of the basin. The tracing of identified dissolution horizons to large areas of deep dissolution west of existing halite beds shows that it is removal of salt from the lower part of the Salado and upper part of the Castile Formation that has caused collapse of the depressions."

Bachman, G.O. 1973. Surficial Features and Late Cenozoic History in Southeastern New Mexico. Open-File Report 4339-8. U.S. Geological Survey, Reston, VA..

ABSTRACT, p. 1;

" Since deposition of the Ogallala Formation during Pliocene time, southeastern New Mexico has been subjected to erosion, solution, subsidence, and widespread eolian activity. These processes have combined to influence the formation and morphology of major drainage systems. Aligned drainage patterns resulted from solution of caliche localized by longitudinal sand dunes. San Simon Swale appears to have formed by processes of erosion and solution-subsidence of Permian evaporites, and was formerly an important tributary to the Pecos River. The combination of processes that formed San Simon Swale was similar to the combination of erosion and coalescing sinks that formed the lower Pecos Valley in southern New Mexico.

Caliche on the Mescalero Plain, p 17;

" A prominent caliche formed on deposits overlying the Mescalero Plain is the most extensive physiographic surface in southeastern New Mexico. The surface is an uneven one that has been disrupted by solution-subsidence. It is about 150-250 feet above the floodplain of the Pecos on the west and rises gradually toward the High Plains on the east. To the northeast, near Mescalero Ridge, the surface rises to 3,800-4,100 feet in altitude; south of Big Sinks, it descends to about 3,100 feet.

Caliche on the Mescalero Plain is 3-5 feet thick, light gray to white, and sandy. The beds are nodular, with some concretionary growth on the nodules; but the concretionary growth is not as pronounced as on the pisolitic limestone of the Ogallala. Most of the nodules are randomly oriented, but the long axes of some are horizontal. Vertical caliche veinlets indicate several generations of solution and recementation. Occasional pipes 1 foot in diameter or more penetrate 2 or 3 feet into the caliche from the top and are filled with light-reddish-brown sandy soil. Some of these pipes pass entirely through the caliche bed. They presumable represent the former position of roots. Dissolution of this caliche is greater at the depressions. At numerous places on the Mescalero Plain the caliche thins towards depressions, and in some of these depressions the caliche is entirely absent.

The caliche on the Mescalero Plain is the remnant of an extensive soil profile. At places a younger sandy soil is preserved above the caliche but the surface is covered over broad areas by Pleistocene or Holocene windblown sand. This surface is correlative with Surface II of Leonard and Frye (1962, p. 11-12) in the Pecos region of Texas. The Mescalero Plain is analogous to the Jornada-La Mesa surface in the Rio Grande trough in southern New Mexico. Faunal remains indicate that rounded gravels on the Jornada-La Mesa surface are Kansan or younger (Ruhe, 1962, p. 163). Owing to lack of more positive evidence, it is here suggested that the Mescalero Plain formed in early to middle Pleistocene time."

Bachman, G.O., 1974. Geologic Processes and Cenozoic History Related to Salt Dissolution in Southeastern New Mexico, Open-File Report 74-194, U.S. Geological Survey. Denver, CO.

ABSTRACT, P 1;

" Salt of Permian age in the subsurface of an area near The Divide, east of Carlsbad, N. Mex., is being considered for a nuclear waste repository. The geologic history of the region indicates that dissolution of salt has occurred in the past during at least three distinct epochs: (1) after Triassic but before middle Pleistocene time; (2) during middle Pleistocene; and (3) during late Pleistocene. Thus, destructive geologic processes have been intermittent through more than 100 million years.

Nash Draw, near The Divide, formed during late Pleistocene time by the coalescing of collapse sinks. The rate of its subsidence is estimated to have been about 10 cm (0.33 ft) per thousand years. The immediate area of the Divide adjacent to Nash Draw has not undergone stress by geologic processes during Pleistocene time and there are no present indications that this geologic environment will change drastically within the period of concern for the repository."

SUMMARY OF EROSION AND SALT DISSOLUTION, p 6, para 3;

" 1. The western part of the Delaware basin (fig. 2) was exposed to erosion, and presumably salt dissolution, possibly as early as Triassic time and certainly as early as Jurassic time. This period of exposure may have been as long as 50 m.y. However, surface relief was probably low and erosion was not deep. Rocks of Triassic age covered much of the Delaware basin and helped to protect some of the underlying Permian beds. In the western part of the basin, however, Triassic rocks were stripped away, if they were ever deposited, and some erosion and dissolution of Permian rocks probably occurred.

2. During Cretaceous tine the Delaware basin was submerged beneath the sea, but at the close of cretaceous time regional uplift and major erosion occurred. This period of erosion lasted from the close of Cretaceous until late in Tertiary (Miocene) time, possibly a period of as much as 50 m.y. At the beginning of Tertiary time Cretaceous rocks blanketed the basin and protected the underlying rocks, but before the Ogallala Formation was deposited most of these Cretaceous rocks had been eroded away from the western half of the basin. Erosion again exposed the Permian rocks to dissolution. Some dissolution of Permian salt occurred at this time in the vicinity of San Simon Swale.

3. While the Ogallala Formation was being deposited there was very little, if any, erosion in the Delaware basin. During the past 3-4 m.y. since Ogallala time, wide fluctuations in climate have occurred and erosion and dissolution have been intermittent. The most humid climate and the greatest erosion were during middle Pleistocene time when the Gatuna Formation was being deposited. Then streams were capable of severely eroding the western escarpment of the High Plains as well as eroding and carrying pebble debris from as far to the west as the Sierra Blanca and Capitan uplifts (fig. 9). Rainfall probably exceeded 600 mm (25 in.) per year and it is assumed that major dissolution of salt in the Delaware

basin occurred at this time--more than 600,000 years ago.

4. After Gatuna time, but still during the middle Pleistocene, the region became more stable and semiarid. The Mescalero caliche accumulated in this climate. During late Pleistocene time, however, there were again periods of humidity accompanied by erosion and dissolution of salt. As a result of these processes the Mescalero caliche has subsided locally and collapsed into sinks.

5. Although erosion and dissolution are still, active processes, the climate during Holocene time has been somewhat more arid than during the late Pleistocene. Present climate is neither as humid nor as arid as extremes of the past and it may represent an average of the past 1 m.y.

6. I have estimated that at one place in Nash Draw, dissolution of salt and accompanying subsidence of the surface has been about 58.5 m (180 ft) during the past 600,000 years."

Gatuna Formation, p. 22, Para. 2;

" The Gatuna Formation of Pleistocene age was named for exposures of light-reddish-brown sandstone and conglomerate more than 25 m (80 ft) thick in Gatuna Canyon, eastern Eddy County (Robinson and Lang, 1938, p. 84-85). A type section has not been described. The physical stratigraphy and field relationships of this formation indicate that it was deposited during the most moist conditions that prevailed in southeastern New Mexico during Pleistocene time. Because of the indications of climatic conditions inherent in the Gatuna Formation it was examined carefully at many exposures during the present study.

The Gatuna Formation is well represented along the east side of Clayton Basin where it rests on rocks of Permian age and is overlain by the Mescalero caliche that formed during Pleistocene time. The Gatuna is also present around Nash Draw where it was mapped by Vine (1963, p. 31) who stated that Gatuna deposition 'followed immediately after, or in part accompanied, a period of active solution in the Rustler and Salado Formations.' In the vicinity of Crow Flats, Chaves County, the Gatuna Formation is also associated with extensive solution of gypsum and salt and subsequent collapse of the surface. The Gatuna is well exposed in Long Arroyo, Chaves County, and is present at many outlying localities along the Pecos River drainage.

The Gatuna Formation was examined in the type area during the present study. A stratigraphic section was measured on the north side of Gatuna Canyon (SW 1/4 SW 1/4 sec. 36, T. 19 S., R. 30 E.). Although the Gatuna is estimated to be thicker at other localities, this locality is the least disturbed by slumping and is one of the better exposed in Gatuna Canyon. For these reasons it is here proposed that this locality be regarded as a reference section for the Gatuna Formation in the type area."

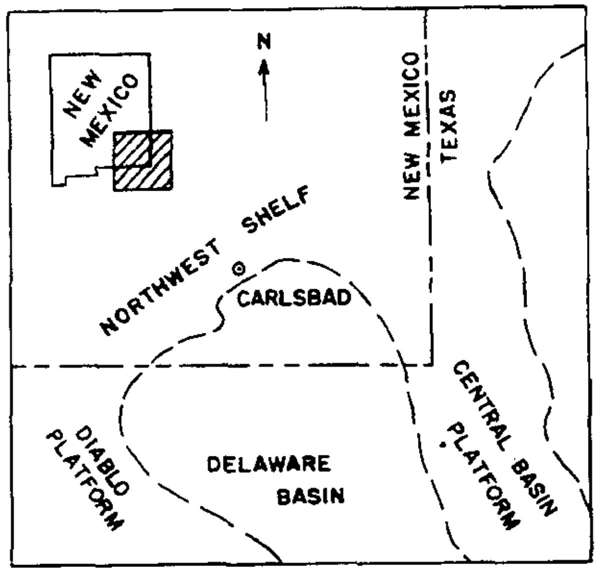


Figure 2.--Index map showing subsurface features in southeastern New Mexico.

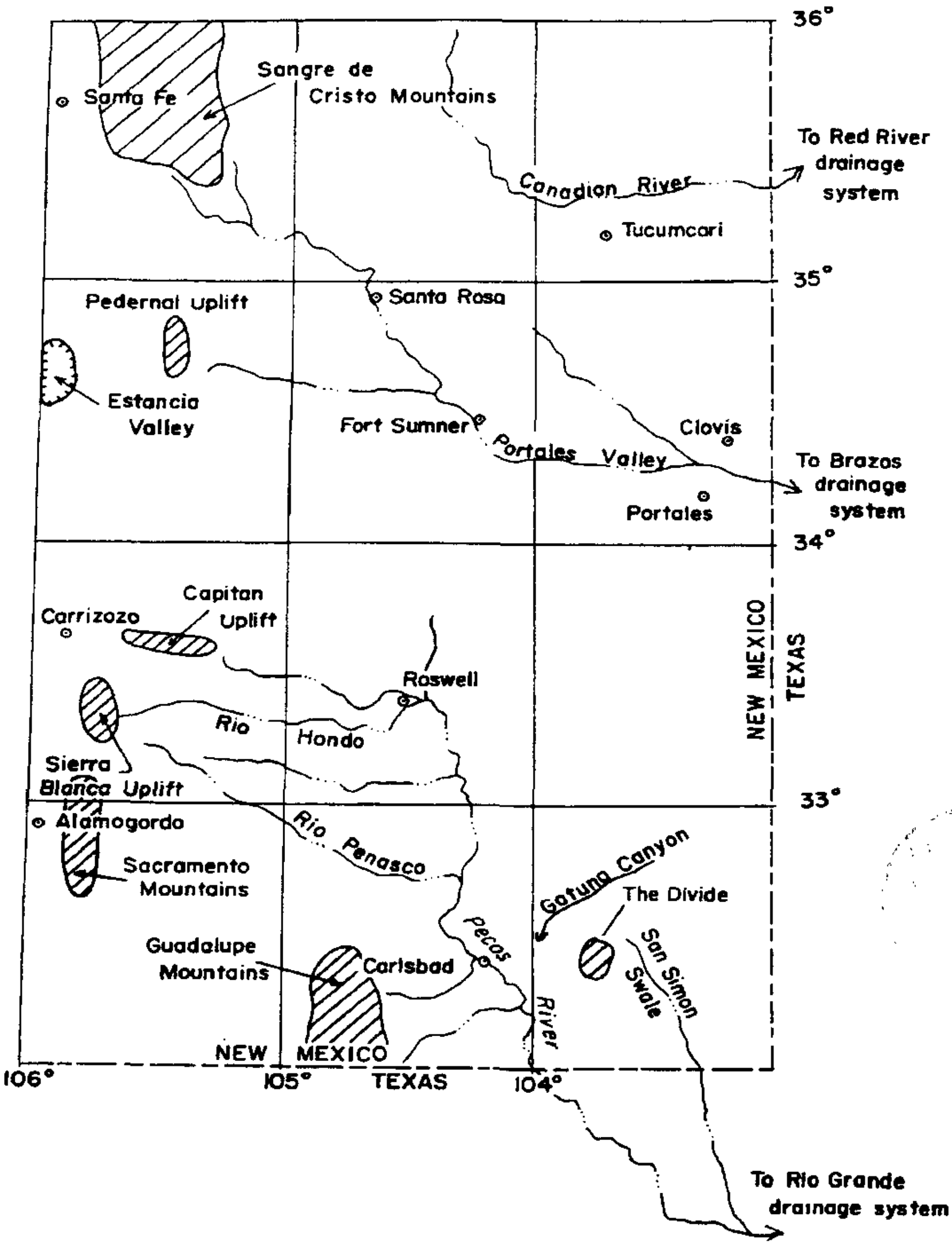


Figure 9.--Map showing middle Pleistocene drainage systems in southeastern New Mexico.

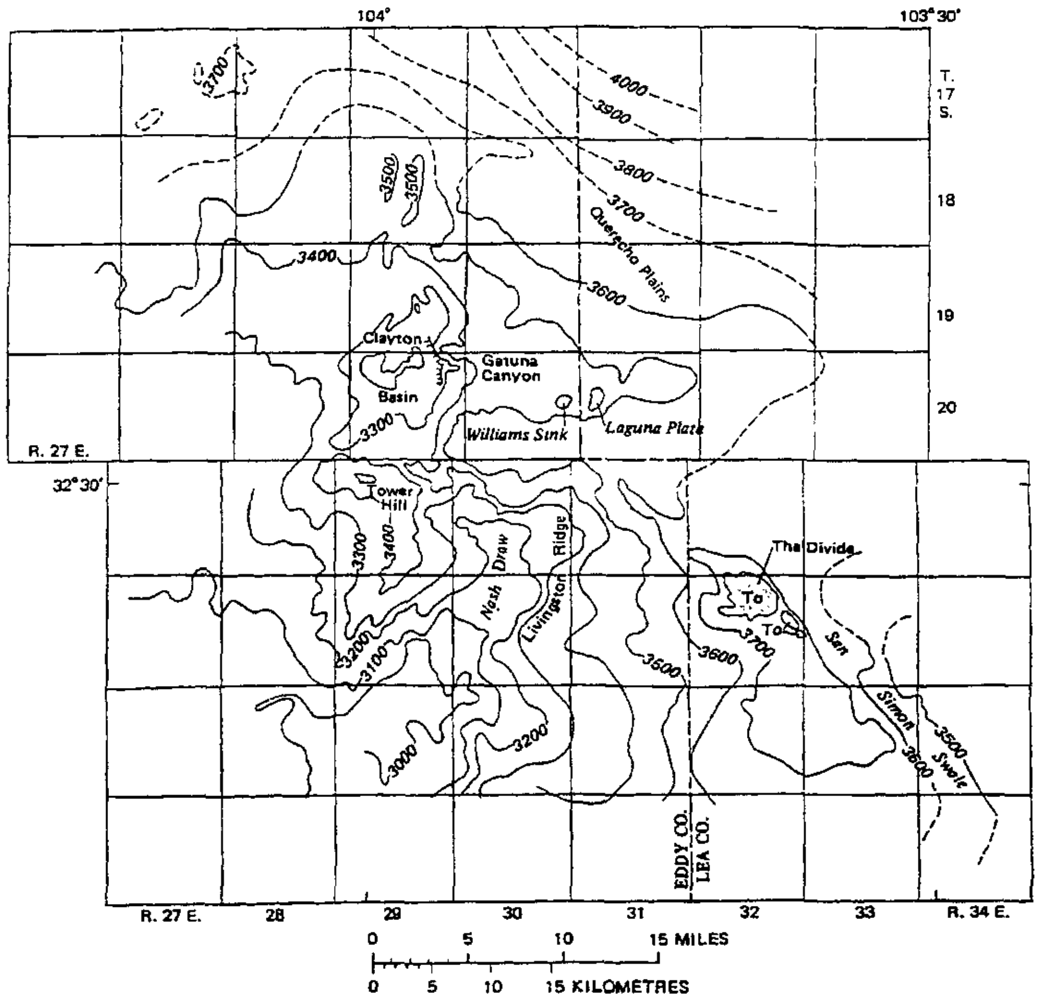
Bachman, G.O., 1976. "Cenozoic Deposits of Southeastern New Mexico and an Outline of the History of Evaporite Dissolution." Journal of Research, Vol. 4, No. 2, pp. 135-149. U.S. Geological Survey.

ABSTRACT, p 135;

" Sedimentary records of Cenozoic history in Southeastern New Mexico begin with the Ogallala Formation , Miocene and Pliocene age. Later records include the Gatuna Formation of early or middle Pleistocene age, Mescalero caliche, an informal term, of middle Pleistocene age, and fluvial deposits of late Pleistocene age but there are many gaps in some record. The modern landscape is the result of erosion and deposition in climates that have ranged from semihumid to semiarid as well as dissolution of soluble rocks in Permian Formations in the subsurface. This dissolution may have been as early as Jurassic time and has continued intermittently to the present.

TABLE 1.--Summary of late Tertiary and Quaternary events in southeastern New Mexico

Age		Stratigraphic unit	Deposits	Events	Probable climate	Tentative correlations
Holocene		Young sand dunes	Sand	Working wind from southwest	More dry than present.	
		Old soil	....	....	More moist than present.	
		Old sand dunes	....	....	More dry than present.	
Pleistocene	Late	Lakewood terrace deposits.	River conglomerate, pond, marsh, and lake silts.	Pecos River developed as axial stream from Fort Sumner to Roswell.	More moist than present. Probably cooler.	Wisconsin.
		Orchard Park alluvial deposits.	Limestone-porphyry conglomerate. Caliche caprock.	Reworking of Blackdom deposits.	More moist than present. Probably cooler.	Probably early Wisconsin.
		Blackdom alluvial deposits.	Limestone-porphyry conglomerate. Caliche caprock.	Major erosion of back slope of Sierra Blanca and Sacramento and Capitan Mountains.	More moist than present. Probably cooler.	Do.
		Hiatus	....	....		
	Middle	Mescalero caliche, an informal name.	Caliche	Land surface stable. Soil evolopment over much of southeast New Mexico.	More dry than present. Probably warmer.	Yarmouth(?). Unnamed gravel surface West of Pecos.
	Middle or early	Gatuna Formation	Gravel. Stream gravels, pond sediments, solution basin fill. Conglomerate, sand, silt, some gypsum.	Pediments formed in area between Carlsbad and San Simon Swale. Streams cut High Plains escarpment eastward. Extensive solution of salt and gypsum in subsurface. Collapse of Nash Draw and Clayton Basin. San Simon Swale may have been of major stream.	Much more moist than present. Probably cooler.	Analogous to Kansan deposits in Trans-Pecos Texas.
	Early (?)	Hiatus	....	....	....	
Pliocene		Ogallala "climax-soil."	Caliche	Land surface stable. Soil development.	Similar to, or more dry than, present.	



EXPLANATION

Slump in Mescalero caliche

To Ogallala Formation at The Divide

3300 Structure contours on Mescalero caliche — *3200* Dashed where control is sparse. Interval is 100 feet (30.5 m)

FIGURE 8.—Structure contour map of Mescalero caliche.

Bachman, G.O., 1980. Regional Geology and Cenozoic History of Pecos Region, Southeastern New Mexico. Open-File Report 80-1099, U.S. Geological Survey, Denver, CO.

ABSTRACT, p 1;

" This report summarizes the Cenozoic history of the Pecos drainage in the Delaware basin, southeastern New Mexico, and incorporates an outline of the dissolution and karst development in Permian evaporites in the region.

Evaporites include anhydrite, gypsum, halite and related minerals. They are included in the Castile, Salado and Rustler Formations of Late Permian (ochoan) age. These formations have been transgressed by strata of the Dockum Group of Late Triassic age and unnamed formations of early Cretaceous age.

Complex karst features include collapse sinks, karst mounds (new term), karst domes (new term) and caves. Karst mounds are erosional remnants of regional breccia. Karst domes are structural features which have formed on a very irregular dissolution surface. They are analogous to towers, kegelkarst or mogotes in tropical regions except that karst domes are almost buried by their own dissolution residue.

Breccia chimneys are collapse sinks which have formed over the Capitan aquifer system. They appear to be the result of unsaturated water rising under a strong hydraulic head through fractures and dissolving upward into the evaporite sequence.

Breccia chimneys, karst mounds and karst domes studied during this work were formed during middle Pleistocene time.

Dissolution has been an active process in the Delaware basin at least since Triassic time and it is impractical to attempt to calculate a rate of dissolution for the basin. Earlier estimates of the rate of dissolution are considered to be conservative. Subsurface evidence does not suggest that deep dissolution is presently an active process in the Castile Formation beneath the thick beds of Salado salt.

Pleistocene glaciation in the northern and central United States was probably accompanied by 'pluvial' periods in southeastern New Mexico. Pluvials are characterized by less extreme temperatures, less evaporation and more effective moisture than at present."

Rocks of Cretaceous Age, p. 28, para 4;

" Rocks of Early cretaceous age are preserved at a few localities in the Pecos drainage system as collapse debris in areas of dissolution. Lang (1947) reported an occurrence of fossiliferous Lower Cretaceous sandy limestone in Black River Valley about 9.6 km (6 mi) southwest of Whites City (NW 1/4 sec. 31. T. 25 S., R. 25 E., Eddy County, N.M.) (fig. 9).

These rocks containing Cretaceous marine fossils are scattered as collapse debris on the surface of the Castile Formation. This locality was examined during the present study and the Cretaceous debris appears to rest in a collapse sink about 60 m (200 ft) in diameter in the Castile Formation. Another occurrence of Cretaceous rocks and associated fossils resting on the Castile Formation is about 11.5 km (7.8 mi) southwest of Whites City (NE 1/4 sec. 1, T. 26 S., R. 24 E.), Lower Cretaceous rocks are mingled with debris of Culebra

Dolomite Member of the Rustler Formation and Triassic conglomerate.

All these Lower Cretaceous rocks in southeastern New Mexico are of equivalent age. The locality northeast of Carlsbad contains the following marine fauna:

Echinoid (probably Holectypus)
Texigryphea washitaensis (Hill)
Ostrea quadriplicata Shumard"

Ogallala Formation, p 35, para 2;

" In southeastern New Mexico the Ogallala Formation consists largely of well-sorted windblown sand. There are minor poorly sorted stream deposits and local carbonate pans. Generally the sediments suggest that the climate during Ogallala time was not much different from that in the region today. The pedogenic caliche caprock indicates a long period of quiescence during which constructive and destructive processes approached a steady state."

Mescalero caliche, p 42, para 3;

" many workers have attempted to develop techniques for measuring the rate of carbonate accumulation in pedogenic caliche (Arkley, 1963; Gardner, 1972; Goudie, 1973; Szabo, 1969; Bachman and Machette, 1977). Of the various methods studied the most promising is a technique which measures uranium series disequilibrium. This technique has been applied to the Mescalero caliche with notable results (table 3). Using this technique it has been determined that the Mescalero began to accumulate about 510,000 years ago (J.N. Rosholt, written commun., 1979). The upper crust of this caliche formed about 410,000 years ago."

Berino soil, p 44;

" The Berino soil is an informal stratigraphic unit, but the term 'Berino series' is used by the U. S. Department of Agriculture for mapping soils in Eddy County (Chugg and others, 1971). As used in this report the Berino is a dark red, sandy argillic paleosol which overlies the Mescalero caliche at some places in the vicinity of the WIPP site. It is usually overlain by windblown sand, but it is exposed along pipeline roads and at other construction sites. It varies in thickness but is rarely more than 1 m thick.

It is probable that the Berino soil represents a remnant B horizon of the underlying Mescalero caliche. The Berino is noncalcareous which suggests that the carbonates have been leached. The uranium-series disequilibrium technique indicates that the Berino began to form about 350,000 (±60,000) years ago (J. N. Rosholt, written commun., 1979)(table 3).

Hill A, p 62, para 3;

" Hill A of this report was designated 'Dome A' by Vine (1960, p. 1905). It is in Eddy County about 38 km (18.5 mi) east of Carlsbad on U. S. Highway 62-180 (SW1/4 sec. 35, T. 20 S., R. 30 E.). It is about 0.4 km (0.25 mi) north of the highway and is transected by a spur of the Atchinson, Topeka and Santa Fe Railroad. It is expressed as a low, circular breached hill with relief of about 12-15 m (40-50 ft) and about 370 m (1,200 ft) in diameter. During the present study, Hill A was mapped at a scale of 30 m to 25 mm (110 ft equals 1 inch) and the map was reduced for presentation in this report (fig. 12, in pocket).

The central part of Hill A has been eroded to form a shallow basin with an outlet to the west. The rim of the hill is capped by Mescalero caliche which engulfs slopes dipping rather uniformly about 15° away from the rim.

Dewey Lake Red Beds are exposed in the east, north, and west sides of the shallow basin. These beds are lithologically typical of the formation and dip away from the center of the hill. These dips average about 15° but locally steepen to 20°-22°. Rocks of the Triassic Dockum Group are well exposed along the east and south side of the basin with dips approximately parallel to the underlying Dewey Lake Red Beds.

Superficially Hill A has some of the characteristics of a collapse sink. Within the basin, brecciated debris composed of angular blocks of Triassic claystone, sandstone, and conglomerate are confined within a circular area about 245 m (800 ft) in diameter. The circular contact surrounding the central brecciated core is a fracture and was termed a 'peripheral fault or ring-fault' by Vine (1960, p. 1905). He stated that the brecciated core is composed of blocks similar to the Triassic beds exposed around the flanks of the hill but with greater range in lithologic character. He indicated that some breccia was derived from rocks stratigraphically higher than any now exposed around the flanks. . . ."

Dissolution During Geologic History, p. 81, Para. 1;

" Major dissolution occurs while land masses are above sea level. Regional uplifts have occurred in southeastern New Mexico following both Permian and Cretaceous times. Consequently, there is a long history of dissolution in the Delaware Basin. Although Castile and Salado rocks are transitional in the central part of the basin, some dissolution occurred locally after Castile and before Salado time (Adams, 1944, p. 1622-1624). Dissolution occurred again along the western edge of the basin after Salado and before Rustler time during Triassic time (Adams, 1944, p. 1622-1624). In addition to being above sea level throughout Triassic time the region was above sea level through Jurassic and again from the beginning of Tertiary time to the present. In summary, the region has been above sea level for a minimum of 154 million years and below sea level less than 71 million years since the end of Permian time (see table 1)."

p. 85, Para. 2;

" The estimates for the age of Nash Draw proposed by Bachman (1974, p. 68-71) are also too young. More recent work indicates that much of Nash Draw formed by solution-and-fill before Mescalero, and even Gatuna, time. Although there are places in Nash Draw where the Mescalero caliche has slumped since its deposition, there are many localities along the east side of Nash Draw where the caliche was deposited on the slopes and in the bottom of an ancient topographic basin. This caliche has been weathered and eroded but remnants of depositional morphology are present."

SUMMARY AND CONCLUSIONS, p 97;

" The purpose of this study has been to determine if there are continuing geologic processes in the Delaware Basin which may pose a threat to the proposed WIPP site. The preserved geologic record of erosion and dissolution have been examined to learn the pattern of these processes in geologic history.

The salt beds at the proposed site have been preserved for about 225 million years. Some dissolution, in places of major proportions, has occurred in the Delaware Basin intermittently during this long period of time. The Salado Formation itself has been dissolved and preserved only as a mass of chaotic breccia along its western line of outcrop. The nearest exposures of this breccia to the WIPP site are in karst domes in the vicinity of Malaga Bend 19 km (12 mi) southwest of the proposed WIPP site. The main belt of outcrop of Salado breccia is 24 km (15 mi) to the west of Malaga Bend.

Evidence is presented here that dissolution of the Salado Formation along its western belt of outcrop began at least as early as Triassic time more than 190 million years ago. Dissolution in the subsurface near this belt of outcrop is presumed to be continuing today. This dissolution has been intermittent throughout its history, and it is unrealistic to attempt to calculate an average rate of dissolution for the region. However, if dissolution continues to be no more severe than during the time since the formation of the Mescalero caliche about 500,000 years ago there is no reason to believe that the repository horizon will be threatened by dissolution for another 500,000 years.

Deep-seated breccia chimneys collapsed over the Capitan aquifer system about 600,000 years ago. Dissolution is presently an active process over the Capitan aquifer system along San Simon Swale about 32 km (20 mi) east of the WIPP site. However, this aquifer system does not underlie the site and there is no presently known aquifer system or process of dissolution in this area which is undermining the site. Near-surface dissolution has been and is presently active along Nash Draw about 10 km (6 mi) west of the site but this dissolution has not penetrated the major salt bodies in the Salado Formation.

Fluctuations in climate have not greatly accelerated the process of dissolution in terms of geologic time and the longer history of the salt bodies. Dissolution during past glacio-pluvial intervals was probably at a more rapid rate than today but the present state of the evaporite deposits is a summation of the processes operating on them throughout 225 million years. It is improbable that a continuation of these fluctuations on their past scale will pose a threat to the deposits during the life of the WIPP repository."

Bachman, G.O. 1981. Geology of Nash Draw, Eddy County, New Mexico. Open-File Report 81-31. U.S. Geological Survey, Denver, CO.

ABSTRACT, p. 1;

" Nash Draw is a partially closed depression about 29 km (17 mi) east of Carlsbad, Eddy County, New Mexico. It has been mapped geologically in conjunction with detailed studies to evaluate the proposed nuclear Waste Isolation Pilot Plant (WIPP). Maps at scales of 1:24,000 accompany this report.

The stratigraphic section exposed in Nash Draw includes the Rustler Formation and Dewey Lake Red Beds of Late Permian (Ochoan) age, the Dockum Group of Late Triassic age, and the Pleistocene Gatuna Formation. Other deposits of Middle to late Quaternary age include the Mescalero caliche, spring deposits, and windblown sand.

Dissolution of evaporites has been a major process in the formation of Nash Draw. Nash Draw formed before, and during, Gatuna time about 600,000 years ago. Near-surface dissolution of gypsum in the Rustler Formation is presently active and is responsible for numerous collapse sinks and related karst features."

Bachman, G.O., 1984. Regional Geology of Ochoan Evaporites, Northern Part of Delaware Basin. Circular 184, pp. 1-22. New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.

ABSTRACT, p 5;

" The Ochoan Series (Permian) in the northern part of the Delaware Basin, southeastern New Mexico, includes in ascending order the Castile, Salado, and Rustler Formations, and the Dewey Lake Red Beds. The Castile and Salado Formations comprise a sequence of evaporites which include anhydrite, gypsum, halite, and associated potash salts. The Rustler Formation contains some halite and minor amounts of potash minerals. These evaporites were deposited within the basin formed by the Capitan barrier reef, as well as across the reef. The evaporites, as well as the Capitan reef, are all subject to dissolution with resulting karst features analogous to those formed in limestone regions.

An Ancestral Pecos River was the major drainage system in the western part of the Delaware Basin, New Mexico, during the Cenozoic time. That ancient river system was responsible for the formation of an extensive karst terrain along the east side of the present Pecos River in New Mexico and southward into Texas. During late Cenozoic time extensive dissolution occurred in the Salado Formation within the karst area as a result of the ground-water regime. The dissolution front was perched on the upper anhydrite member of the Castile Formation.

On the eastern side of the Delaware Basin in New Mexico, a large collapse sink--San Simon sink--overlies the Capitan reef which is a prominent aquifer system in that area. So-called 'breccia pipes' are ancient sinks which collapsed into the caverns in the reef on the northern margin of the basin. These have since been partially exhumed. The San Simon sink is presumed to be a modern analog of these breccia pipes."

Rustler Formation, p 11, col 2, para 6;

" The Rustler ranges in thickness from a thin dissolution breccia at places on the surface to more than 550 ft in the subsurface in southwestern Lea County. Over much of the study area it averages 300-350 ft in thickness. Much of the variation in thickness is the result of the dissolution of salts. . . . At places where the salts have been dissolved, a 'collapse breccia' occupies their stratigraphic position. At these places the anhydrite is usually altered to gypsum."

Bachman, G.O., 1985. Assessment of Near-Surface Dissolution at and Near the Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico. SAND84-7178, Sandia National Laboratories, Albuquerque, NM. WPO 24609.

ABSTRACT, p. 3;

" The area at and near the WIPP site was examined for evidence of karst development on the geomorphic surface encompassing the site. Certain surficial depressions of initial concern were identified as blowouts in sand dune fields (shallow features unrelated to karstification). An ancient stream system active more than 500,000 years ago contained more water than any system since. During that time (Gatuña, Middle Pleistocene), many karst features such as Clayton Basin and Nash Draw began to form in the region. Halite was probably dissolved from parts of the Rustler Formation at that time. Dissolution of halite and gypsum from intervals encountered in Borehole WIPP-33 west of the WIPP site occurred during later Pleistocene time (i.e., <450,000 yr ago). However, there is no evidence of active near-surface dissolution within a belt to the east of WIPP-33 in the vicinity of the WIPP shaft."

p 19, column 1, para 2;

" Soil formation is a relatively slow process requiring a stable surface for development. Soils do not mature on constantly eroding surfaces or surfaces disrupted by subsidence, collapse, or persistent tectonic adjustment. Extensive soil development should not be expected at places where specific karst processes are extremely active. Soil classes depend on the nature of parent material, the amount of rainfall, the temperature, and the absence or presence of organic material. Soils may change character or may even be destroyed by radical changes in climate. For these reasons soils are a valuable tool for estimating the duration of stability of a geomorphic surface and the persistence of a climatic regime."

p 20, column 1, para 1;

" The basal part of the Mescalero caliche began to form ~510,000 yr ago, as determined by measuring the disequilibrium of the uranium series. The upper crust of the caliche began to form ~410,000 yr ago (Rosholt, written communication, 1979). The technique used in these determinations has been described by Szabo (1969) and Rosholt (1980)."

p 23, column 2, para 3;

Karst terminology should be defined with precision. Careless treatment of concepts of karst phenomena, and even carelessly using karst terminology, can contribute to misunderstanding and false impressions. The interpretation of karst activity in the vicinity of the WIPP site depends in part on understanding the distribution and physical nature of the stratigraphic units in the area. Although deep-seated dissolution has been active at localities around the periphery of the Delaware Basin in units associated with the Capitan Limestone and in the Pecos River drainage system overlying the Castile Formation (Lambert, 1983; Bachman, 1980 and 1984), deep-seated dissolution within the Delaware Basin is less probable because of physical limitations on the circulation of fresh water at depth. In contrast, dissolution of near-surface evaporites is responsible for the visible karst features in Nash Draw and at other places at and near the WIPP site. The caves, collapse sinks, and spring deposits in Nash Draw indicate a relatively long geologic history of dissolution of gypsum and associated evaporites.

Stream gravels in the Gatuña Formation on both the east and west sides of Nash Draw indicate flowing streams across the area now encompassed by Nash Draw before it became a topographic depression (Figure 11). The Gatuña stream system eroded into the evaporites of the Rustler Formation, and collapse sinks began to form near the end of Gatuña time before the formation of Mescalero caliche was well underway (Bachman, 1980). As a result of following the strike of the Rustler Formation for a time, Gatuña drainage contributed to coalescing these sinks. Thus, part of Nash Draw is a paleokarst feature. Paleokarst is prominent in Pierce Canyon ~20 mi (33 km) south of the WIPP site."

Discussion and Conclusions, p 26, col 2, para 3, line 18;
"Despite the statement of Barrows and others (1983) that 'all [gravity anomalies] are assumed to have a common origin' (p 63), karstic features are by definition associated with surface collapse; not all the gravity anomalies show surface collapse or even topographic depressions. In fact, the center of one -- 0.8 mgal gravity anomaly is 1/4 mi (400 m) east of the WIPP-14 topographic depression, which is here interpreted as a blowout. WIPP-14 contained no subsurface cavities. Thus, the 'modeled gravity...from the infinitely long polygonal bodies [the assumed 'karst conduits']' (p 63) does not provide a unique or inescapable interpretation of the gravity data, but was evidently the interpretation preferred by Barrows and others.

The absence of true surface karst features at and near the WIPP site may be explained by the depth of burial of the Rustler Formation in that area and by the protective cover of the rocks overlaying the Rustler. The Rustler is at least 500 ft (152 m) beneath the surface at the site. The overlying Dewey Lake has 'minimal permeability and does not contain significant quantities of ground water...The Dewey Lake is a protective cover that retards dissolution of evaporites in the Rustler Formation' (Mercer, 1983, p 70).

Dissolution will become a major process east of WIPP-33 *only* if large quantities of unsaturated water gain access to the Rustler Formation. Except for minor intermittent drainage from Livingston Ridge into Nash Draw, erosion does not appear capable of breaching the Mescalero caliche. At present, the Mescalero is an additional obstruction to infiltrating and recharging underlying beds."

Barrows, L.J., Shaffer, S.E., Miller, W.B., and Fett, J.D. 1983. Waste Isolation Pilot Plant (WIPP) Site Gravity Survey and Interpretation. SAND82-2922, Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p. 3;

" A portion of the WIPP site has been extensively surveyed with high-precision gravity. The main survey (in T22S, R31E) covered a rectangular area 2 by 4-1/3 mi. encompassing all of WIPP site Zone II and part of the disturbed zone to the north of the site. Stations were at 293-ft intervals along 13 north-south lines 880 ft apart. The data are considered accurate to within a few hundredths of a milligal.

Long-wavelength gravity anomalies correlate well with seismic time structures on horizons below the Castile Formation. Both the gravity anomalies and the seismic time structures are interpreted as resulting from related density and velocity variations within the Ochoan series. Shorter wavelength negative gravity anomalies are interpreted as resulting from bulk density alteration in the vicinity of karst conduits.

The WIPP gravity survey was unable to resolve low-amplitude, long-wavelength anomalies that should result from the geologic structures within the disturbed zone. It did indicate the degree and character of karst development within the surveyed area."

Section 1.2.3 Karst; p 19, col 2;

" Evaporite and carbonate rocks dissolve, or corrode, when they contact chemically undersaturated water. Karst refers to a distinctive surface morphology and groundwater hydrology resulting from such dissolution. Karst surface morphology is characterized by collapse sinks, alluvial dolines, caves, grikes, and various domes and mounds. The hydrology is characterized by sinking streams, swallow holes, the absence of surface runoff, and integrated arterial system of sub-surface conduits, and a few large irregular springs. The general principles of karst morphology are discussed by M. Sweeting (1973), and karst hydrology is discussed by A. Bogli (1980).

A large area of southeastern New Mexico and west Texas, including the Delaware Basin, is underlain by soluble carbonates and evaporites. Much of this material has been removed by dissolution, and the area is recognized as one of the karstlands of the United States (Davies and LeGrand, 1972; LeGrand et. al., 1976). Regional karst is described by G. O. Bachman (1980) in his report on the geology and Cenozoic history of the Pecos region, and by Powers et. al. (1978)."

3.2.1 The WIPP 14 Anomaly, p. 57, col. 1, para. 1;

" The negative gravity anomalies are the most distinctive and unanticipated feature of the gravity field. These anomalies were first detected on the detailed grid surveyed over the closed topographic depression midway along the line between Sections 9 and 16 (later drilled as WIPP 14). They were later found to extend in an east-west direction across the northern part of the survey area. Reconsideration of data from a coarsely spaced, poorly documented survey at the 'old site' (Gera, 1974) showed their presence east of our survey area; the reconnaissance profiles around WIPP 33 show their presence to the west.

The interpretation of the negative anomalies involves consideration of shallow geologic structure, densilogs, velocity surveys, seismic profiles, surface topography, and regional and local geology. Different portions of the anomalies are interpreted with various logs from various holes. This was done because not all holes were logged with the same tools and not all logs were usable. The interpretation may seem piecemeal, but it is mutually consistent. The negative anomalies are here interpreted as caused by rock density decrease, solution/removal, and gypsum hydration in the vicinity of karst conduits. Interpretation begins with comparisons of WIPP 14/WIPP 34 density logs. These densilogs indicate sufficient mass deficiency in the Dewey Lake and Rustler Formations to account for the negative gravity at WIPP 14. Next, the negative anomaly is modeled at its intersection with seismic line 77X2. The seismic line indicates a seismic time syncline coincident with the negative gravity anomaly. Both the seismic time syncline and the negative anomaly are explained by lateral velocity and inferred density variations comparable to those observed in uphole velocity surveys. Finally, the negative gravity anomaly and alluvial doline at WIPP 33 are related to the solution cavities encountered in that hole."

p. 58, col. 2, para 1;

" Depositional facies variations and buried stream channels were considered as possible causes of the WIPP 14 gravity anomaly. Both of these interpretations are inconsistent with the observations and are considered highly unlikely.

'Facies' refers to those aspects of the lithology that are attributable to lateral variations in the depositional environment. The Dewey Lake and Rustler Formations were deposited over tens of thousands of square miles in a broad basin that extended over the Capitan Reef and Central Basin Platform (Snider, 1966, Figure 34). C. L. Jones (1954, p. 110) notes that some of the halite of the Rustler Formation thins reefward and pinches out in the shelf area. He also notes that the two dolomite members and several siltstone and sandstone layers form remarkably persistent stratigraphic markers. The implication of the areal extent and the lateral persistence is that, while some gradational north-south variations may be attributable to depositional facies, the east-west thinning (Figures 1.2.1-4 and 1.2.3-1) cannot. In particular, there is nothing in the depositional environment that suggests abrupt lateral variations over distances of several hundred feet.

When the WIPP 14 gravity anomaly was first detected, a buried stream channel was one of the hypotheses considered to explain it. A model of such a channel had a density contrast of 0.3 g/c^3 and a maximum thickness of 150 ft. A shallower channel would require a greater density contrast; a lesser density contrast would require a deeper channel. Both the 0.3 g/c^3 density contrast and the 150-ft thickness are larger than reasonably anticipated at this location. The lithologic character of such a feature should have been clearly discernible in the core.

When WIPP 14 was drilled, neither stratigraphic facies variations nor buried stream channels were identified in the core. Rather, the gravity anomaly was found to be reasonably attributed to diffuse density reductions in the Dewey Lake and Rustler

Formations. The relation between these density reductions and the closed topographic depression will become clearer after considering the other elements in the interpretation."

3.2.3 The WIPP 33 Anomaly, p. 63, col. 1, para. 2;

" The relation between negative gravity anomalies and karst conduits is clarified at borehole WIPP 33 (SNLA and USGS, February 1981). This hole was drilled in Section 13, R31E, T22S to determine the nature of a closed topographic depression."

Section 4. Summary, p 65;

" The WIPP gravity survey demonstrates both the utility and limitations of microgravity in a karst terrain. We were unable to resolve the low-amplitude long-wavelength anomolies that should originate in the Castile Formation geologic structures. We did map short-wave length anomolies that may reveal the style and extent of karst development in the Dewey Lake and Rustler Formations. The implications of this karst to the WIPP geohydrology are being carefully assessed (Barrows, 1982)."

Beauheim, R.L., Hassinger, B.W., and Klaiber, J.A. 1983. Basic Data Report for Borehole Cabin Baby-1 Deepening and Hydrologic Testing, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico. WTSD-TME-020, U.S. Department of Energy, Albuquerque, NM.

Section 1.0 ABSTRACT, p 1-1;

" Borehole Cabin Baby-1 was originally drilled to a depth of 4159.0 feet below kelly bushing (8.0 feet above ground surface) in 1974 and 1975 as a 'wildcat' hydrocarbon exploratory well. Control of the borehole was given to the U. S. Department of Energy (DOE) after it was found to be a 'dry hole'. Cabin Baby-1 was reentered, deepened, and hydrologically tested in August and September, 1983. The well is located in Section 5, T23S, R31E, just outside the limit of WIPP Zone III, approximately 2.5 miles south of the WIPP exploratory shaft.

The deepening and testing of Cabin Baby-1 was undertaken for several reasons:

- To provide data on the hydrologic properties, including hydrostatic head potential of selected permeable zones in the Bell Canyon Formation.
- To provide representative fluid samples from selected permeable zones in the Bell Canyon Formation for determination of fluid composition and density.
- To define further the stratigraphy of the upper Bell Canyon Formation at the Cabin Baby-1 location.

The borehole was deepened from the previous total depth to a new depth of 4298.6 feet below kelly bushing by continuous coring. Field operations related to deepening and logging of the borehole began August 12, 1983 and were completed August 30, 1983. Hydrologic testing activities began August 30, 1983 and were completed September 29, 1983. Drill-stem tests were conducted in four zones in the Bell Canyon Formation, and one test of the Salado Formation was performed. Fluid samples were collected from the Hays and Olds sandstones of the Bell Canyon Formation."

4.6 <u>TEST RESULTS</u>, p. 4-9;

" Testing began on September 4, 1983 and ended on September 23, 1983. A summary of the tests performed is provided in Table 5. The results of the tests are summarized in Table 6, and discussed below. The FFL analyses are not presented because first flows are typically dominated by drilling fluid unloading, and serve primarily to help clean the hole for the more important SFL. Flow tests and slug tests are similar, repetitive tests. The quality of the data should increase with each successive test, as the effects of loading the formation with drilling fluid are progressively lessened. For this reason, and because slug tests are performed until a greater degree of recovery is achieved than during flow tests, the slug tests provide the results most representative of actual reservoir properties of all the flow tests. Of the buildup period analyses, the SBU results are regarded as the more reliable because the SFL's better meet the theoretical assumptions of the analysis technique than the FFL's, and because the SBU's were continued until a greater degree of recovery was obtained than during the FBU's.

4.6.1 DST-4178: Hays Sandstone

The Hays sandstone was tested between the depths 4178.0 and 4298.6 feet below KB. Two flow tests (DST-4178/FFL and SFL), two buildup tests (FBU and SBU), and one slug test (SLUG) were performed (Figure 8). As shown in Table 6 and Figures 9 and 10, the analyses of the first and second buildups provided permeability estimates of 0.57 md and 0.71 md, respectively. These correspond to hydraulic conductivity values of 1.3 x 10^{-3} ft/day and 1.7 x 10^{-3} ft/day, respectively. The flow-period permeability estimates are slightly higher, with the second-flow data yielding a value of 1.7 md (Figure 11) and the slug-test data yielding a value of 0.94 md (Figure 12). These values correspond to hydraulic conductivity estimates of 3.9 x 10^{-3} ft/day and 2.2 x 10^{-3} ft/day.

The Horner plot of DST-4178/FBU (Figure 9) shows an early-time deviation below the Horner straight line, representing a slight positive skin, perhaps a mudcake, on the borehole wall. A similar effect was apparent in early-time data from DST-4178/SBU not shown in Figure 10. When the FBU data are extrapolated to infinite recovery time, they yield a static formation pressure (p_{ext}) of 1883 psig (Figure 9). The very late-time SBU data show a slight deviation above the Horner straight line, probably reflecting the fact that the SFL was initiated before complete recovery from the FFL was achieved. This upward-deviation phenomenon reflects a superposition of buildups from separate flow events, and is typically distinguishable only when the buildup from the most recent flow becomes of very small magnitude. When the latest SBU data are extrapolated to infinite time, they provide a static formation pressure estimate of 1880 psig (Figure 10). With the transducer at a depth of 4165.4 feet below KB, and a fluid pressure gradient of 0.485 psi/ft (SG = 1.12; Table 7), these static formation pressure estimates correspond to a static fluid level (in an open borehole) 283 to 289 feet below KB, which is about the level of the Dewey Lake Redbeds.

4.6.2 DST-4138: Olds Sandstone

The Olds sandstone was tested between the depths 4138.5 and 4170.9 feet below KB. Two flow tests (DST-4138/FFL and SFL), two buildup tests (FBU and SBU), and one slug test (SLUG) were performed (Figure 13). The permeability values derived from the first and second buildups are 2.2 x 10^{-2} md (Figure 14) and 3.5 x 10^{-2} md (Figure 15), respectively. These correspond to hydraulic conductivity estimates of 4.5 x 10^{-5} ft/day and 7.2 x 10^{-5} ft/day, respectively. The flow-period permeability estimates are slightly higher, being 6.7 x 10^{-2} md for the second flow (Figure 16) and 8.2 x 10^{-2} md for the slug test (Figure 17). These values correspond to hydraulic conductivity estimates of 1.4 x 10^{-4} ft/day and 1.7 x 10^{-4} ft/day, respectively.

The Horner plots of DST-4138/FBU (Figure 14) and SBU (Figure 15) both show the very late time data deviating below the Horner straight line. Such deviations are typically the result of some type of negative reservoir boundary, such as a decrease in permeability at some distance from the well. The deviations could also represent depletion of a finite reservoir. Extrapolating the FBU and SBU very late time data to infinite time provides static formation pressure estimates of 1934 psig (Figure 14) and 19101 psig (Figure 15), respectively. With the transducer at a depth of 4125.9 feet below KB, and a fluid pressure gradient of 0.503 psi/ft (SG = 1.16; Table 7), these pressures correspond to static fluid levels (in an open borehole) 281 feet and 329 feet below KB, respectively, which are in the middle of the Dewey Lake Redbeds.

4.6.3 DST-4100: Ramsey Sandstone

The Ramsey sandstone was tested between the depths 4100.5 and 4132.9 feet below KB. Two flow tests (DST-4100/FFL and SFL), two buildup tests ((FBU and SBU) and one slug test (SLUG) were performed (Figure 18). The first and second buildups provided permeability estimates of 2.3 x 10^{-2}md (Figure 19) and 2.9 x 10^{-2}md (Figure 20), respectively. These values correspond to hydraulic conductivity estimates of 4.7 x 10^{-5} ft/day and 6.0 x 10^{-5} ft/day, respectively. Again, the flow-period permeability estimates are slightly higher, being 8.2 x 10^{-2} md for the second flow (Figure 21), and 8.7 x 10^{-2} md for the slug test (Figure 22). These values correspond to hydraulic conductivity estimates of 1.7 x 10^{-4} ft/day and 1.8 x 10^{-4} ft/day, respectively.

The Horner plots of DST-4100/FBU (Figure 19) and SBU (Figure 20) both show a very late time deviation of the data below the Horner straight line similar to that observed in DST-4138/FBU and SBU (Figures 14 and 15). Again, the deviations probably represent some type of negative reservoir boundary. Extrapolating the FBU and SBU very late time date to infinite time provides static formation pressure estimates of 1916 psig (Figure 19) and 1892 psig (Figure 20), respectively. With the transducer at a depth of 4087.9 feet below KB, and assuming a fluid pressure gradient similar to that of the Olds sandstone fluid (0.503 psi/ft), these pressures correspond to static fluid levels (in an open borehole) 279 feet and 326 feet below KB, respectively. These levels are virtually identical to those calculated for the Olds sandstone fluid.

4.6.4 DST-4044: Lamar Limestone

The Lamar limestone was tested between the depths of 4044.2 and 4097.4 feet below KB. Because of the extremely low magnitude response of the unit, only a single flow (FFL) and buildup (FBU) cycle was performed (Figure 23). As shown on Figure 24, the buildup response in the Lamar was slow and prolonged. The permeability estimated from the buildup data is 6 x 10^{-4} md(0.6 μd) (Figure 25). This corresponds to a hydraulic conductivity of 1 x 10^{-6} ft/day. Permeabilities of this order cannot be determined precisely with DST techniques, and thus, these values should be regarded as order-of-magnitude estimates.

The expanded-scale Horner plot of DST-4044/FBU (Figure 25) shows the data deviating below the Horner straight line at extremely late time, probably in response to some type of negative reservoir boundary. The extrapolation of these data to infinite time provides a static formation pressure estimate for the Lamar of 1886 psig. With the transducer at a depth of 4031.6 feet below KB, and assuming a fluid pressure gradient similar to that of the Olds sandstone fluid (0.503 psi/ft), this pressure corresponds to a static fluid level (in an open borehole) 282 feet below KB, virtually identical to that of the underlying sandstones."

The 15 tables and figures refereed to in this text are not included to save space. Refer to the specific reference to see these figures.

Beauheim, R.L., 1986. Hydraulic-Test Interpretations for Well DOE-2 at the Waste Isolation Pilot Plant (WIPP) Site. SAND86-1364. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p 3;
" Eleven different zones were tested in Well DOE-2 in five phases of testing between 1984 and 1986. Testing techniques included a constant-head, borehole-infiltration test, drill-stem tests, slug tests, pressure-pulse tests, and multiwell pumping tests. Four of the zones tested--the lower Dewey Lake Red Beds, the Tamarisk Member of the Rustler Formation, the lower unnamed member of the Rustler Formation and the Rustler/Salado contact, and the entire Salado Formation--had permeabilities too low to measure with the equipment and test techniques used. The other zones had permeabilities ranging over six orders of magnitude. No saturated strata were encountered above the Rustler Formation, although parts of the middle Dewey Lake Red Beds appear to have appreciable permeability.

In the Rustler Formation, the Culebra Dolomite Member is the most permeable unit, having a transmissivity of ~90 ft^2/day. The Culebra behaves hydraulically as a double-porosity system, with the major permeability provided by fractures and the major storage provided by matrix porosity. The Culebra at DOE-2 is well connected hydraulically to the Culebra at Wells H-6b and WIPP-13 to the west, probably by interconnected fractures. Response times between these wells are very short (<1 day/10,000 ft). The Culebra does not appear to be as fractured to the south at Wells WIPP-12 and 18, or to the east at Well H-5b, as indicated by delayed, low-magnitude (or nonexistent) responses to DOE-2 pumping, and by low permeabilities interpreted from other tests conducted at those wells. The other Rustler members at DOE-2, which are not known to be fractured and do not display hydraulic responses typical . . ."

Section 7.4.1 Ramsey Sandstone (DST 4138-4180), p 61, col 2, para 2, line 11;
"The corresponding groundwater units are transmissivities of 5.4×10^{-3} and 5.7×10^{-3} ft^2/day and hydraulic conductivities of 1.9×10^{-4} and 2.0×10^{-4}ft/day for the FBU and SBU, respectively. . . ."

Section 7.4.1 Ramsey Sandstone (DST 4138-4180), p 63, col 1, para 1;
" The late-time SBU data are shown in a Horner plot in Figure 7-34. Extrapolating the data trend to infinite time provides a static formation pressure estimate of ~1816 psia (1805 psig). With the transducer at a depth of 4120.6 ft and a fluid pressure gradient in the borehole from drilling fluid of 0.542 psi/ft (assumed SG = 1.25), 1805 psig corresponds to a formation pressure of 1833 psig at the base of the Ramsey, 4127 ft deep. ..."

Section 7.4.2 Olds Sandstone (DST 4177-4218), p 63, col 2, para 2, line 10;
"The corresponding groundwater units are transmissivities of 7.0×10^{-3} and 6.6×10^{-3} ft^2/day and hydraulic conductivities of 2.3×10^{-4} and 2.2×10^{-4}ft/day for the FBU and SBU, respectively. . . ."

Section 7.4.2 Olds Sandstone (DST 4177-4218), p 66, col 1, para 2, line 4;
" ... The final pressure, 1843.0 psia (1832.5 psig), is the maximum possible static formation pressure for the Olds sandstone. With the transducer at a depth of 4159.2 ft and a fluid pressure gradient in the borehole from drilling fluid of 0.537 psi/ft (measured SG = 1.24), this pressure corresponds to a formation pressure of 1863.6 psig at the base of the Olds, 4217 ft deep. ..."

Section 7.4.3 Hays Sandstone (DST 4220-4325), p 68, col 1, para 2, line 10;
"The corresponding groundwater units are transmissivities of 0.56 and 0.53 ft^2/day and hydraulic conductivities of 5.6 x 10^{-3} and 5.3 x 10^{-3}ft/day for the FBU and SBU, respectively. . . ."

Section 7.4.3 Hays Sandstone (DST 4220-4325), p 68, col 2, para 3, line 11;
" ... The very latest time SBU data extrapolate to a pressure of ~1845.5 psia (1835 psig) at infinite time. This value can be taken as the maximum possible Hays pressure."

Section 7.4.4 Bell Canyon Fluid-Level Measurements, p 72, col 1, para 3, line 1;
" The observed Bell Canyon fluid level at a depth of 384 ft is ~20 ft lower than the observed Culebra fluid level at DOE-2. Because of the higher specific gravity of the Bell Canyon fluid, however, the Bell Canyon *head* at the elevation of the base of the Culebra is slightly higher than that of the Culebra. This indicates that, in the event of an interconnection between the Bell Canyon and the Culebra, the undisturbed head gradient would drive fluid upward from the Bell Canyon into the Culebra.

If the interconnection were through an uncased borehole, however, salt dissolution in the Salado section would increase the specific gravity of the Bell Canyon fluid so that, *at the elevation of the Culebra*, the Culebra head would be higher than that of the Bell Canyon. In this event, the flow direction would be downward. The long-term flow rate would be governed by a combination of factors, including the transmissivity and storativity of both the Culebra and Bell Canyon and the rate of halite dissolution."

Section 8. Summary and Conclusions, p 73, col 1, para 2;
" In the Bell Canyon Formation, the Hays sandstone was the most permeable unit tested, with an average permeability of ~2.4 md (0.55 ft/day). The Olds and Ramsey sandstones, overlying the Hays, have permeabilities almost two orders of magnitude lower. Hydraulic heads in the Bell Canyon sandstones could not be quantified precisely enough to define vertical gradients within the Bell Canyon.

In freshwater terms, the observed Bell Canyon head is higher than the hydraulic head of the Culebra dolomite. If the Bell Canyon and Culebra were connected by an open borehole, however, salt dissolution in the Salado section would increase the specific gravity of the Bell Canyon fluid so that, *at the elevation of the Culebra*, the Culebra head would be higher than that of the Bell Canyon. In this event, the flow direction would be downward from the Culebra into the Bell Canyon."

Beauheim, R.L., 1987a. Interpretations of Single-Well Hydraulic Tests Conducted at and Near the Waste Isolation Pilot Plant (WIPP) Site, 1983-1987. SAND87-0039. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p 3, para 1;

" Both single-well and multiple-well hydraulic tests have been performed in wells at and near the WIPP site as part of the site hydrogeologic-characterization program. The single-well tests conducted from 1983 to 1987 in 23 wells are the subject of this report. The stratigraphic horizons tested include the upper Castile Formation; the Salado Formation; the unnamed, Culebra, Tamarisk, Magenta, and Forty-niner Members of the Rustler Formation; The Dewey Lake Red Beds; and Cenozoic alluvium. Tests were also performed to assess the integrity of a borehole plug isolating a pressurized brine reservoir in the Anhydrite III unit of the Castile Formation. The types of tests performed included drillstem tests (DST's), rising-head slug tests, falling-head slug tests, pulse tests, and pumping tests."

The Castile and Solado testing was performed at well WIPP-12 to try to define the source of high pressures measured at the WIPP-12 wellhead between 1980 and 1985. The test of the plug above the Castile brine reservoir indicated that the plug may transmit pressure, but if so, the apparent surface pressure from the underlying brine reservoir is significantly lower than the pressure measured at the wellhead. The remainder of the upper Castile did not show a pressure response differentiable from that of the plug. All attempts at testing the Salado in WIPP-12 using a straddle-packer DST tool failed because of an inability to locate good packer seats. Four attempts to test large sections of the Salado using a single-packer DST tool and a bridge plug were successful. All zones tested showed pressure buildups, but none showed a clear trend to positive surface pressures. The result of the WIPP-12 testing indicate that the source of the observed high pressures is within the Salado Formation rather than within the upper Castile Formation and that this source must have a very low flow capacity and can only create high pressures in a well shut in over a period of days to weeks.

DST's performed on the lower siltstone portion of the unnamed lower member of the Rustler Formation at H-16 indicated a transmissivity for the siltstone of about 2.4 x 10^{-4} ft^2/day. The formation pressure of the siltstone is higher than that of the overlying Culebra at H-16 (compensated for the elevation difference), indicating the potential for vertical leakage upward into the Culebra. However, the top of the tested interval is separated from the Culebra by over 50 ft of claystone, halite, and gypsum.

The Culebra Dolomite Member of the Rustler Formation was tested in 22 wells. In 12 of these wells (H-4c, H-12, WIPP-12, WIPP-18, WIPP-19, WIPP-21, WIPP-22, WIPP-30 P-15, P-17, ERDA-9, and Cabin Baby-1), falling-head slug tests were performed in H-1, and only a rising-head slug test was performed in P-18. DSTs were performed in conjunction with rising-head slug tests in wells H-14, H-15, H-16, H-17, and H-18. At all of these wells except H-18, the indicated transmissivities were 1 ft^2/day or less and single-porosity models fit the data well. At H-18, the Culebra has a transmissivity of about 2 ft^2/day. The apparent single-porosity behavior of the Culebra at H-18 may be due to the small spatial scale of the tests rather than to the intrinsic nature of the Culebra at that location. Pumping tests were performed in the other 3 Culebra wells. The Culebra appears to behave hydraulically like a double-porosity medium at wells H-8b and DOE-1, where transmissivities are 8.2 and 11 ft^2/day, respectively. The Culebra transmissivity is highest, 43 ft^2/day, at the Engle well. No double-porosity behavior was apparent in the Engle drawdown data, but the observed single-porosity behavior may be related more to wellbore and near-wellbore conditions than to the true nature of the Culebra at that location.

The claystone portion of the Tamarisk Member of the Rustler Formation was tested in wells H-14 and H-16. At H-14, the pressure in the claystone failed to stabilize in three days of shut-in testing, leading to the conclusion that the transmissivity of the claystone is too low to measure in test performed on the time scale of days. Similar behavior at H-16 led to the abandonment of testing at that location as well.

The Magenta Dolomite Member of the Rustler Formation was tested in wells H-14 and H-16. At H-14, examination of the pressure response during DSTs revealed that the Magenta had taken on a significant overpressure skin during drilling and Tamarisk-testing activities. Overpressure-skin effects were less pronounced during the drillstem and rising-head slug tests performed on the Magenta at H-16. The transmissivity of the Magenta at H-14 is about 5.5. x 10^{-3} ft^2/day, while at H-16 it is about 2.7 x 10^{-2} ft^2/day. The static formation pressures calculated for the Magenta at H-14 and H-16 are higher than those of the other Rustler members.

The Forty-niner Member of the Rustler Formation was tested in wells H-14 and H-16. Two portions of the Forty-niner were tested at H-14: the medial claystone and the upper anhydrite. DST's and a rising-head slug test were performed on the claystone, indicating a transmissivity of about 7 x 10^{-2} ft^2/day. A buildup test of the forty-niner anhydrite revealed a transmissivity too low to measure on a time scale of days. a pulse test, DST's, and a rising-head slug test of the Forty-niner clay at H-16 indicated a transmissivity of about 5.3 x 10^{-3} ft^2/day. Formation pressures estimated for the Forty-niner at H-14 and H-16 are lower than those calculated for the Magenta (compensated for the elevation differences), indicating that water cannot be moving downwards from the Forty-niner to the Magenta at these locations. . . ."

Section 5.2.1 Unnamed Lower Member., p 50, col 1, para 4;

" The unnamed lower member of the Rustler was tested only at H-16. This testing had two objectives: 1)to determine the transmissivity of the unit; and 2) to determine the hydraulic head of the unit. The transmissivity is a parameter needed to calculate potential leakage rates from the unnamed lower member into the WIPP shafts. The hydraulic head is also needed for leakage calculations, as well as to evaluate directions of potential vertical movement of groundwaters within the Rustler Formation. . . ."

p 50, col 2, para 4;

" The simulation in Figure 5-12 is of a single-porosity medium with a transmissivity of 2.7 x 10^{-4} ft^2/day (Table 5-2). Assuming a porosity of 30%, a total-system compressibility of

1.0×10^{-5} psi^{-1}, and a fluid viscosity of 1.0 cp, the skin factor for the well in this simulation is -0.4, indicating a very slightly stimulated well. The dimensionless Horner plot of the FBU (Figure 5-13) shows an excellent fit of the simulation to the data, and indicates that the static formation pressure is about 213 psia.

The SLF lasted about 29 minutes, and was followed by a 50-hr SBU. The log-log plot of the SBU data (Figure 5-14) shows behavior similar to that seen in the FBU plot (Figure 5-12). The single-porosity simulation shown, however, uses a transmissivity of 2.2 x $10^{-4}ft^2/day$, and a skin factor of 0.2 (Table 5-2). These values imply a slightly less permeable formation and a slightly more damaged well than were indicated by the FBU analysis."

$$\frac{2.7 \times 10^{-4}\,ft^2}{day} \times \frac{12^2\,in^2}{ft^2} \times \frac{m^2}{39.3^2\,in^2} \times \frac{day}{24\ hour} \times \frac{hour}{3600\ sec.} = \frac{2.9 \times 10^{-10}\,m^2}{second}$$

$$\frac{2.2 \times 10^{-4}\,ft^2}{day} \times \frac{12^2\,in^2}{ft^2} \times \frac{m^2}{39.3^2\,in^2} \times \frac{day}{24\ hour} \times \frac{hour}{3600\ sec.} = \frac{2.4 \times 10^{-10}\,m^2}{second}$$

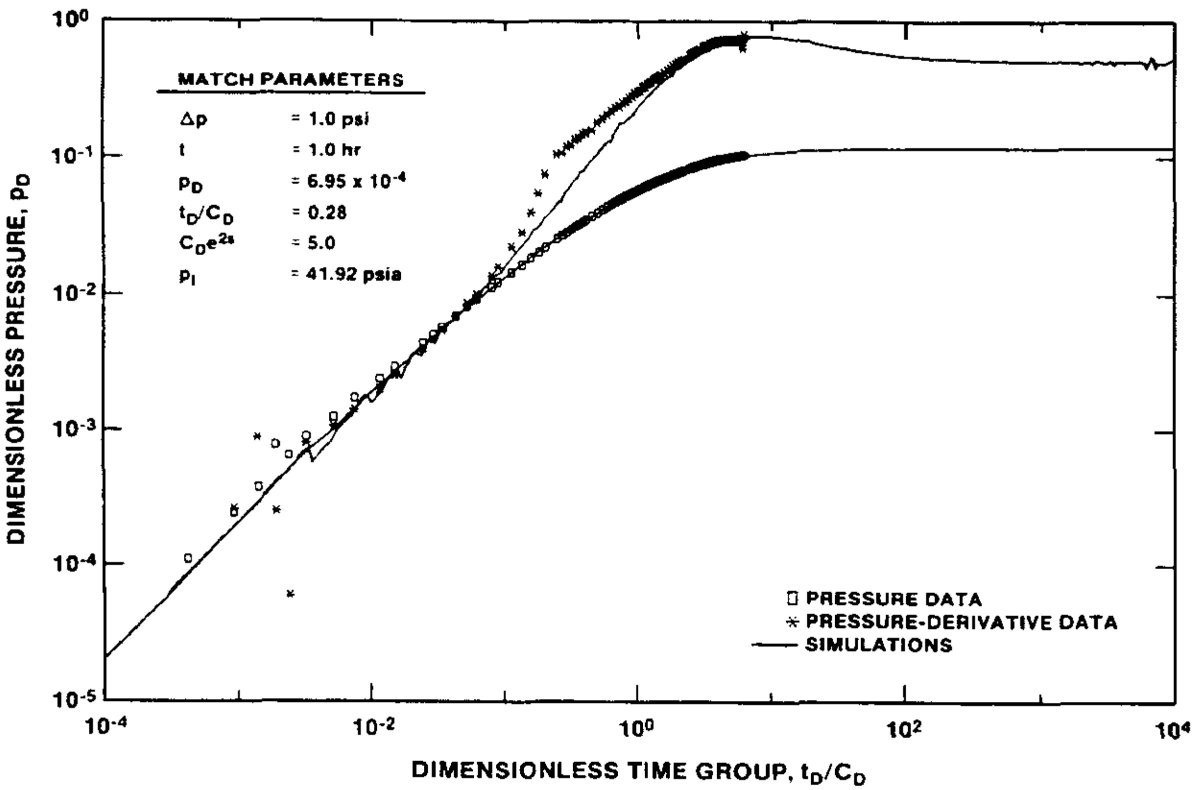


Figure 5-12. H-16/Unnamed Lower Member Siltstone First Buildup Log-Log Plot with INTERPRET Simulation

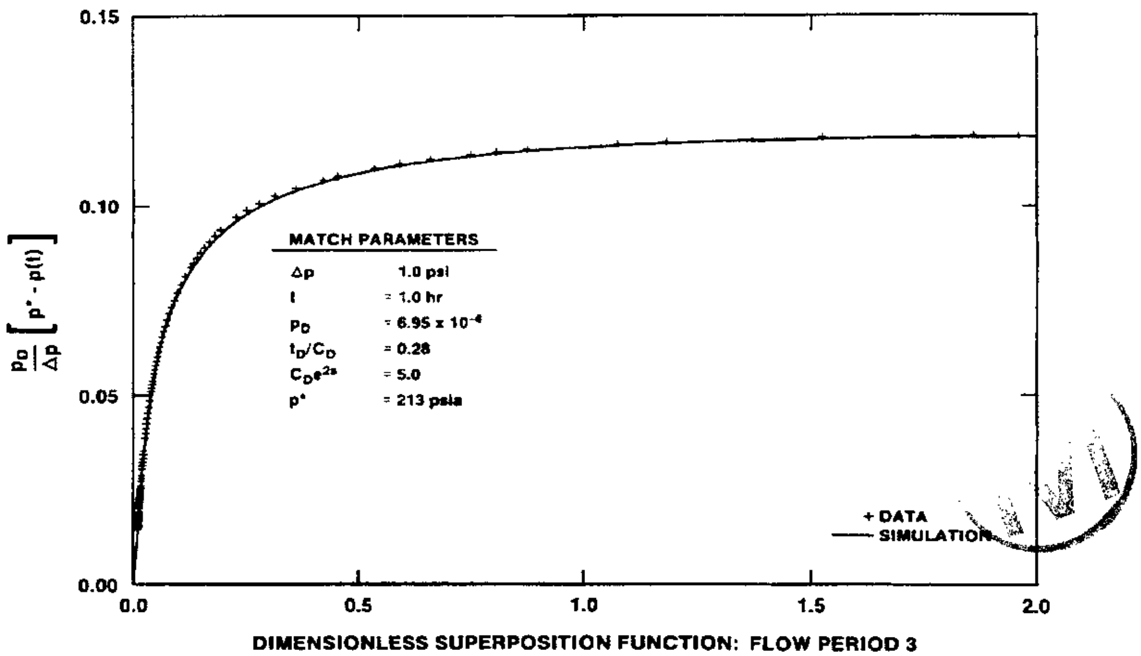


Figure 5-13. H-16/Unnamed Lower Member Siltstone First Buildup Dimensionless Horner Plot with INTERPRET Simulation

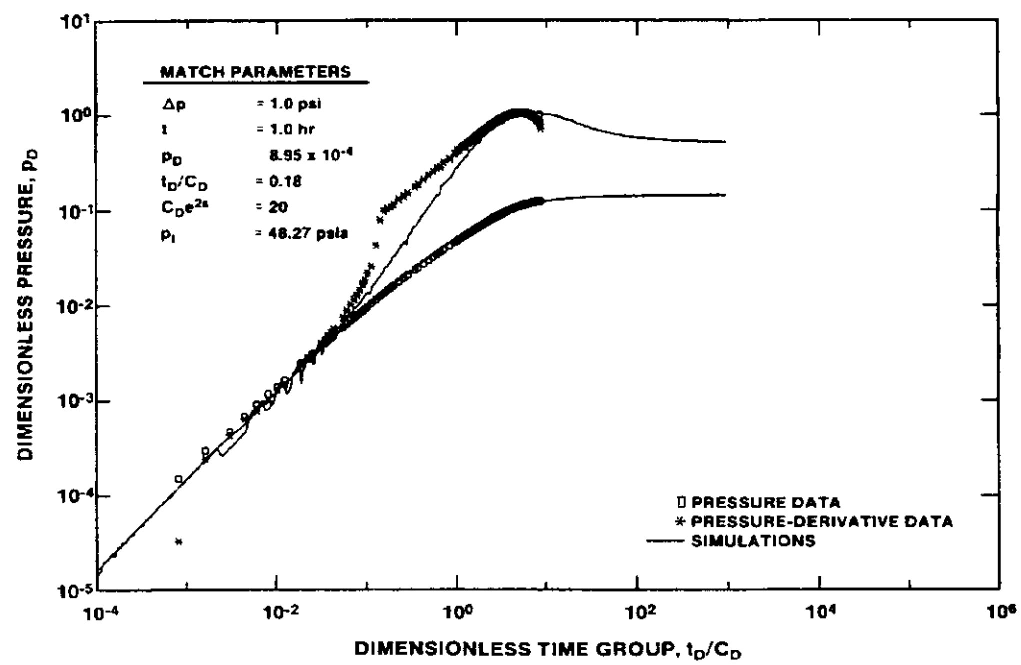


Figure 5-14. H-16/Unnamed Lower Member Siltstone Second Buildup Log-Log Plot with INTERPRET Simulation

TABLE 5-2
SUMMARY OF NON-CULEBRA SINGLE-WELL TEST RESULTS

WELL	ZONE NAME	ZONE DEPTH INTERVAL (ft)	DEPTH INTERVAL TESTED (ft)*	TEST TYPE	TRANSMISSIVITY (ft²/day)	SKIN FACTOR
H-16	Unnamed lower member siltstone	778-842	739-851	DST/FBU	2.7×10^{-4}	-0.4
				DST/SBU	2.2×10^{-4}	0.2
H-14	Magenta	424-448	420-448	DST/FBU	5.6×10^{-3}	0.5
				DST/SBU	5.6×10^{-3}	0.4
				DST/TBU	5.3×10^{-3}	0.3
H-16	Magenta	590-616	589-621	DST/FBU	2.8×10^{-2}	-0.4
				DST/SBU	2.8×10^{-2}	-0.8
				slug	2.4×10^{-2}	–
H-14	Forty-niner claystone	390-405	381-409	DST/FBU	7.1×10^{-2}	3.2
				DST/SBU	6.9×10^{-2}	3.3
				slug	3.0×10^{-2}	–
H-16	Forty-niner clay	563-574	560-581	pulse	2.2×10^{-4}	–
				DST/FBU	5.3×10^{-3}	0.7
				DST/SBU	5.6×10^{-3}	0.6
				slug	5.0×10^{-3}	–
Carper	Cenozoic alluvium	263-386	263-386	pumping	55	–

*Actual intervals open to the wells.

Section 5.2.3 Tamarisk Member, p. 108, col. 1, para 2;

" The Tamarisk Member of the Rustler Formation was tested in wells H-14 and H-16. The purposes of the Tamarisk testing were to: 1) define the hydraulic head of the unit; and 2) measure the transmissivity of the unit. Information on the hydraulic head of the Tamarisk is needed to evaluate potential direction of vertical movement of groundwater between the Rustler members. The transmissivity of the Tamarisk is a parameter needed for vertical cross-sectional or three-dimensional modeling of groundwater flow in the Rustler. The claystone/mudstone/siltstone portion of the Tamarisk (referred to hereafter simply as the claystone) is believed to be more permeable than the anhydrite/gypsum sections, and therefore easier to test. Consequently, tests were attempted only on the claystone portion of the Tamarisk at H-14 and H-16.

5.2.3.1 H-14.

At H-14, the Tamarisk claystone extends from about 517 to 525 ft deep (Figure 3-6). The initial test was performed over an interval from the base of a packer at a depth of 494.5 ft to the then-bottom of the hole 533 ft deep. Thus, the test interval included the 8-ft thickness of claystone, and 30.5 ft of overlying and underlying anhydrite and gypsum. Descriptions of the test instrumentation and the test data are contained in Stensrud et al. (1987).

Testing began on October 7, 1986, by setting the packer, swabbing the tubing to decrease the pressure in the test interval, and closing the shut-in tool to isolate the test interval and allow the test-interval pressure to recover and equilibrate at the existing static formation pressure. The pressure response observed during the testing is shown in Figure 5-82. After being shut in for nearly 37 hr, the fluid pressure in the Tamarisk claystone test interval had still not stabilized, but was rising at an ever-decreasing rate. The pressure in the wellbore above the packer, in contrast, was dropping as fluid was apparently entering the exposed Magenta and Forty-niner Members. Because the Tamarisk pressure had not stabilized, and did not appear likely to stabilize for several days or weeks, no drillstem tests were performed.

To verify that the observed response during the shut-in period was representative of the Tamarisk claystone and not caused by a tool malfunction, the packer was deflated and the DST tool was reset 8 ft deeper in the hole on October 9, 1986. After swabbing and shutting in the new test interval, a pressure buildup similar to that observed at the previous depth was measured for 4.5 hr (Figure 5-82). At this point, we concluded that the permeability of the Tamarisk at H-14 is too low to allow testing on the time scale of a few days, and abandoned the effort.

No conclusions about the static formation pressure of the Tamarisk can be drawn from the observed pressure buildups, because we have no way of evaluating the role played by the overpressure skin that was probably created during drilling. Subsequent testing of the Magenta and Forty-niner Members, discussed below, revealed fluid-pressure buildups to be significantly affected by overpressure skins.

5.2.3.2 H-16

At H-16, the Tamarisk claystone extends from 677.5 to 690.1 ft deep (Figure 3-8).

The interval tested extended from 674.5 to 697.9 ft, the bottom of the hole at that time, thus including 10.8 ft of overlying and underlying gypsum. Descriptions of the test instrumentation and the test data are presented in Stensrud et al. (1988).

Testing was performed on August 5, 1987. After the packer was set, the tubing was swabbed and the shut-in tool was opened to relieve the pressure that had been exerted on the formation by the column of drilling fluid in the well. The test interval was then shut in to allow the wellbore and formation pressures to equilibrate. Figure 5-83 shows the slow pressure rise that resulted over the next 10 hr. This pressure recovery was very similar to that observed for the Tamarisk claystone at H-14 (Figure 5-82). Based on the similarity to the H-14 response and the conclusion that the Tamarisk could not be tested on the time scale of a few days at H-14, the testing effort at H-16 was abandoned.

This decision was borne out by subsequent pressure measurements made by the transducer installed at the Tamarisk horizon as part of the 5-packer installation in H-16 (Figure 3-8). From August 31, 1987, 4 days after the 5-packer installation was completed, until December 15, 1987, the pressure in the Tamarisk interval declined from 204 psig to 169 psig (Stensrud et al., 1988 and in preparation), with complete stabilization apparently several months in the future. The Tamarisk transducer in the 5-packer system is mounted at a depth of 647.1 ft. IN a borehole containing brine with a specific gravity of 1.2, the pressure at the midpoint of the Tamarisk claystone 684 ft deep is about 19 psi higher than that measured by the transducer. Hence, the most that can be said at present is that the static formation pressure of the Tamarisk is less than 188 psig. The very slow pressure stabilization of the Tamarisk claystone likely indicates that its transmissivity is one or more orders of magnitude lower than that of the least-transmissive unit successfully tested in H-16, the unnamed lower member siltstone (2 x 10^{-4}ft^2/day; Table 5-2)."

Section 5.2.4.1 H-14, p 111, col 1, para 2, line 3;

" The simulation is representative of a single-porosity medium with a transmissivity of 5.6 x 10^{-3} ft^2/day (Table 5-2). Assuming a porosity of 20%, a total-system compressibility of 1.0 x 10^{-5}psi^{-1}, and a fluid viscosity of 1.0 cp, the skin factor of this simulation is about 0.5 indicating a well with very little wellbore damage. The simulation does not fit the observed early-time data very well, but it does fit the middle- and late-time pressure data adequately."

Section 5.2.4.2 H-16, page 115, col 2, para 2, line 3;

" The simulation is representative of a single-porosity medium with a transmissivity of 2.8 x 10^{-2}ft^2/day (Table 5-2). Assuming a porosity of 20%, a total system compressibility of 1.0 x 10^{-5}psi^{-1}, and a fluid viscosity of 1.0 cp, the skin factor for this simulation is -0.4, indicating a very slightly stimulated well. The pressure derivative shows oscillations similar, although with much lower amplitudes, to those observed in the H-14 Magenta SBU and TBU data (Figures 5-87 and 89)."

Section 5.2.5 Forty-niner Member, p. 119;

" The Forty-niner Member of the Rustler Formation was tested in wells H-14 and H-16.

The objectives of the testing were to obtain hydraulic-head and transmissivity estimates. The hydraulic-head measurements are particularly important in helping to determine whether or not water from the Dewey Lake Red Beds, and by extension from the surface, can be recharging the Magenta and Culebra dolomites at the WIPP site. The transmissivity estimates allow an evaluation of the ability of the Forty-niner to provide water to the WIPP shafts, as well as providing data for cross-sectional or three-dimensional modeling of groundwater flow in the Rustler.

5.2.5.1 H-14.

Two sets of Forty-niner tests were performed at H-14, tests of the medial claystone/mudstone/siltstone unit (hereafter referred to simply as claystone) and tests of the upper anhydrite unit. The claystone tests were to provide data on the hydraulic head and transmissivity of the most permeable section of the Forty-niner. The anhydrite tests were intended to verify the assumptions that the Rustler anhydrites are much less permeable than the claystones, and that they cannot be tested on the time scale of days.

Forty-niner Claystone:

At H-14, the claystone portion of the Forty-niner lies between 390 and 405 ft deep (Figure 3-6). The claystone was tested in a DST straddle interval extending from 381.0 to 409.5 ft deep. Thus, about 13.5 ft of Forty-niner anhydrite and gypsum were included in the test interval. Descriptions of the test instrumentation and the test data are contained in Stensrud et al. (1987).

The Forty-niner claystone was tested on October 13 and 14, 1986. Testing consisted of two flow periods, two buildup periods, and a rising-head slug test (Figure 5-95). The FFL lasted about 18 minutes, and was followed by a 92-minute FBU. The SFL lasted about 32 minutes, and was followed by a SBU almost 16 hr long. To obtain equivalent constant-rate flow periods, each of the flow periods was divided into two shorter periods. The FFL was divided into two periods with flow rates of 0.028 and 0.021 gpm, and the SFL was divided into periods with flow rates of 0.022 and 0.017 gpm (Table 5-1). The slug test lasted slightly over 6 hr, by which time about 57% of the induced pressure differential had dissipated.

Overpressure skin effects were apparent during the Forty-niner claystone testing, just as they were during all other testing at H-14. The fluid pressure reached a maximum of 67.9 psia during the initial equilibration period, was essentially constant at 66.8 psia at the end of the FBU, and peaked at 66.2 psia during the SBU (Figure 5-95). The superposition of pressure-skin effects manifested in the Magenta test data (see Section 5.2.4.1) was not apparent, however, in the Forty-niner claystone test data.

Figure 5-96 shows a log-log plot of the Forty-niner claystone FBU data with an INTERPRET-generated simulation. The late-time pressure derivative shows the decline indicative of overpressure skin. The simulation is representative of a single-porosity medium with a transmissivity of 7.1 x 10^{-2} ft^2/day (Table 5-2). Assuming a porosity of 30%, a total-system compressibility of 1.0 x 10^{-5} psi^{-1}, and a fluid viscosity of 1.0 cp, the skin factor for this simulation is about 3.2, indicating a damaged well.

The dimensionless Horner plot of the FBU data is shown in Figure 5-97. The simulation matches the observed data very well until late time, when the data deviate towards a static pressure lower than the 67.8 psia specified for the simulation. This discrepancy between the observed data and the simulation is entirely consistent with the effects of an overpressure skin.

The log-log plot of the SBU data is shown in Figure 5-98. Overpressure-skin effects are once again evident in the late-time pressure derivative. The simulation shown was generated by INTERPRET using a single-porosity model and a transmissivity of 6.9 x $10^{-2}ft^2$/day (Table 5-2). With the assumed parameter values listed above, the skin factor for this simulation is about 3.3, comparable to the value obtained from the FBU analysis.

A log-log early-time plot of the rising-head slug-test data is shown in Figure 5-99, along with the best-fit type curve. The fit is quite good until near the end, when the observed data oscillate for an unknown reason. The type-curve fit shown provides a transmissivity estimate of 3.0 x $10^{-2}ft^2$/day (Table 5-2), which is slightly less than half of the values provided by the FBU and SBU analyses. A slightly different type-curve fit might have been indicated had the late-time data been better behaved.

The static formation pressure for the Forty-niner claystone is difficult to estimate because of the overpressure-skin effects present during the buildup tests, and because of the nonideal behavior during the latter portion of the slug test. The static formation pressure must be less than the final pressure measured at the end of the SBU, 65.5 psia. The slug-test analysis relied on a static formation pressure estimate of 62 psia, although a reasonably good fit was also obtained using an estimate of 65 psia. Considering that the transducer during these tests was set 362.9 ft deep, that the transducer measured an atmospheric pressure of 12 psia before testing began, and that the borehole contained brine with a specific gravity of 1.2, 65 psia corresponds to a static formation pressure of 71 psig at the midpoint of the claystone 398 ft deep. This value is reliably a maximum.

Forty-niner Anhydrite.

The upper anhydrite and gypsum unit of the Forty-niner Member lies 359.5 to 390 ft deep at H-14 (Figure 3-6). The unit is roughly 75% anhydrite and 25% gypsum, based on interpretation of a neutron log. The unit was tested in a DST straddle interval extending from 356.0 to 384.5 ft deep. Thus, the bottom 3.5 ft of the Dewey Lake Red Beds and the Dewey Lake/Rustler contact were included in the test interval. Descriptions of the test instrumentation and the test data are contained in Stensrud et al. (1987).

The Forty-niner anhydrite was tested from October 14 to 15, 1986. Because the anhydrite was expected to have too low a permeability to allow quantitative testing the few days available for testing, no pressure-equilibration period preceded the testing. Instead, as soon as the packers were set, the tubing was swabbed with the shut-in tool open, and the test interval was left open to the tubing for about 16 minutes for a flow period (Figure 5-100). Very little fluid entered the tubing at this time. The test interval was then shut in for about 16.5 hr. The pressure increased by about 1 psi over the first 1.5 hr of the buildup, and by another psi over the last 1.5 hr. At that time, the testing was terminated. The Forty-niner anhydrite was judged to have a permeability much lower than that of the claystone, and quantitative testing of the anhydrite appeared to require weeks to months of effort."

Pg. 124, col. 2;

" Figure 5-102 is a semilog plot of the Forty-niner pulse-test data, showing the best type-curve match achieved. That data and type curve match reasonably well, with the greatest discrepancy occurring at early time. The transmissivity calculated from this match is 2.2 X 10^{-4} ft^2/day (Table 5-2).

Figure 5-103 is a log-log plot of the DST FBU data, along with a simulation generated by INTERPRET. The simulation fit the data very well, and is representative of a single-porosity medium with a transmissivity of 5.3 X 10^{-3} ft^2/day (Table 5-2). Assuming a porosity of 30%, a total-system compressibility of 1.0 X 10^{-5} psi^{-1}, and a fluid viscosity of 1.0 cp, the skin factor for this simulation is 0.7, indicating a wellbore with little damage. The decline in the pressure derivative at late time reflects minor overpressure-skin effects. The dimensionless Horner plot of the FBU data (Figure 5-104) shows an excellent fit between the data and the simulation using a static formation pressure estimate of 117.2 psia."

Pg. 126, col. 1, para. 1;

" The log-log plot of the SBU data (Figure 5-105) is very similar to that of the FBU data (Figure 5-103). The INTERPRET simulation is also similar, using a transmissivity of 5.6 X 10^{-3} ft^2/day and a skin factor of 0.6 (Table 5-2). Again, overpressure-skin effects are evident in the late-time behavior of the pressure derivative.

Figure 5-106 is an early-time log-log plot of the Forty-niner slug-test data. Because of the low degree of pressure recovery during the slug test, the data are inadequate to provide definitive results on their own, but they do serve to confirm the DST results. The type-curve match shown provides a transmissivity estimate of 5.0 X 10^{-3} ft^2/day (Table 5-2), and uses a static formation pressure estimate of 116.1 psia. Both of these values are in reasonable agreement with the DST interpretations.

In contrast, the transmissivity value provided by the pulse-test interpretation is over an order of magnitude lower than the transmissivity values estimated from the DST and slug-test analyses. This low apparent value of transmissivity may have been caused by two, perhaps interrelated, factors. First, pulse tests inherently, factors. First, pulse tests inherently test very small volumes of rock around the borehole, much smaller than do DST's and slug tests. The average transmissivity of the rock tested could easily change between the two scales of tests. Second, the pulse test was the first test performed and was an injection test, whereas the DST's and slug test were withdrawal tests. Any skin that may have been present on the borehole wall after drilling, such as a mud cake, could be loosened by a withdrawal test, but would be intensified by an injection test. Consequently, the pulse-injection test may have measured an average transmissivity of both the nearby rock <u>and</u> the wellbore skin. The subsequent DST's and slug test, which caused water to flow <u>into</u> the well, should have served to decrease any skin present, and this may be evidenced by the slight drop in skin values between the FBU and the SBU (Table 5-2). For these reasons, and because of the consistency of the DST and slug-test results, the most reliable value for the transmissivity of the Forty-niner clay at H-16 is probably about 5.3 X 10^{-3} ft^2/day."

Section 6. DISCUSSION OF RUSTLER FLOW SYSTEM, p. 131;

" The single-well testing discussed in this report has provided significant information on the transmissivities and hydraulic-head relations of the five Rustler members. IN particular, our knowledge of the distribution of transmissivity within the Culebra dolomite has increased considerably. Section 6.1 attempts to explain the distribution of Culebra transmissivity in the context of geologic models of halite deposition and dissolution within the Rustler. Section 6.2 discusses the hydraulic-head relations among the Rustler members, and their implications regarding recharge to the Rustler Formation."

Section 6.1 Culebra Transmissivity, p. 131;

" Mercer (1983) reported values for Culebra transmissivity at 20 locations. The testing described in this report has provided values for Culebra transmissivity at 15 new locations, and new estimates at 7 locations for which values had previously been reported. Combined with other recent work performed at DOE-2 (Beauheim, 1986), H-3 (Beauheim, 1987a), H-11 (Saulnier, 1987), and WIPP-13 (Beauheim, 1987b), the WIPP project has tested 38 locations and the transmissivity values at each provided by this report or those referenced above.

Figure 6-2 shows the areas around the WIPP site where halite is present in the non-dolomite Rustler members, as indicated by Snyder (1985 and personal communication) and Powers (personal communication). According to Snyder, halite was originally deposited in the unnamed lower, Tamarisk, and Forty-niner Members of the Rustler over the entire area covered by Figure 6-2. The present-day absence of halite from these members reflects the eastward progression of a dissolution front. This dissolution front apparently affects the uppermost Rustler halite, that in the Forty-niner, first, and works progressively downsection to the upper Salado Formation. Thus, the eastward extent of the Forty-niner dissolution front is greater than that of the Tamarisk dissolution front, which is in turn greater than the eastward extent of the dissolution front in the unnamed lower member (Figure 6-2). Dissolution of the upper Salado follows dissolution of halite from the unnamed lower member of the Rustler. Lagging behind the dissolution front in each member is a second front where anhydrite is being hydrated to gypsum. In Snyder's view, as halite is removed beneath the Rustler dolomites, the dolomites subside and fracture. Similar subsidence and fracturing may affect the anhydrites, allowing more groundwater flow through them which may effect their hydration to gypsum. Note that the areas shown on Figure 6-2 indicate that only some halite is present in the appropriate members, not that the full thicknesses originally deposited are present. For example, Snyder (1985) states that only about half of the halite originally present in the unnamed lower member at WIPP-21 is there today.

Alternatively, Holt and Powers (1988) believe that the different amounts of halite seen in the Rustler members at the WIPP site more likely represent original depositional differences and/or syndepositional dissolution that later progressive dissolution. They relate fracturing to stress relief caused by unloading of the Rustler, citing a preponderance of horizontal (as opposed to vertical) fractures within the Rustler as evidence. According to their hypothesis, fracturing would be expected to become less pronounced eastward as the depth of burial of the Rustler increases. Holt and Powers (1988) also do not believe that all of the gypsum present in the Rustler is related to the hydration of anhydrite, but that it is instead primary, pointing to the preservation of primary sedimentary structures as evidence. Hold and Powers do find evidence for late-stage dissolution of halite from the upper Salado in Nash Draw, however, and relate disruption of the overlying Rustler to this dissolution.

As can be seen on Figure 6-2, the highest values of Culebra transmissivity are found in areas in or close to Nash Draw where no halite is present in the Rustler. At DOE-2 and WIPP-13, which are very close to the boundary west of which no halite is present in the unnamed lower member, the transmissivity of the Culebra is also relatively high. Relatively high transmissivities are also found, however, ate DOE-1 and H-11, where little or no halite is missing beneath the Culebra. WIPP-30, on the other hand, lies in an area of no Rustler halite, and yet the transmissivity of the Culebra is low at that location. Neither Snyder's (1985) nor Holt and Powers' (1988) model of halite deposition and dissolution can adequately explain the entire transmissivity distribution observed around the WIPP site.

If the absence of halite in the unnamed lower member is caused by dissolution and if this dissolution causes fracturing of the Culebra as Snyder (1985) suggests, then the high transmissivities shown in the area of no halite on Figure 6-2 would be expected. Further, the high transmissivities at DOE-2 and WIPP-13 could be explained as the result of partial dissolution of halite from the unnamed lower member. The lower transmissivity at WIPP-30, however, cannot be explained by this hypothesis, nor can the low transmissivities at H-14 and P-15, which are closer to the no-halite boundary than is H-18. The relatively high transmissivities at DOE-1 and H-11 also cannot be related to dissolution of underlying halite.

Holt and Powers' (1988) model could predict the high transmissivities in Nash Draw by relating them to dissolution of the upper Salado. Their model further states that no Rustler halite was deposited and no dissolution of the Salado has occurred at WIPP-30, thus explaining the low Culebra transmissivity at that location. If their argument that fracturing is related to unloading is correct, then a correlation between the present-day depth of burial of the Culebra and the transmissivity of the Culebra might be expected to exist. Preliminary evaluation by Holt (personal communication) indicates that some correlation between depth of burial and Culebra transmissivity is evident, but that the correlation is not perfect. For example, despite the fact that the Culebra is approximately 200 ft shallower at WIPP-30 than at DOE-2, the Culebra transmissivity is over two orders of magnitude lower at WIPP-30 than at DOE-2. Other, as yet undefined, factors may be as important as depth of burial in controlling the transmissivity of the Culebra. The Holt and Powers (1988) model also fails to explain the relatively high transmissivities at DOE-1 and H-11.

Clearly, neither of the geologic models cited above provides a complete understanding of the distribution of transmissivity within the Culebra. The two models need not be considered completely mutually exclusive, however, and as discussed above, elements of both models provide reasonable explanations of some features observed in the Culebra. Nondeposition (or syndepositional dissolution) of halite may have been more widespread than believed by Snyder (1985), and late-stage dissolution may have occurred more than is believed by Holt and Powers (1988). The most significant problem area is in the vicinity of

DOE-1 and H-11, where relatively high transmissivities would not be expected based on either model.

One additional observation that can be made from consideration of Figure 6-2 is that all measurements of Culebra transmissivity greater than 1 ft^2/day coincide with areas having no halite in the Tamarisk. The simple dissolution of Tamarisk halite would not seem likely to affect the transmissivity of the Culebra. The lack of high Culebra transmissivity <u>everywhere</u> that halite has been removed from the Tamarisk further argues against a direct relationship between Culebra transmissivity and Tamarisk halite. Nevertheless, absence of Tamarisk halite appears to be a necessary, but not sufficient, condition for high Culebra transmissivity. Perhaps the removal of Tamarisk halite makes possible a second process that directly affects the transmissivity of the Culebra."

p. 137, col. 2, line 7;
" ... Attempts to collect representative data on the formation pressure of the Tamarisk have failed to date, but recent data from DOE-2, H-14, and H-16 support Mercer's observation of downward hydraulic gradients from the Magenta to the Culebra at the WIPP site. Together these observations imply that the Culebra, the most transmissive member of the Rustler, acts as a drain on the overlying and underlying Rustler"

p 138, col 2, para 1;
" The unnamed lower member of the Rustler Formation was tested only in well H-16, where DST's were performed on the lower siltstone portion of the unit. The transmissivity of the siltstone is about 2.4 x $10^{-4}ft^2$/day (Table 5-2). . . ."

p 138, col 2, para 3;
" The claystone portion of the Tamarisk member of the Rustler Formation was tested in wells H-14 and H-16. At H-14, the pressure in the claystone failed to stabilize in three days of shut-in testing, leading to the conclusion that the transmissivity of the claystone is too low to measure in tests performed on the time scale of days. Similar behavior at H-16 led to the abandonment of testing at that location as well."

Section 7. SUMMARY AND CONCLUSIONS, p 139, col 1, para 3;
" The Forty-niner Member of the Rustler Formation was also tested in wells H-14 and H-16. Two portions of the Forty-niner were tested in H-14: the medial claystone and the upper anhydrite. DST's and a rising-head slug test were performed on the claystone. The transmissivity of the claystone is about 7 x $10^{-2}ft^2$/day (table 5-2). A prolonged buildup test performed on the Forty-niner anhydrite revealed a transmissivity too low to measure on a time scale of days. A pulse test, DST's, and a rising-head plug test were performed on the Forty-niner clay at H-16, indicating the clay has a transmissivity of about 5 x $10^{-3}ft^2$/day (Table 5-2). Formation pressures estimated for the Forty-niner at H-14 and H-16 are lower than those calculated for the Magenta (compensated for the elevation differences), indicating that water cannot be moving downwards from the Forty-niner to the Magenta at these

locations."

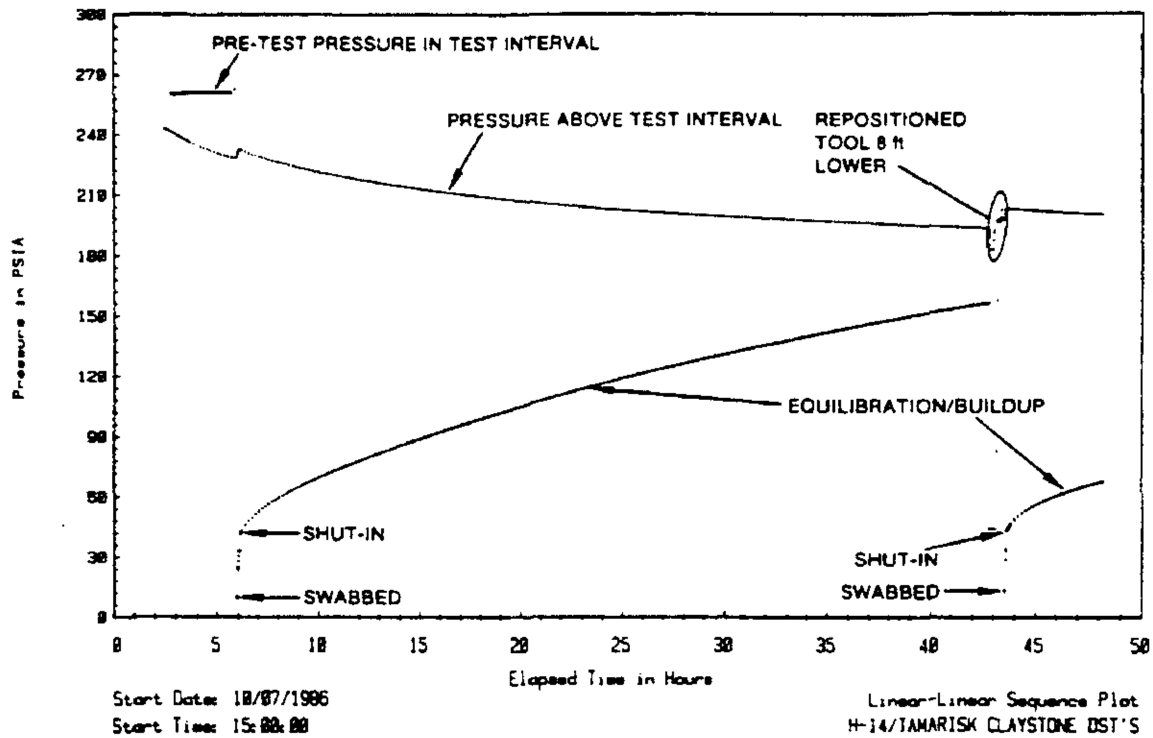


Figure 5-82. H-14/Tamarisk Claystone Shut-In Test Linear-Linear Sequence Plot

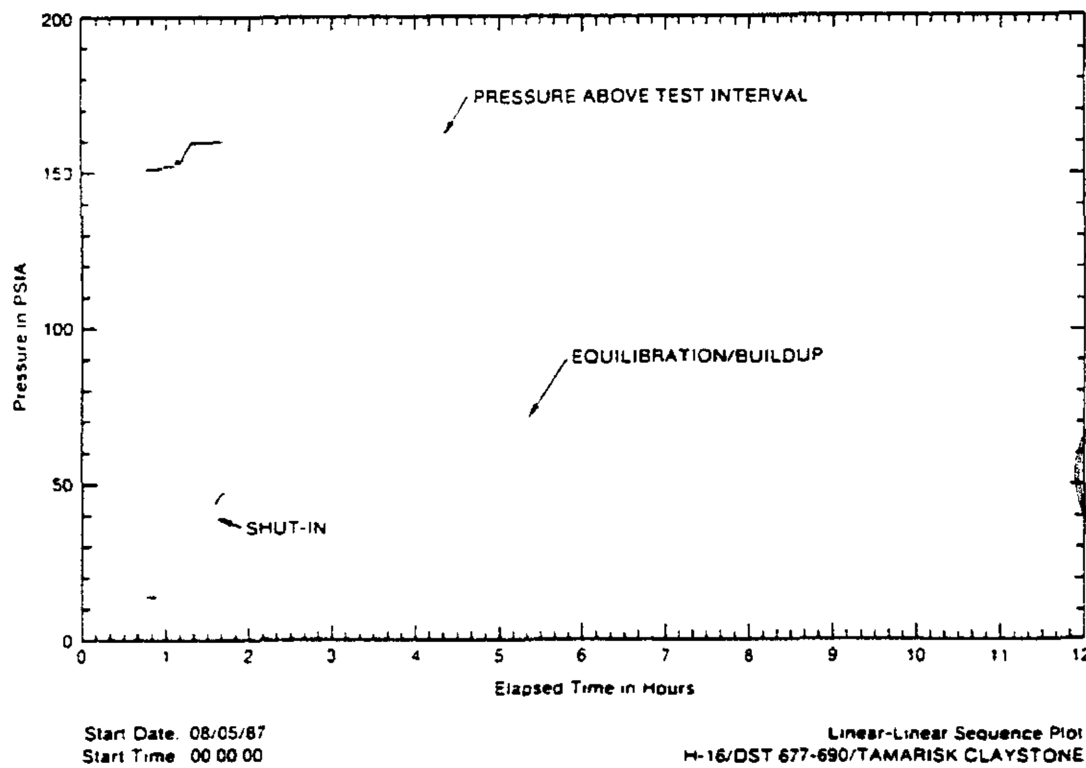


Figure 5-83. H-16/Tamarisk Claystone Shut-In Test Linear-Linear Sequence Plot

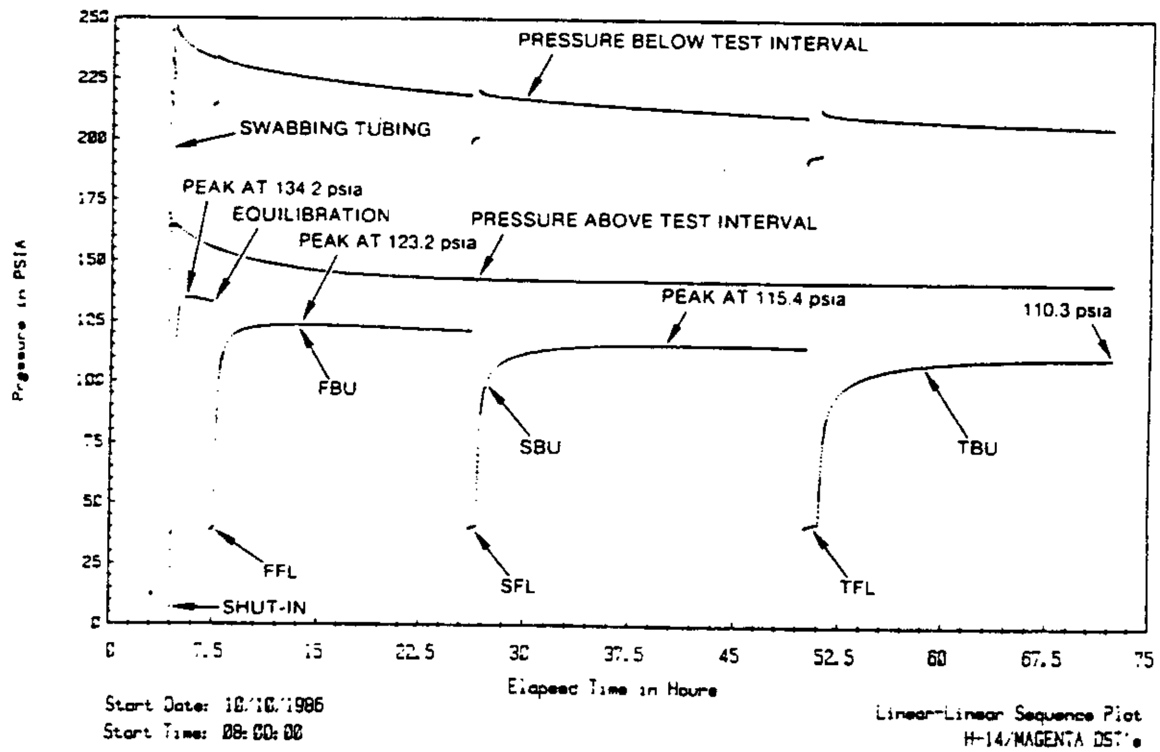


Figure 5-84. H-14/Tamarisk Claystone Shut-In Linear-Linear Sequence Plot

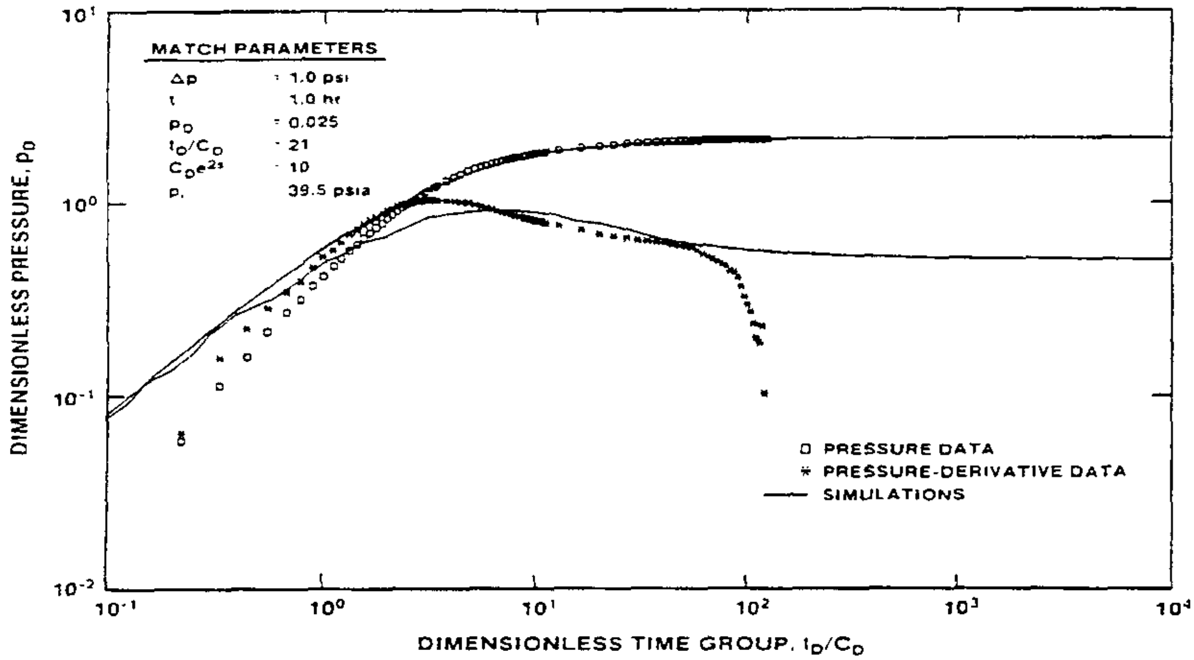


Figure 5-85. H-14/Magenta First Buildup Log-Log Plot with INTERPRET Simulation

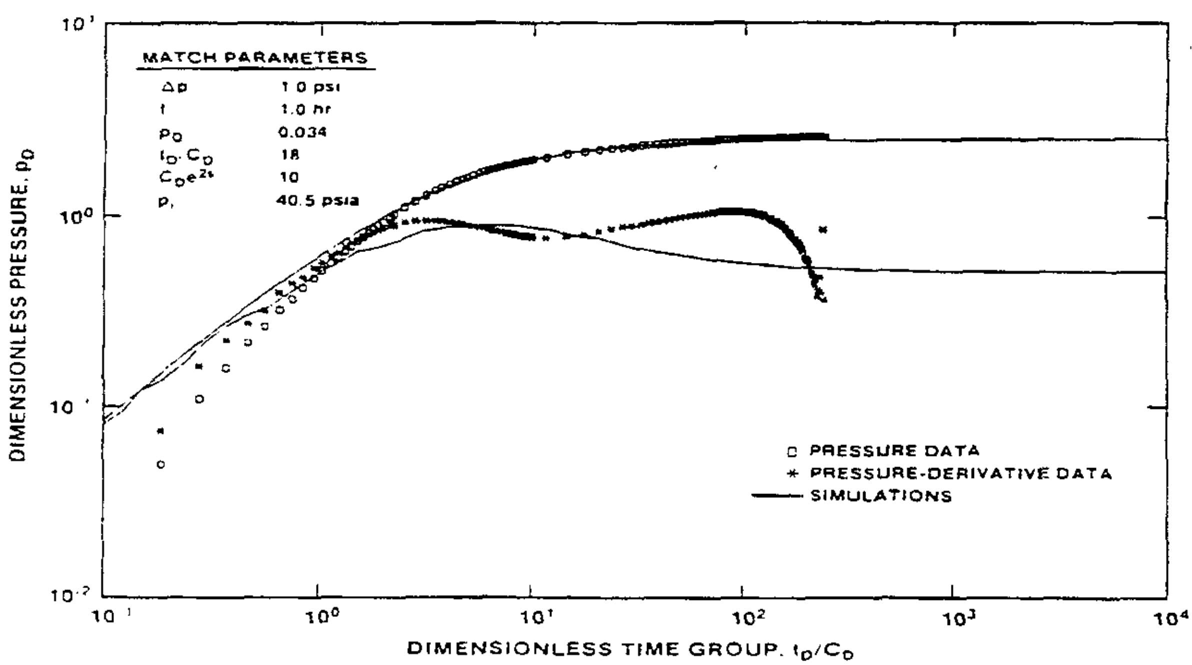
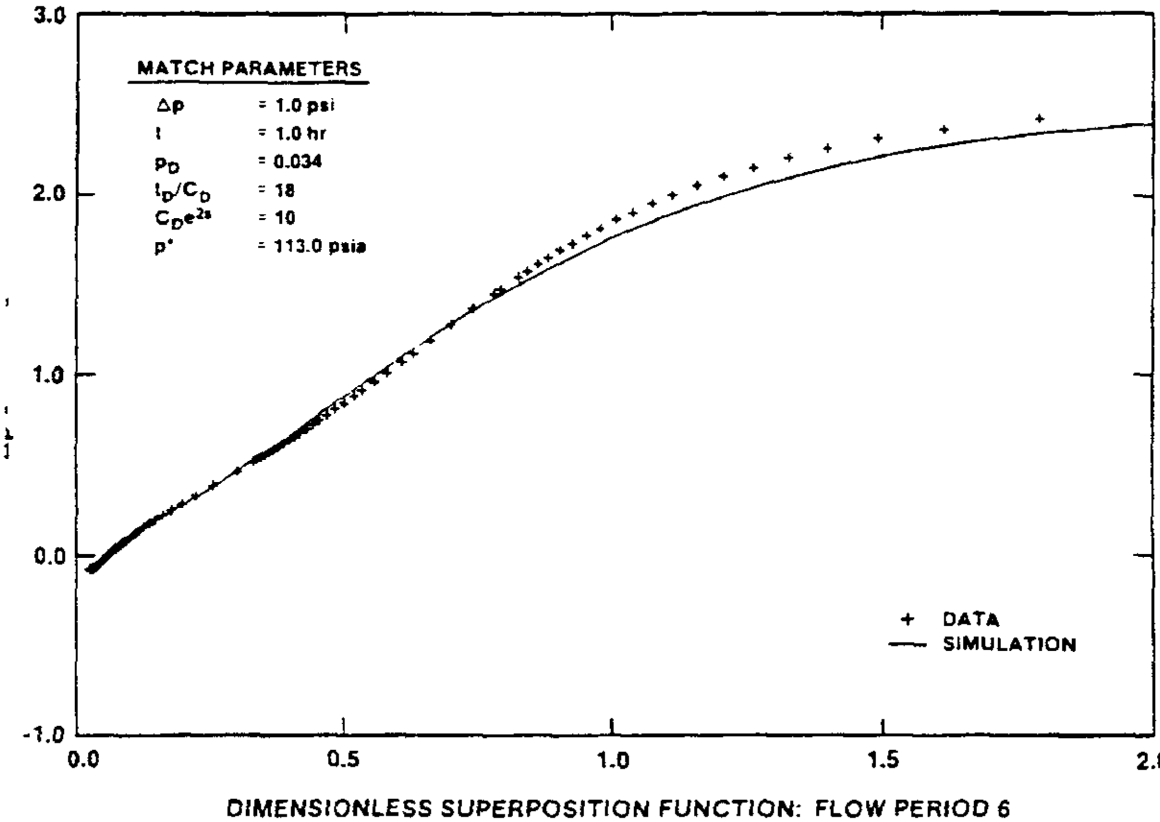


Figure 5-86. H-14/Magenta Second Buildup Log-Log Plot with INTERPRET Simulation



ıre 5-87. H-14/Magenta Second Buildup Dimensionless Horner Plot with INTERPRET Simulation

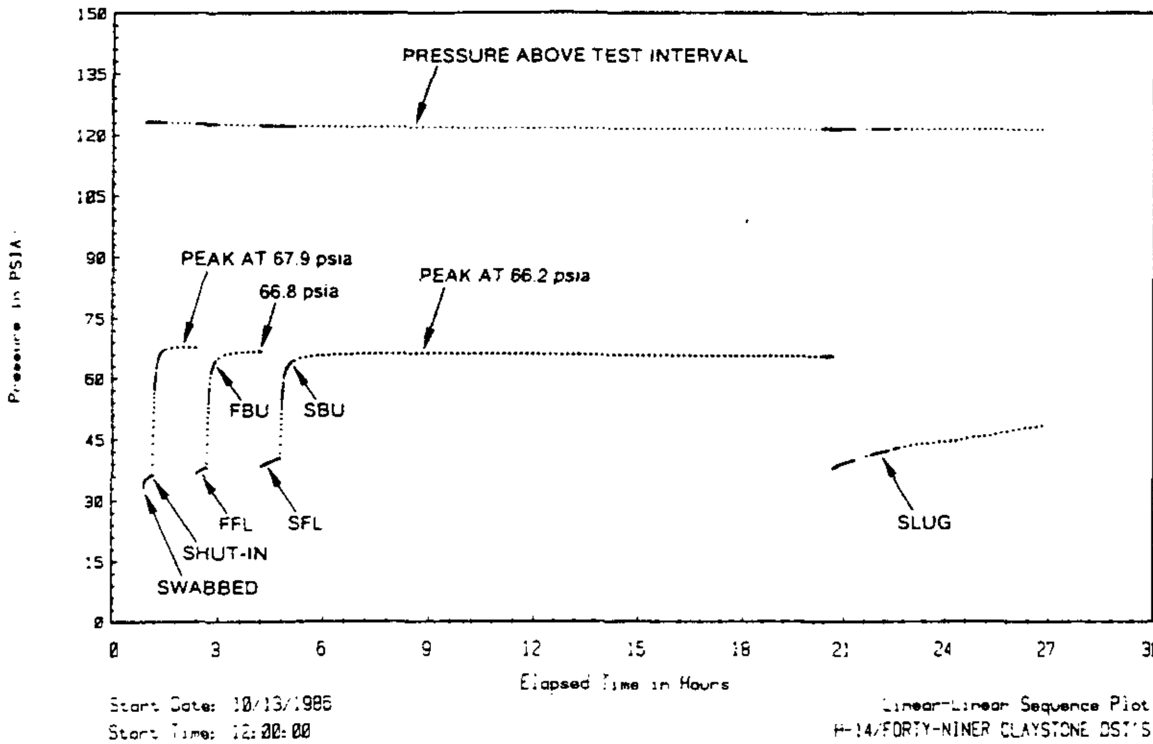


Figure 5-95. H-14/Forty-Niner Claystone Drillstem and Slug Testing Linear-Linear Sequence Plot

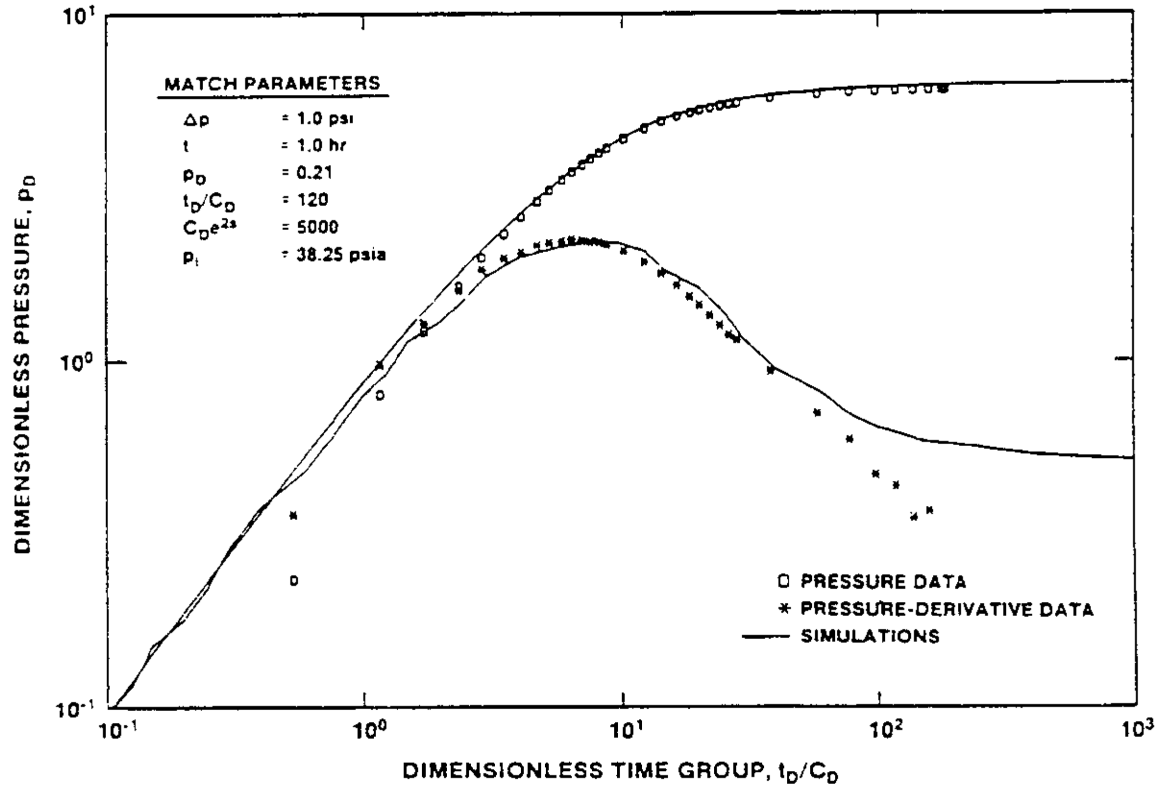
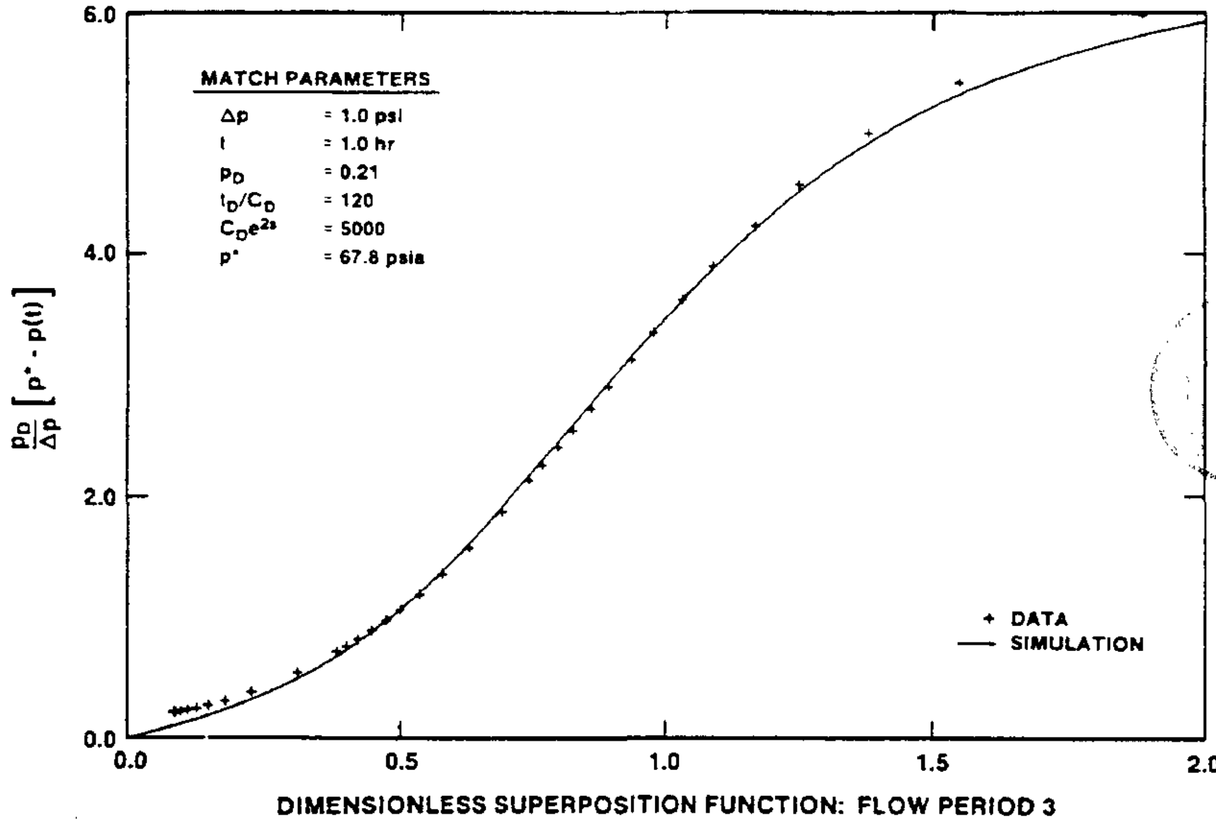


Figure 5-96. H-14/Forty-Niner Claystone First Buildup Log-Log Plot with INTERPRET Simulation



MATCH PARAMETERS
Δp = 1.0 psi
t = 1.0 hr
p_D = 0.21
t_D/C_D = 120
C_De^2s = 5000
p* = 67.8 psia
+ DATA
SIMULATION
6.0
4.0
2.0
0.0
0.0
0.5
1.0
1.5
2.0
p_D/Δp [p* - p(t)]
DIMENSIONLESS SUPERPOSITION FUNCTION: FLOW PERIOD 3

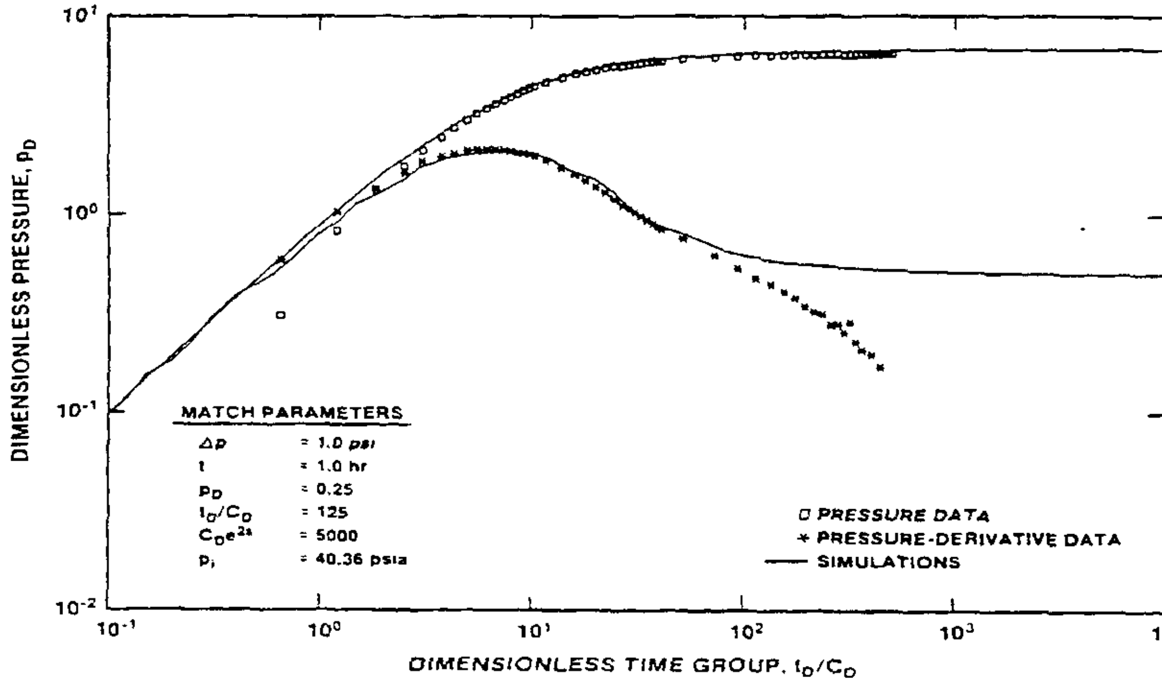


Figure 5-98. H-14/Forty-Niner Claystone Second Buildup Log-Log Plot with INTERPRET Simulation

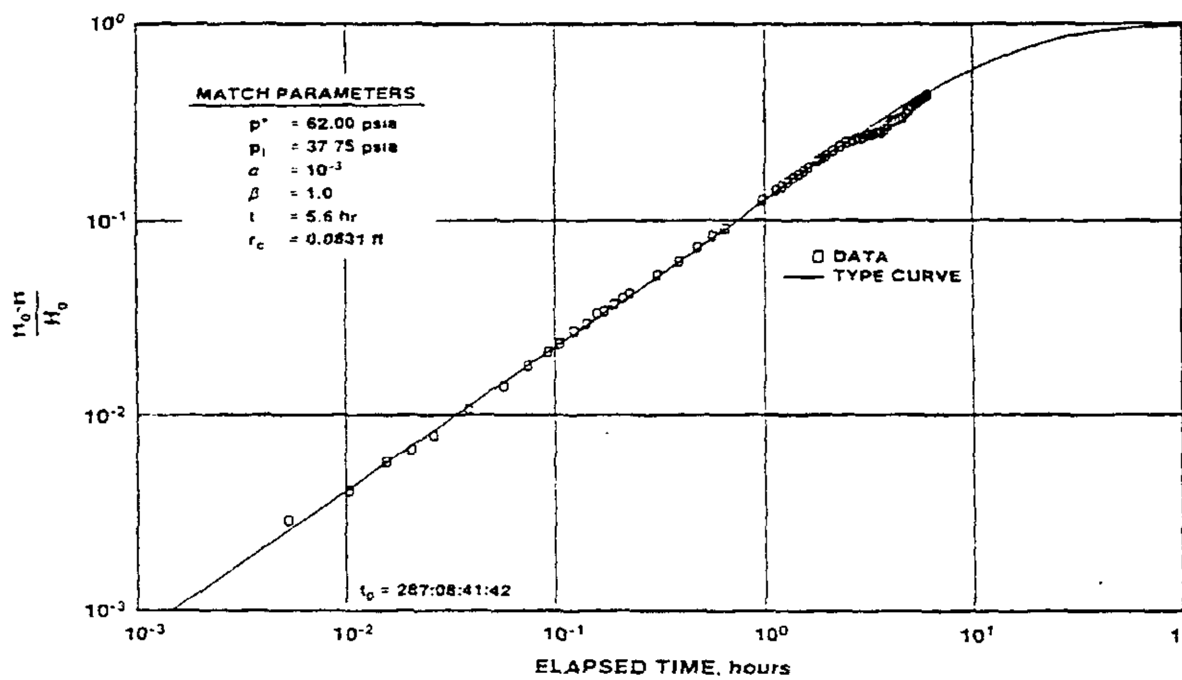


Figure 5-99. H-14/Forty-Niner Claystone Early-Time Slug-Test Plot

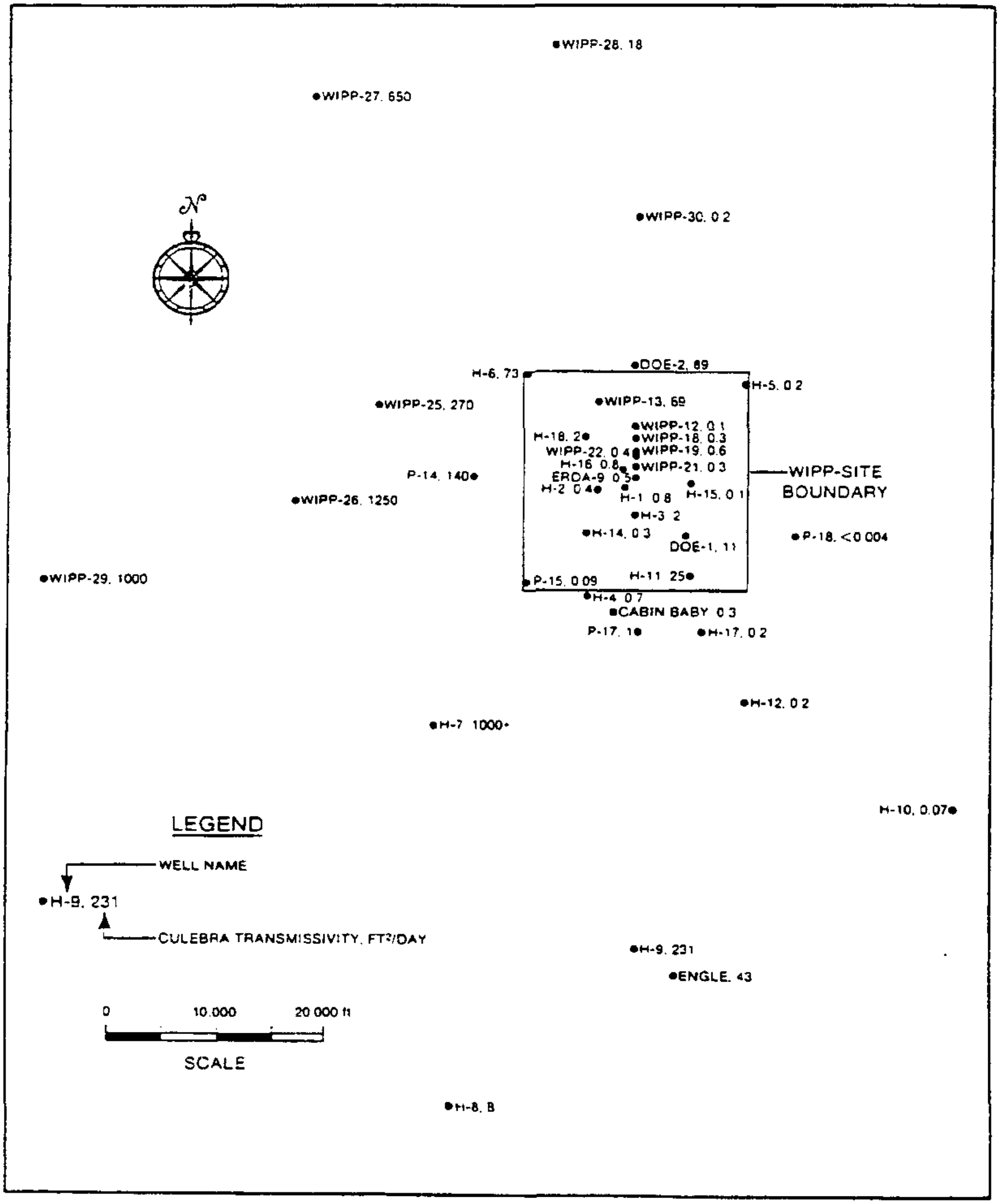


Figure 6-1. Culebra Wells Tested by the WIPP Project

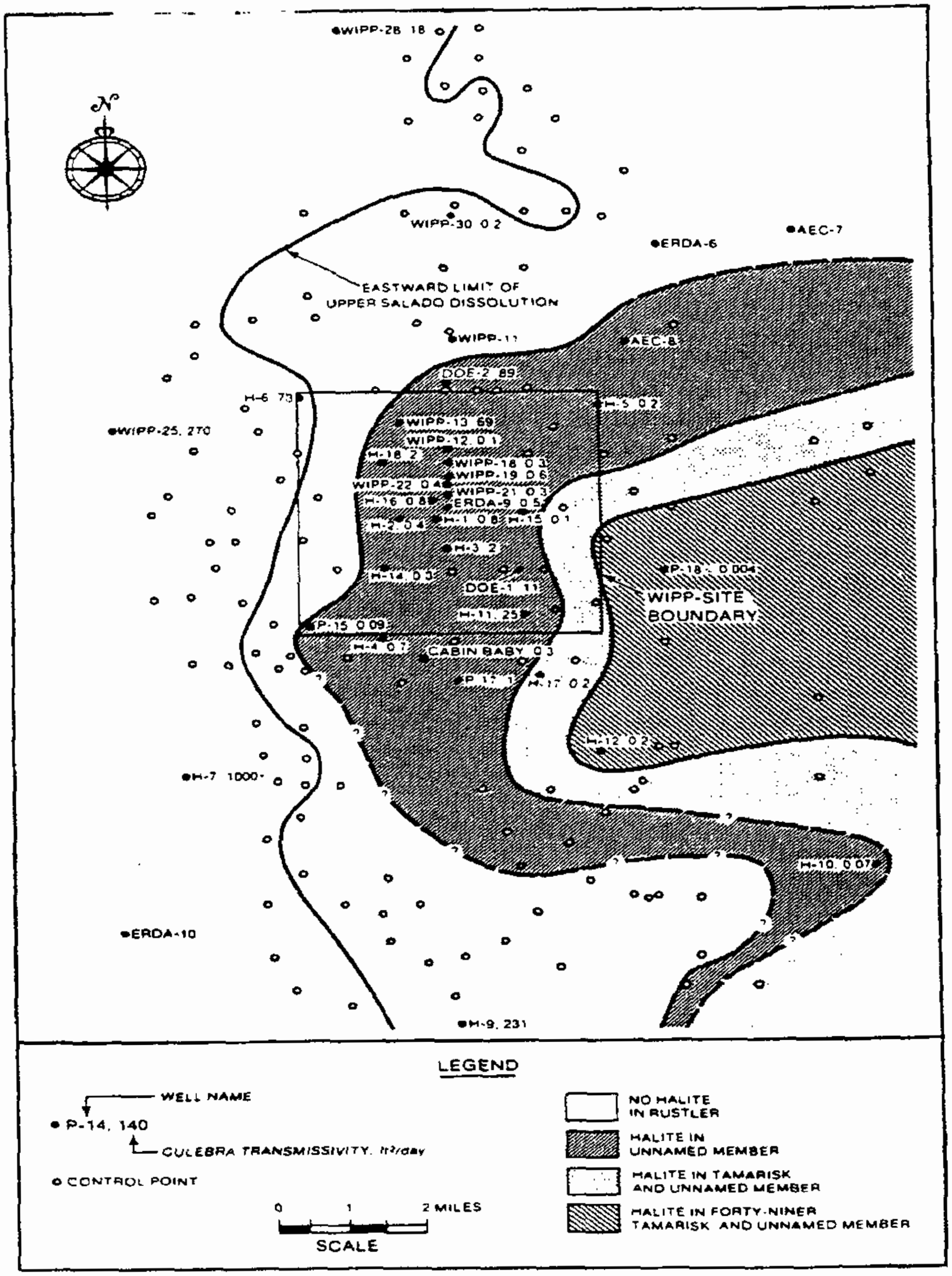


Figure 6-2. Distribution of Rustler Halite and Culebra Transmissivity Around the WIPP Site.

Beauheim, R.L. 1987b. Analysis of Pumping Tests of the Culebra Dolomite Conducted at the H-3 Hydropad at the Waste Isolation Pilot Plant (WIPP) Site. SAND86-2311. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT;

" Two pumping tests were conducted in the Culebra Dolomite Member of the Rustler Formation at the H-3 hydropad at the Waste Isolation Pilot Plant (WIPP) site. The first test was in 1984, with well H-3b3 pumped for 14 days at an average rate of 4 gpm. The second test, the H-3 multipad test, was in late 1985 and early 1986, with well H-3b2 pumped for 62 days at an average rate of 4.8 gpm. Both tests provided information on the hydraulic properties of the Culebra at the H-3 hydropad. The second test provided information on average Culebra hydraulic properties on a much larger scale; responses were observed up to 8000 ft from the pumping well.

The interpretation of these tests had three principle objectives. The first was to determine the most appropriate conceptualization of the nature of the Culebra flow system around the H-3 hydropad. The pumping well responses during the H-3 tests appear to be those of wells completed in a double-porosity medium with unrestricted interporosity flow. In such a system, fractures provide the bulk of the permeability, while matrix pores provide the majority of the storage capacity. The importance of fracture flow is indicated by the speed with which the observation wells on the H-3 hydropad respond to pumping and the nearly identical behaviors of these wells and the pumping well. The similarity between pumping- and observation-well behavior on the H-3 hydropad is so pronounced that the responses of all three wells on the hydropad can be interpreted only by using pumping-well analytical techniques, not observation-well analytical techniques. H-3b1 and H-3b3, in particular, appear to be very well connected by fractures.

The second objective was to quantify the hydraulic properties of the Culebra in the vicinity of the H-3 hydropad. The total-system (fractures plus matrix) transmissivity of the Culebra derived from the first test is 2.9 ft^2/day; that from the second test is 1.7 ft^2/day. The lower value derived from the second test probably represents lower transmissivity (lower fracture connectivity) at H-3b2 than at H-3b3, and/or lower average transmissivity of the volume of Culebra stressed in the multipad test as opposed to the smaller volume stressed in the first test. The fracture-to-total-system storativity ratios derived from the various analyses range from 0.03 to 0.25, indicating a relatively high degree of storage within the fractures. The highest storativity ratios were consistently found at H-3b1. Wellbore skin values are highly negative, indicating direct wellbore connection with fractures.

The third objective was to quantify the average hydraulic properties of the Culebra between the H-3 hydropad and more-distant observations wells. Meeting this objective . . ."

Pg. 100 Table A-3

Table A-3. Water Levels and Pressures in Observation Well DOE-1 During the 1984 H-3 Pumping Test

Day	Hr	Min	Elapsed Time (hr)	Depth to Water (ft)	Pressure* (psi)	Comments
101	16	32	-305.970	499.18	47.69	
108	14	10	-140.330	499.21	47.67	
110	8	55	-97.583	499.31	47.63	
110	14	5	-92.417	499.08	47.74	
110	15	44	-90.767	499.21	47.67	
111	12	45	-69.750	499.18	47.69	
114	8	45	-1.750	499.74	47.42	
114	12	7	1.617	499.61	47.48	PUMP ON AT H-3B3 114:10:30
115	9	42	23.200	499.61	47.48	
117	13	46	75.267	499.41	47.58	
118	13	40	99.167	500.00	47.30	
121	13	17	170.783	500.75	46.95	
122	13	20	194.833	500.85	46.90	
123	11	52	217.367	501.05	46.80	
124	9	24	238.900	501.35	46.66	
125	10	6	263.600	501.51	46.59	
128	13	48	339.300	502.46	46.14	

*Pressure = (600 ft - Depth to Water) x 0.473 psi/ft

Beauheim, R.L., 1987c. Interpretation of the WIPP-13 Multipad Pumping Test of the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) Site. SAND87-2456. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p 3;

" A large-scale pumping test of the Culebra Dolomite Member of the Rustler Formation was performed in early 1987 at the Waste Isolation Pilot Plant (WIPP) site in southeastern New Mexico. This test (the WIPP-13 or northern) multipad test, complemented the H-3 (or southern) multipad test (conducted in late 1985 and early 1986) by creating a hydraulic stress that could be measured over the northern portion of the WIPP site. The test consisted of pumping well WIPP-13 at a rate of 30 gpm for 36 days and monitoring drawdown and recovery responses in 17 observation wells and one WIPP shaft. Responses were observed in 14 of these wells, including one well 20 550 ft from WIPP-13 and in the WIPP exhaust shaft. Several of these wells had also responded during the H-3 multipad test.

Individual well tests at locations around the WIPP site have demonstrated that the Culebra is a heterogeneous, water-bearing unit. The responses measured at observation wells to pumping tests in heterogeneous systems cannot be rigorously interpreted using standard analytical (as opposed to numerical) techniques developed for tests in homogeneous, porous media. Application of analytical techniques to data from heterogeneous media results in evaluations of average hydraulic properties between pumping and observation wells that are nonunique in the sense that they are representative only of the responses observed when a hydraulic stress is imposed at a certain location. These 'apparent' hydraulic properties do, however, provide a qualitative understanding of the nature and distribution of both hydraulic properties and heterogeneities or boundaries within the tested area.

The interpretations of the responses at the pumping and observation wells are consistent with the following conceptualization: The Culebra is a fractured, double-porosity system around WIPP-12, H-6, and DOE-2, with relatively high transmissivity ($\sim$70 ft^2/day) and relatively low storativity (5×10^{-6} to 8×10^{-6}). This system appears to extend further to the north toward WIPP-30, although WIPP-30 itself lies in a lower transmissivity zone. The apparent transmissivity between WIPP-13 and observation wells toward the center of the WIPP site to the south and east, where fracturing in the Culebra decreases, decreases to 16 to 28 ft^2/day, and apparent storativity increases to 3.6×10^{-5} to 5.5×10^{-5}. To the west toward Nash Draw, the apparent transmissivity increases to 265 to 650 ft^2/day, reflecting increased fracturing in that direction, while the apparent storativity increases to 5.2×10^{-5} to 6.4×10^{-5}.

The analyses of the responses measured at observation wells to the WIPP-13 multipad pumping test provide a qualitative conceptualization of three distinct domains within a heterogeneous portion of the Culebra north of the center of the WIPP site. This conceptualization is being refined by using numerical-modeling techniques to simulate the WIPP-13 multipad test and other tests at the WIPP site in an attempt to define the distribution of hydraulic properties that will reproduce the responses observed."

Beauheim, R.L. 1989. Interpretation of H-14b4 Hydraulic Tests and the H-11 Multipad Pumping Test of the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) Site, SAND89-0536. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p. 3;

" Drillstem tests, slug tests, a small-scale pumping test, and a large-scale pumping test of the Culebra Dolomite Member of the Rustler Formation were performed in 1988 at the H-11 hydropad at the Waste Isolation Pilot Plant (WIPP) site in southeastern New Mexico. The drillstem, slug, and small-scale pumping tests were conducted in well H-11b4 to evaluate well and aquifer properties in preparation for a tracer test. The large-scale pumping test, known as the H-11 multipad test, was performed by pumping well H-11b1 in the southern part of the WIPP site at a rate of six gpm for 63 days and monitoring drawdown and recovery responses in three other wells on the H-11 hydropad and at 11 observation wells within a three-mile radius. Responses were observed in 10 of these distant wells. The H-11 multipad pumping test complemented the H-3 and WIPP-13 multipad pumping tests conducted in the central and northern portions of the WIPP site in late 1985 and early 1987, respectively.

Individual well tests at various locations around the WIPP site have demonstrated that the Culebra is a laterally heterogeneous water-bearing unit. The responses measured at observation wells to pumping tests in heterogeneous systems cannot be rigorously interpreted using standard analytical (as opposed to numerical) techniques developed for tests in homogeneous results in evaluations of average hydraulic properties between pumping and observation wells that are nonunique in the sense that they are representative only of the responses observed when a hydraulic stress is imposed at a certain location. These 'apparent' hydraulic properties do, however, provide a qualitative understanding of the nature and distribution of both hydraulic properties and heterogeneities or hydraulic boundaries with the tested area.

The interpretations of the responses at the test and observation wells provided the following information: The Culebra is a fractured, double-porosity system at H-11 with a transmissivity between 27 and 43 ft^2/day and a storativity between 3.4 x 10^{-5} and 1.5 x 10^{-4}. Drawdown during the multipad test appeared to be largely concentrated to the north and south of H-11; wells to the east and west showed relatively low-magnitude responses. The rapid and high-magnitude responses observed at DOE-1, H-3b2, and H-15 during the multipad test are believed to reflect the presence of a fracture network extending to the north from H-11. Numerical simulations indicate that the fracture network extends south of H-11. but no wells are currently situated within it.

Double-porosity hydraulic behavior was observed at DOE-1 during the multipad test, and at both DOE-1 and H-3b2 during other pumping tests performed at those locations. The fractures appear to continue past DOE-1 to the north toward H-15, although H-15 itself lies in a lower transmissivity, apparently single-porosity zone. Apparent transmissivities in the region north of H-11 range from 7.1 to 9.0 ft^2/day and apparent storativities range from 2.4 x 10^{-6} to 8.4 x 10^{-6}. Apparent transmissivities between H-11 and observation wells to the

west, southwest, and southeast, where fracturing in the Culebra decreases and single-porosity hydraulic behavior is observed, range from 6.0 to 21.0 ft^2/day and apparent storativities range from 1.8 x 10^{-5} to 6.5 x 10^{-5}. Interpretation of the responses to the multipad test observed at the western and southern wells was complicated by an anomalous and widespread rise in water levels of unknown origin.

Thus, the analyses of the responses measured at observation wells to the H-11 multipad pumping test are consistent with a conceptualization of two distinct domains within a heterogeneous portion of the Culebra south of the center of the WIPP site: a fractured region having low storativity extending to the north and south from H-11, and a relatively unfractured region west, southwest, and southeast of H-11 having higher storativity. This conceptualization is being refined using numerical-modeling techniques to simulate the H-11 multipad test and other tests at the WIPP site, in an attempt to define a distribution of hydraulic properties that will reproduce the response observed."

Beauheim, R.L., and Holt, R.M. 1990. "Hydrogeology of the WIPP Site." In Geological and Hydrological Studies of Evaporites in the Northern Delaware Basin for the Waste Isolation Pilot Plant (WIPP), New Mexico, Geological Society of America 1990 Annual Meeting Field Trip #14 Guidebook, pp. 131-179. Dallas Geological Society, Dallas, TX. WPO 29378.

Introduction, p 2, col. 1;

" The field trip provides an on site introduction to the geology and hydrology of the Waste Isolation Pilot Plant (WIPP) site in southeastern New Mexico. The mission of the WIPP is to dispose of transuranic (TRU) waste generated since 1970 by the U. S. defense programs. After 18 years of study and the publication of hundreds of documents, these studies remain unknown to many geologists. Although many of the studies are unique, they lack recognition. This field trip and guidebook begin to redress this imbalance."

Unnamed Lower Member Hydrology, p 144, col 2;

" The unnamed lower member of the Rustler consists of interbedded siltstone, sandstone, halite, and anhydrite (Figure 12) (Holt and Powers, 1988). Holt and others (in prep.) recognize two confining beds and two water-producing units within the unnamed lower member.

Holt and others (in prep.) consider the sulfate unit at the base of the Rustler to be the lowermost confining bed within the Rustler, although this hydrologic role is mostly due to low permeability halite in the Salado. Where dissolution has affected the upper Salado, this stratigraphic unit is hydrologically compromised, and the lower confining bed for water-bearing unit 1 is the top of intact Salado halite.

Water-producing unit 1 (WPU-1) of Holt and others (in prep.) consists of the bioturbated clastic interval and transitional sandstone, and it includes the M-1/H-1 interval when halite is not present. WPU-1 is confined by anhydrite. The bioturbated clastic interval is the principle water-bearing zone within WPU-1. The siltstone and sandstone within this zone are argillaceous and cemented with halite (Holt and Powers, 1988; Holt and others, in prep.). The transitional sandstone is also cemented with halite and locally with sulfate (Holt and Powers, 1988). The M-1/H-1 interval contains bedded and argillaceous halite with some halitic clastic rocks. Halite cements are dissolved in the units to create secondary intergranular porosity and permeability. Dissolution of halite from the upper part of the Salado causes structural collapse of, and upward sloping through, overlying units. Fracture porosity develops around displaced blocks of collapsed material, and the thickness of the water-bearing zone increases to include the interval hydraulically connected by fractures. After collapse, the evaporite cements within the collapsed blocks are more readily dissolved. Hydrologic testing of WPU-1 is difficult as the borehole may only effectively intersect a few fractures and the permeability between collapse blocks may be limited by clay skins developed on the margins of the blocks during the collapse process.

Transmissivity values for WPU-1 (Mercer, 1983; Beauheim, 1987) generally show a transmissivity increase in the direction of Nash Draw (Figure 13). Holt and others (in prep.) suggest that the transmissivity values from areas where Salado dissolution and collapse of overlying strata have occurred may not be representative of the entire WPU-1 interval thickness at the tested locations.

Few measurements have been made of the stabilized water level or fluid pressure of WPU-1 (Figure 14). Although freshwater head calculations are somewhat limited due to the quality of specific gravity measurements, estimated freshwater head values are probably accurate to within 10 ft (Holt and others, in prep.). The freshwater heads in those wells completed within the collapse material associated with Salado dissolution do not appear to differ significantly from the hydraulic heads in wells completed in intact Rustler siltstone, indicating good lateral hydraulic connection. The heads are consistent with Mercer's (1983) interpretation that flow through the low transmissivity sections of WPU-1 is generally westerly or southwesterly across the WIPP site towards Nash Draw, while flow within Nash Draw is generally southwesterly towards Malaga Bend on the Pecos River."

Culebra Hydrology, p 150, col 1, para 4;

" The transmissivity of the Culebra across the WIPP region varies by six orders of magnitude (Figure 17) due to varying degrees of fracturing within the Culebra. In the vicinity of the WIPP, the Culebra has been tested in 41 locations, including the combined testing of the WIPP project and Project Gnome (Beauheim, 1988). . . ."

Culebra Hydrogeology, p 157, col 1, para 2;

" Gypsum and anhydrite commonly fill pores within the Culebra near the WIPP site. Sulfate (usually gypsum) occurs as cements, passive void-fillings, nodules, and incremental fracture-fillings. A clear pattern of alternation occurs within the Culebra from east to west. Anhydrite vugs and crystals are replaced by gypsum, and gypsum occurs as incremental fracture fillings within the Culebra dolomite. Further west, all sulfate consists of gypsum, and gypsum fracture-fillings, cements, and vug-fillings are partly to completely dissolved. Continuing west, gypsum is almost totally removed, and many of the vugs and vug complexes are collapsed, thereby increasing local fracture porosity. In the westernmost part of the region, no gypsum occurs. The areal distribution of this relationship is best shown by the percentage of natural fractures filled with gypsum (Figure 21). This map shows a general inverse relationship between the presence of gypsum pore-fillings and transmissivity (Figure 17). Presence or absence of gypsum pore-fillings may, therefore, be one of the factors controlling the distribution of transmissivity within the Culebra."

Culebra Hydrogeology, p 157, col 1, para 3;

" The effective porosity within the Culebra is related to fractures, and the transmissivity values at various locations indicate degree of fracturing. This allows the degree of fracturing to be compared with other geologic information on a regional scale. The Culebra fractured significantly in response to differential unloading, dissolution of evaporites from above and below the Culebra, and dissolution of large vug-fillings or fillings within zones of vugs in the Culebra. . . ."

Culebra Hydrogeology, p 159, col 1, para 3;
" Much of the fracturing within the Culebra in the vicinity of the WIPP site can be attributed to unloading (Holt and others, 1988). An isopach map of the Culebra overburden shows a general decrease of overburden from east to west, with the overburden north and south of the WIPP site slightly less than that across the WIPP site (Figure 22). Culebra transmissivity (Figure 17) is generally higher where there is less overburden. As the transmissivity contours do not correlate precisely with the amount of overburden present, other mechanisms must contribute to the variations of transmissivity and the degree of fracturing in the Culebra across the WIPP area."

Culebra Hydrogeology, p 159, col 1, para 4;
" Aside from unloading, the most significant control on fracturing within the Culebra is the dissolution of evaporites from strata above and below the Culebra. The overlying strata collapse, and stress in the underlying strata is relieved. Both collapse and stress relief can cause or enhance the fracturing within a brittle unit such as the Culebra. Holt and others (in prep.) evaluate the extent of dissolution from the Salado and Rustler on the basis of core, shaft, and geophysical log data (Figure 23). Salado dissolution affects the area south and west of the WIPP site, while Rustler dissolution is concentrated along the depositional margins of halite within the Rustler."

The uppermost halite within the Salado is dissolved in the area in and around Nash Draw and in a region south of the WIPP site. Salado dissolution parallels the course of the ancestral Pecos River and its major tributaries, such as Nash Draw. Salado dissolution was hydrologically driven by the groundwater system associated with the ancestral Pecos River and its major tributaries. This system was most active during the Cenozoic, although dissolution of Salado continues to occur within Nash Draw.
Culebra core from areas of Salado dissolution shows evidence of fracturing and high transmissivity values due to collapse.

Salado dissolution close to a halite depositional margin within the Rustler increases the potential for dissolution of halite within the Rustler. Collapse associated with Salado dissolution tends to increase the vertical hydraulic connection between Rustler water-bearing zones and Rustler intervals containing halite. One such zone penetrates the southern part of the WIPP site. Features attributable to dissolution of halite and attendant collapse are found within the interval M-3/H-3 (Holt and Powers, 1988). This zone, although not well defined, corresponds with the highly transmissive zone within the Culebra in the southern part of the WIPP site. As dissolution has not occurred below the Culebra at this location, fracturing responded to stress-relief following dissolution."

Culebra Hydrogeology, p 159, col 2, para 1, line 9;
" Culebra core from areas of Salado dissolution shows evidence of fracturing and high transmissivity values due to collapse."

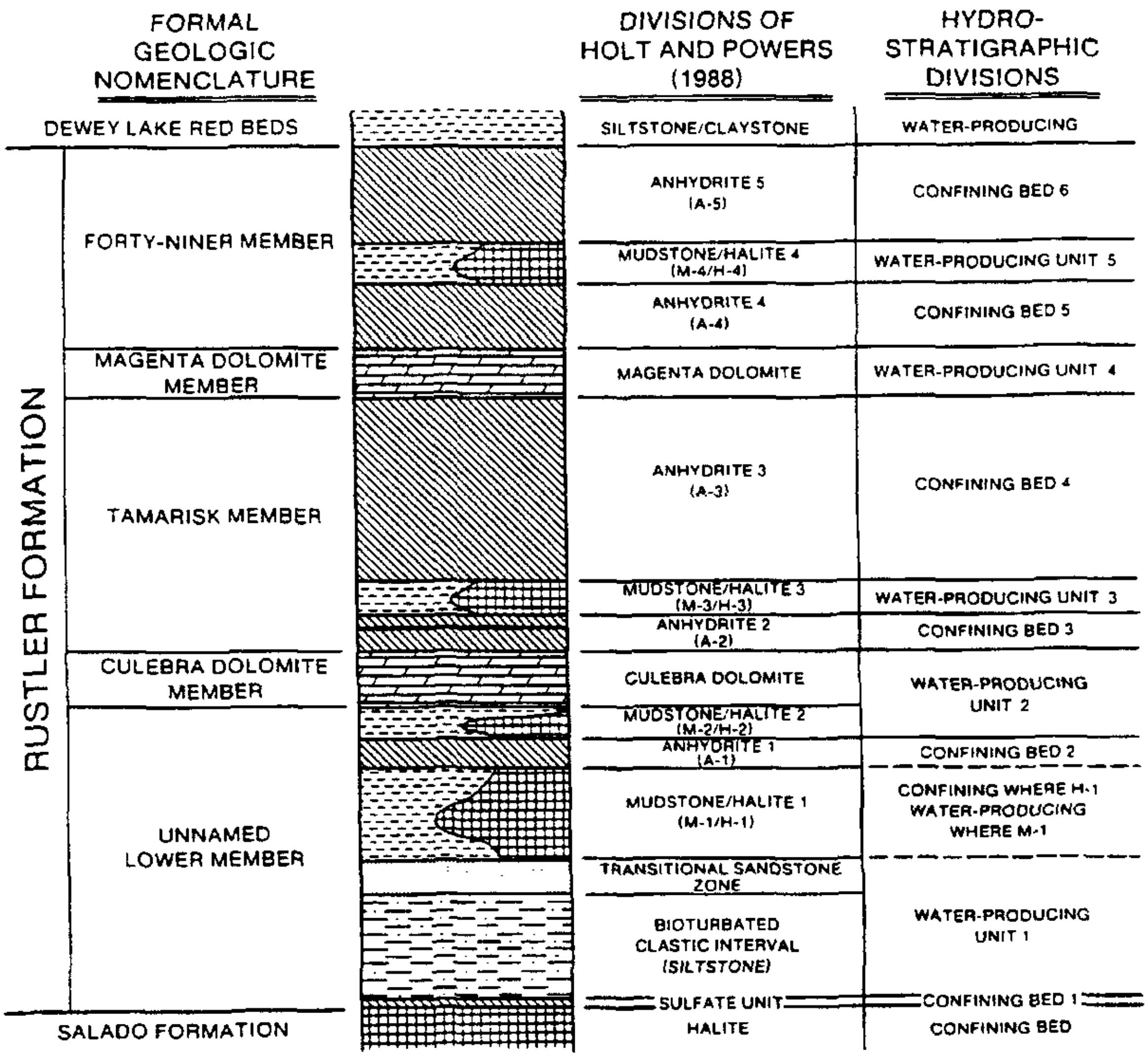


Figure 12. Relationship of lithostratigraphic and hydrostratigraphic units for the Rustler Formation (from Holt and others, in prep.).

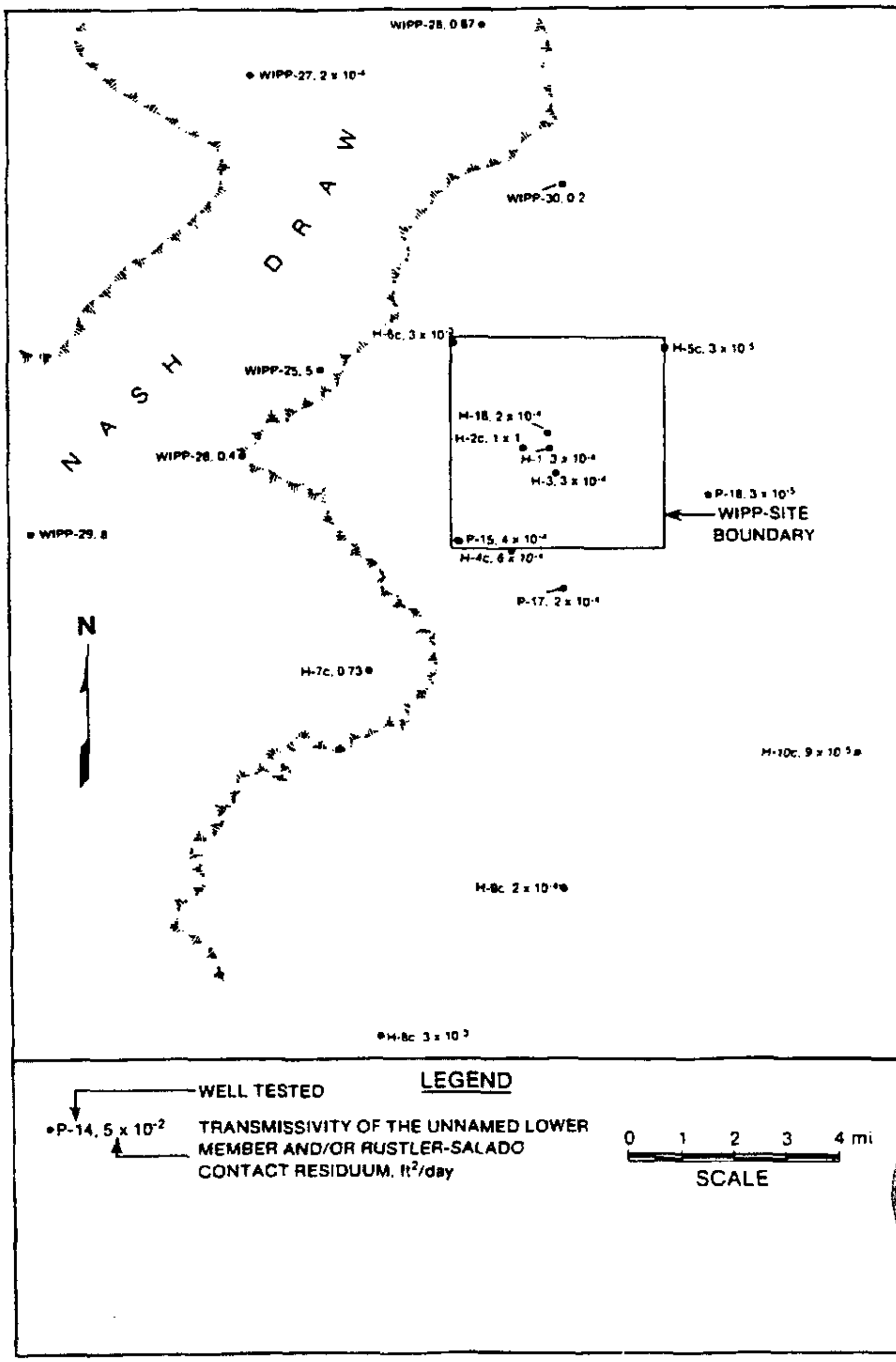


Figure 13. Transmissivity of the unnamed lower member of the Rustler and/or residuum along the Rustler/Salado contact (from Holt and others, in prep.).

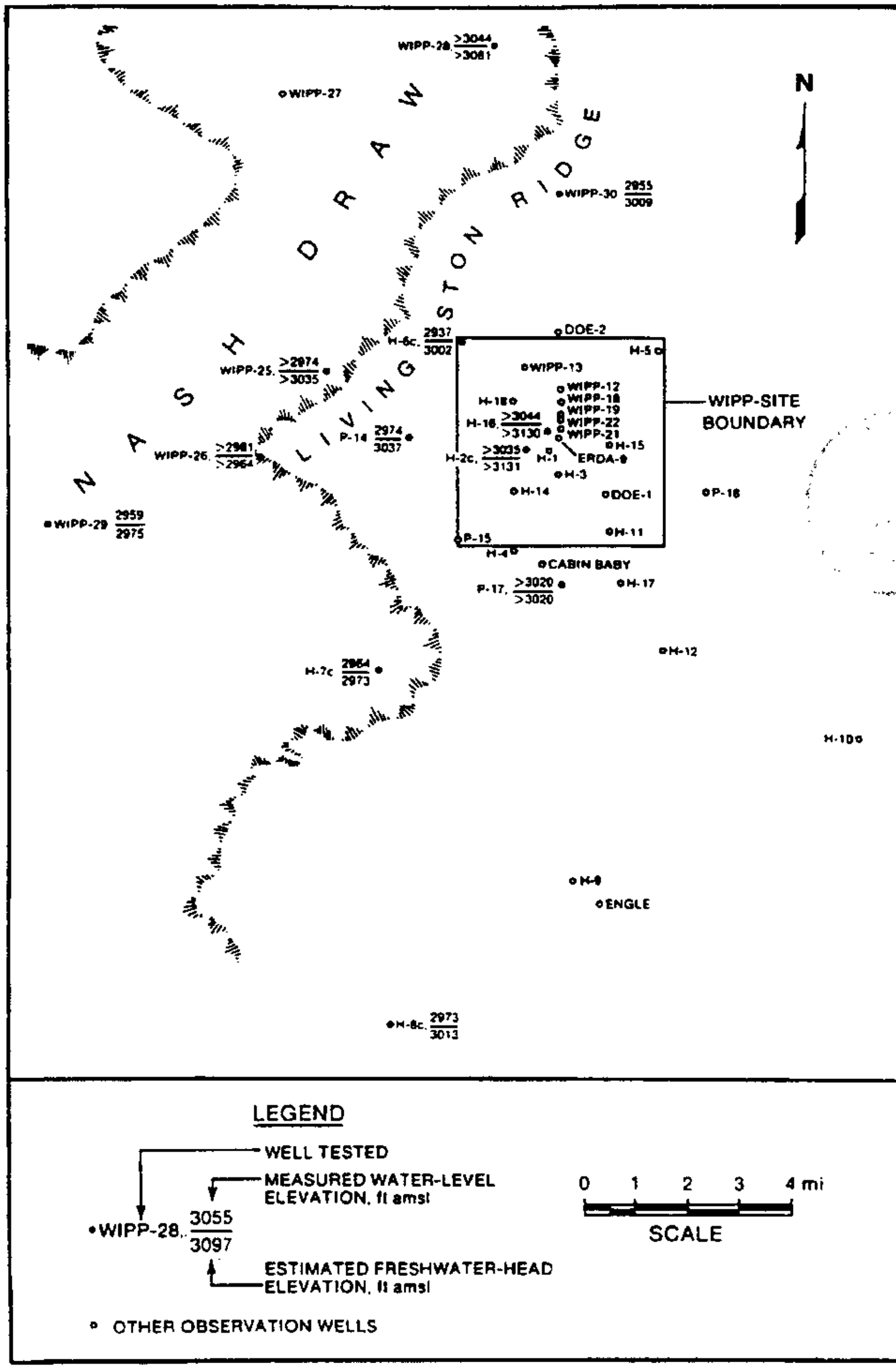


Figure 14. Measured water level and estimated freshwater head elevation of the unnamed lower member of the Rustler and/or residuum along the Rustler/Salado contact (from Holt and others, in prep.).

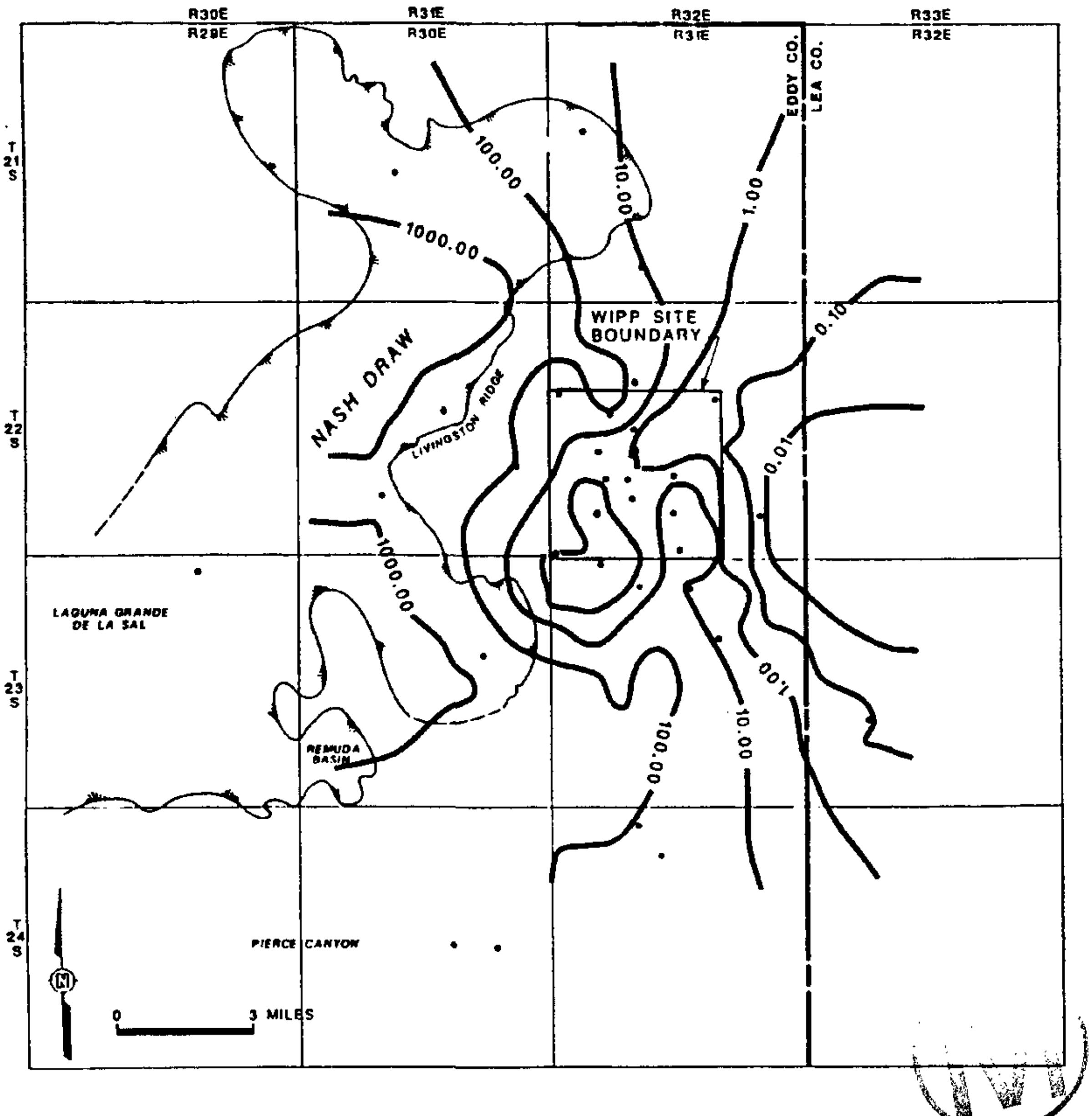
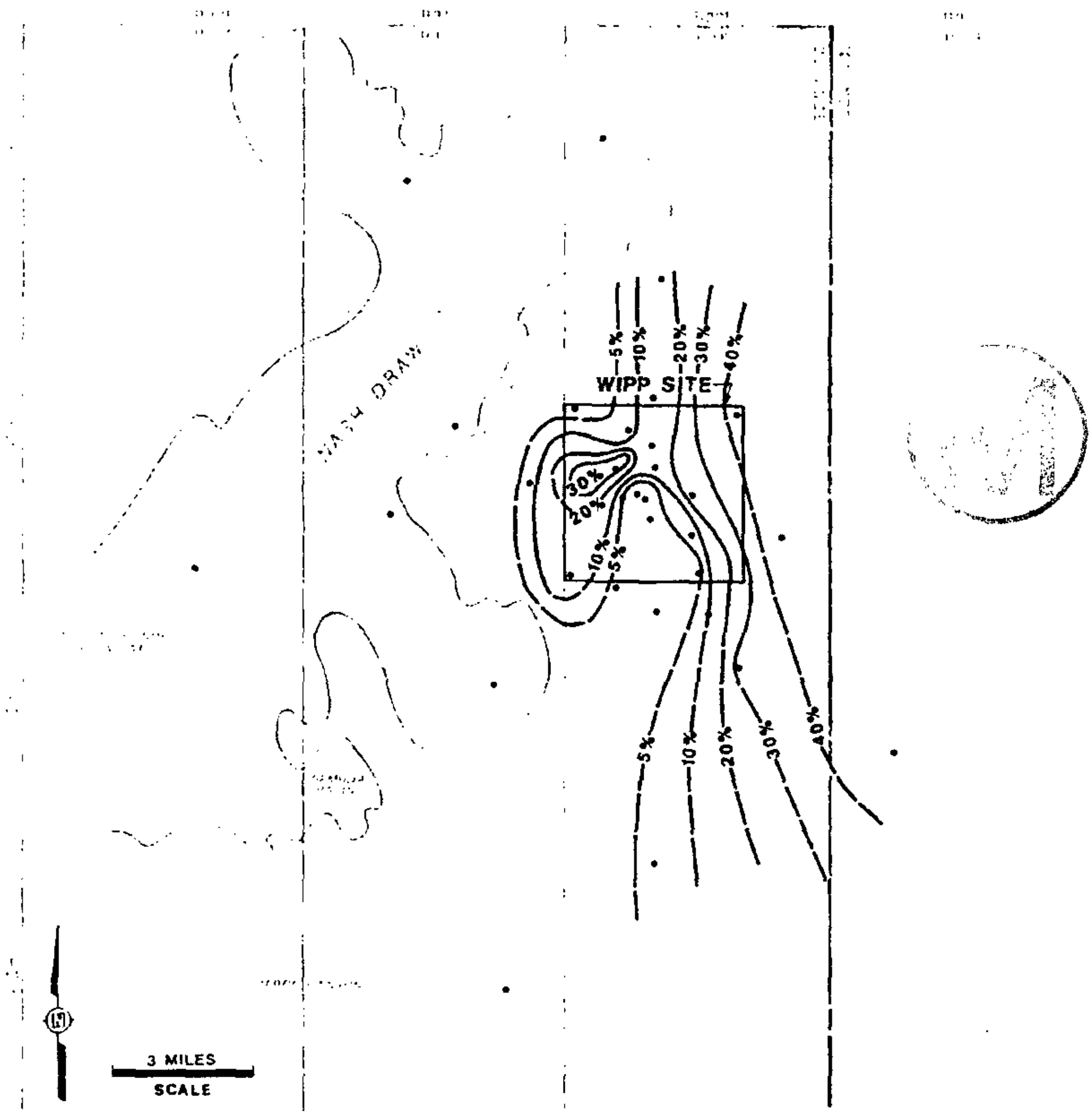


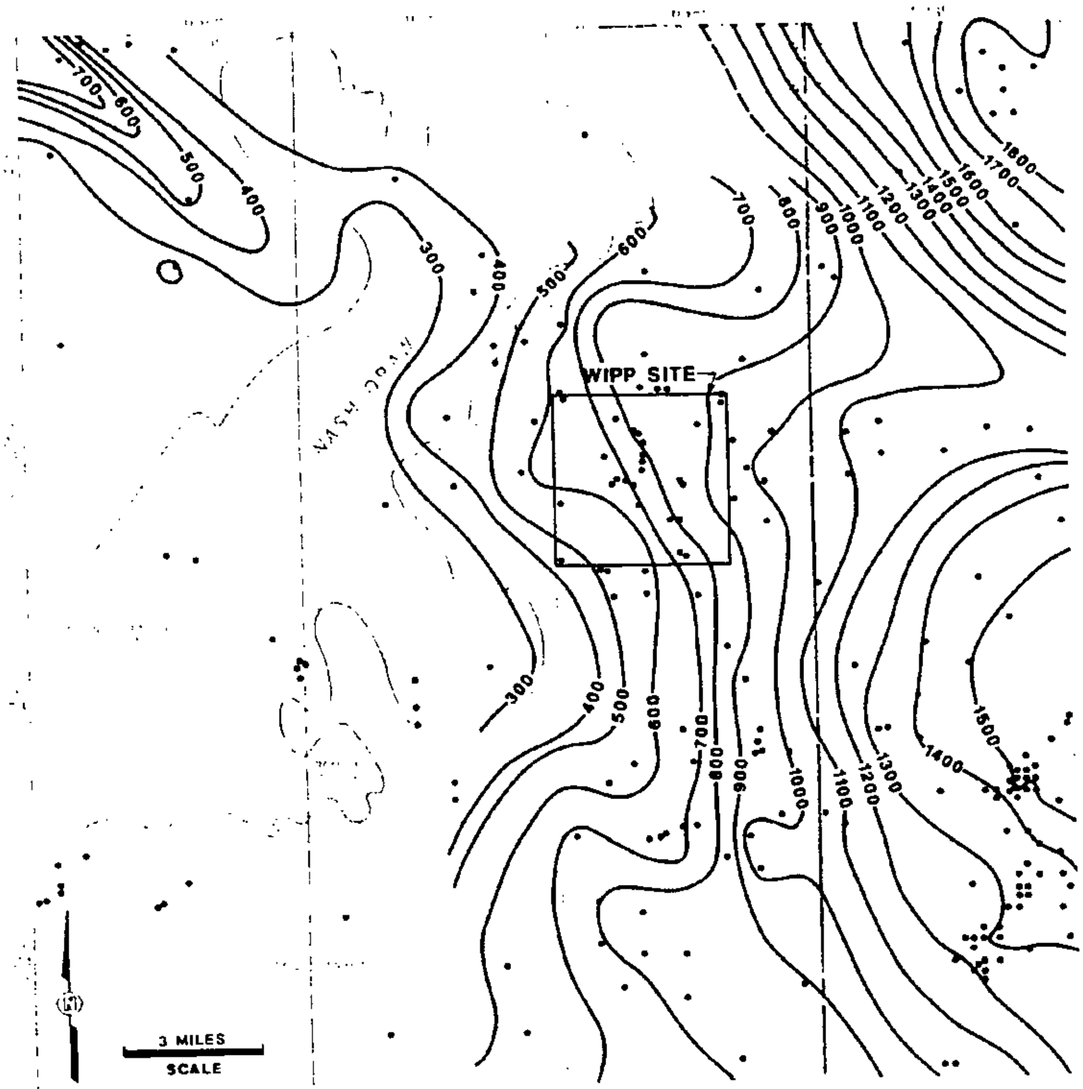
Figure 17. Calculated transmissivities for the Culebra Dolomite Member (ft^2/day) (from LaVenue and others, 1988).



EXPLANATION

• WELLS EXAMINED   CONTOUR INTERVAL 10%   5% LINE SHOWN FOR CLARITY

Figure 21. Percentage of natural fractures in the Culebra Dolomite Member filled with gypsum (from Holt and others, in prep.).



EXPLANATION

• DRILL HOLES CONTOUR INTERVAL • 100 FEET

Figure 22. Isopach of overburden for the Culebra Dolomite Member (from Holt and others, in prep.).

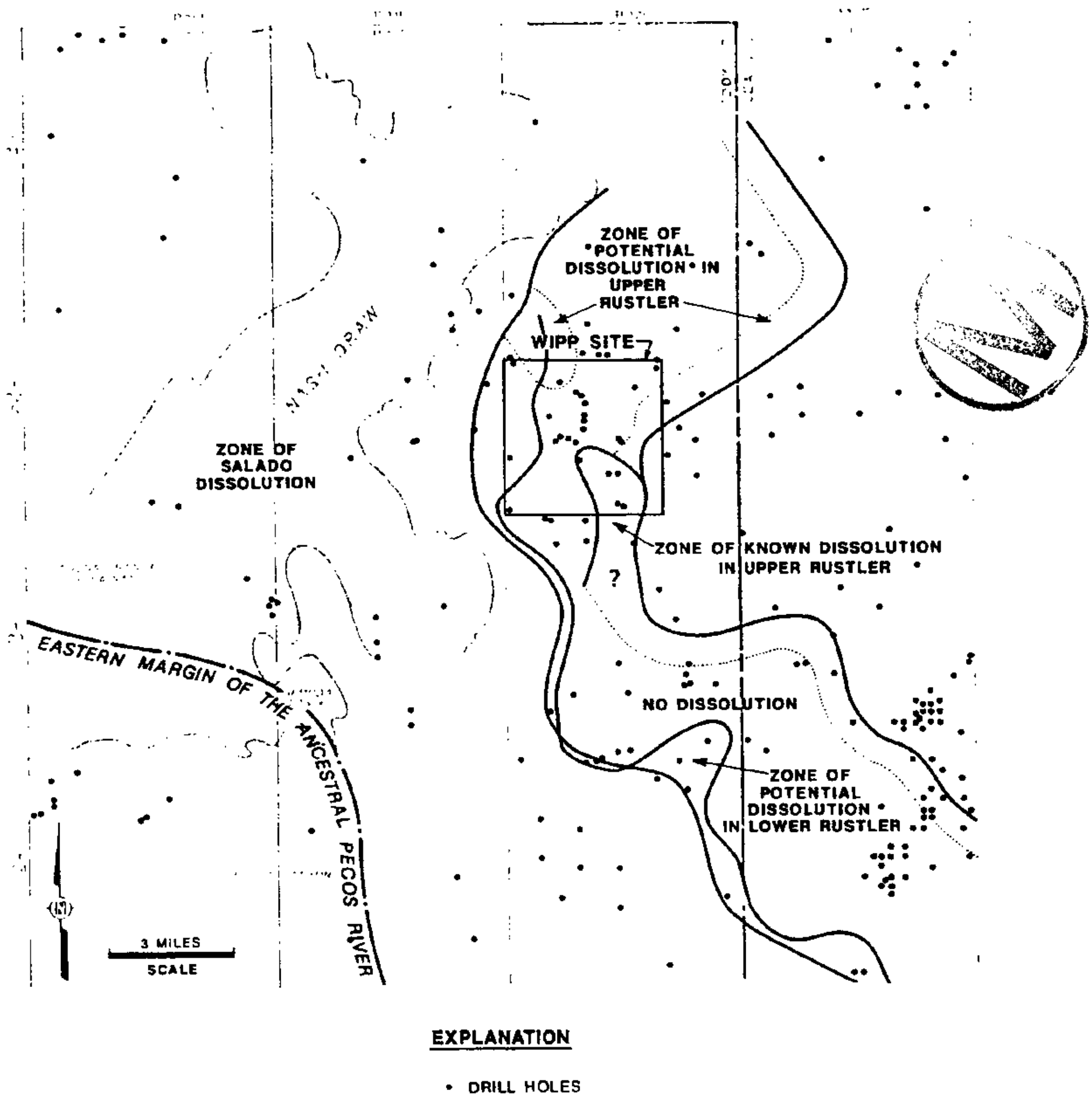


Figure 23. Distribution of Rustler and Salado dissolution near the WIPP site (from Holt and others, in prep.).

Beauheim, R.L., Roberts, R.M., Dale, T.F., Fort, M.D., and Stensrud, W.A. 1993. Hydraulic Testing of Salado Formation Evaporites at the Waste Isolation Pilot Plant Site: Second Interpretive Report. SAND92-0533. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT;

" Pressure-pulse, constant-pressure flow, and pressure-buildup tests have been performed in bedded evaporites of the Salado Formation at the Waste Isolation Pilot Plant (WIPP) site to evaluate the hydraulic properties controlling brine flow through the Salado. Transmissivities ranging from about 7 x 10^{-15} to 5 x $10^{-13} m^2/s$ have been interpreted from six sequences of tests conducted on five stratigraphic intervals within 15 m of the WIPP underground excavations. The corresponding vertically averaged hydraulic conductivities of the intervals range from about 1.1 x 10^{-14} to 2 x 10^{-12} m/s (permeabilities of 2 x 10^{-21} to 3 x $10^{-19} m^2$). Storativities of the tested intervals range from about 1 x 10^{-8} to 2 x 10^{-6}, and values of specific storage range from 9 x 10^{-8} to 1 x $10^{-5} m^{-1}$. Pore pressures in eight stratigraphic intervals range from about 2.5 to 12.5 MPa, and appear to be affected by stress relief around the excavations. Anhydrite interbeds appear to be one or more orders of magnitude more permeable than the surrounding halite, primarily because of subhorizontal bedding-plane fractures present in the anhydrites. Interpretations of the tests revealed no apparent hydrologic boundaries within the radii of influence of the tests, which were calculated to range from about 2 to 20 m from the test holes. An assumption of Darcy flow through the evaporites is thought to be a reasonable interpretive approach because Darcy-flow models are able to replicate the flow and pressure behavior observed during entire testing sequences involving different types of tests performed with different hydraulic gradients."

Section 8.1, p 139, col 1, para 2;

" The primary objectives of the hydraulic tests were to estimate the transmissivities, storativities, and formation pore pressures of different stratigraphic intervals in the Salado formation around the WIPP facility. Pressure-pulse, constant-pressure withdrawal, and/or pressure-buildup tests of five stratigraphic units were successfully conducted in six intervals. Interpreted transmissivities range from 3.8 x 10^{-14} to 5.3 x 10^{-13} m^2/s for anhydrite intervals, with vertically averaged hydraulic conductivities ranging from 3.8 x 10^{-13} to 2.2 x 10^{-12} m/s(permeabilities of 5.1 x 10^{-20} to 2.9 x 10^{-19} m^2). The transmissivity of a halite interval tested was about 7.4 x 10^{-15} m^2/s, with an average hydraulic conductivity of either 1.4 x 10^{-14} or 7.2 x 10^{-15} m/s(permeability of 1.8 x 10^{-21} or 9.6 x 10^{-22} m^2), depending on whether flow was horizontal or radial toward the slanted test interval. The transmissivity of another halite interval in the SCP01-A guard zone was apparently too low to measure over a six-month period. . . ."

Section 8.1 Results of Testing, p 139, col 2, para 3;

" The formation pore pressures of the anhydrite intervals tested range from zero (or atmospheric) in anhydrites 'a' and 'b' directly above Room 7 of Waste Panel 1 to 12.55 MPa in Marker Bed 139 beyond the westernmost extreme of the Core-storage library. Pore pressures in halite intervals range from about 2.55 MPa to greater than 4.2 MPa. Pore pressures in halite may be decreased more by stress relief around the excavations than those in anhydrite because of the different mechanical and rheological responses of the two rock types."

Section 8.3 Conclusions, p 142, col 1, para 3;

" Pressure-pulse, constant-pressure flow, and pressure-buildup tests have been performed in bedded evaporites of the Salado Formation at the WIPP site to evaluate the hydraulic properties controlling brine flow through the Salado. Transmissivities ranging from about 7 x 10^{-15} to 5 x 10^{-13} m^2/s have been interpreted from six sequences of tests conducted on five stratigraphic intervals within 15 m of the WIPP underground excavations. The corresponding vertically averaged hydraulic conductivities of the intervals range from about 1 x 10^{-14} to 2 x 10^{-12} m/s (permeabilities of 2 x 10^{-21} to 3 x 10^{-19} m^2). Storativities of the tested intervals range from about 1 x 10^{-18} to 2 x 10^{-6}, and values of specific storage range from 9 x 10^{-8} to 1 x 10^{-5} m^{-1}. Pore pressures in eight stratigraphic intervals range from about 2.5 to 12.5 MPa, and appear to be affected by stress relief around the excavations. Anhydrite interbeds appear to be one or more orders of magnitude more permeable than the surrounding halite, primarily because of subhorizontal bedding-plane fractures present in the anhydrites. Interpretations of the tests revealed no apparent boundaries within the radii of influence of the tests, which were calculated to range from about 2 to 20 m from the test holes. An assumption of darcy flow through the evaporites is thought to be a reasonable interpretive approach because Darcy-flow models are able to replicate the flow and pressure behavior observed during entire testing sequences involving different types of tests performed with different hydraulic gradients."

Beauheim, R.L., Saulnier, Jr., G.J., and Avis, J.D. 1991. Interpretation of Brine-Permeability Tests of the Salado Formation at the Waste Isolation Pilot Plant Site: First Interim Report. SAND90-0083. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p i;

" Pressure-pulse tests have been performed in bedded evaporites of the Salado Formation at the Waste Isolation Pilot Plant (WIPP) site to evaluate the hydraulic properties controlling brine flow through the Salado. Hydraulic conductivities ranging from about 10^{-14} to 10^{-11} m/s (permeabilities of about 10^{-21} to 10^{-18} m^2) have been interpreted from nine tests conducted on five stratigraphic intervals within eleven meters of the WIPP underground excavations. Tests of a pure halite layer showed no measurable permeability. Pore pressures in the stratigraphic intervals range from about 0.5 to 9.3 MPa. An anhydrite interbed (Marker Bed 139) appears to be one or more orders of magnitude more permeable than the surrounding halite. Hydraulic conductivities appear to increase, and pore pressures decrease, with increasing proximity to the excavations. These effects are particularly evident within two or three meters of the excavations. Two tests indicated the presence of apparent zero-flow boundaries about two to three meters from the boreholes. The other tests revealed no apparent boundaries within the radii of influence of the tests, which were calculated to range from about four to thirty-five meters from the test holes. The data are sufficient to determine if brine flow through evaporites results from Darcy-like flow driven by pressure gradients within naturally interconnected porosity or from shear deformation around excavations connecting previously isolated pores, thereby providing pathways for fluids at or near lithostatic pressure to be driven towards the low-pressure excavations. Future testing will be performed at greater distances from the excavations to evaluate hydraulic properties and processes beyond the range of excavation effects.

Section 7.1.5.1 Test Zone, p 70, col 2;

" As shown on Figure 7-26, the fluid pressure in the C2H03 test zone did not increase during the 30-day shut-in period, but instead decreased by about 0.01 MPa. Testing of multipacker test tool #5 before and after C2H03 testing revealed no problems that could have caused the tool to fail to hold pressure during the testing. Therefore, the observed behavior is thought to be representative of the formation response to the testing conditions.

For the shut-in pressure to decrease, a combination of events would have to occur. First, the test-zone volume would have to increase slightly. This could occur in response to packer readjustment or hole elongation. Second, little or no inflow from the formation would also be required, implying very low formation permeability. Two possible conditions could explain a lack of inflow to the borehole. First, the relatively pure halite of map unit 9 may not have continuous interconnected porosity that would lead to permeability. Second, map unit 9 may have continuous interconnected permeability, but the permeability may be so low that no observable pressure response could occur on the time scale of the monitoring period. The first possibility cannot be evaluated with the available data; a much longer monitoring period and perhaps a different type of testing would be required to establish the complete absence of permeability. The second possibility can be evaluated, at least qualitatively, by considering the pressure responses that would be expected to occur given a range of permeability (hydraulic conductivity) values. . . ."

p 73, col 2, line 2;

" Presumably, if the permeability of map unit 9 is so low as to preclude any observable pressure response during the C2H03 testing, then that same low permeability should have prevented significant depressurization at the test-zone depth from the excavation of Room C2. Specific storage for the simulations was assumed to be 9.5 x $10^{-8}m^{-1}$. The simulations assume radial flow to the borehole, which in the case of the horizontal borehole C2H03, may be a questionable assumption. Given the lack of an observed pressure-buildup response, however, use of a more complex model designed specifically for tests in horizontal holes appears unwarranted at this time.

Figure 7-27 shows the results of these simulations. At a hydraulic conductivity $\leq 10^{-14}$m/s, less than 0.01 MPa pressure buildup would have occurred during the monitoring period. At a hydraulic conductivity of 10^{-13} m/s, a few hundredths of an MPa pressure increase would have been observed, while at a hydraulic conductivity of 10^{-12}m/s, the pressure would have increased by a few tenths of an MPa. If the test-zone compressibility was less than the value assumed for these simulations, then the simulations shown in Figure 7-27 would be representative of proportionally lower hydraulic conductivities. Considering that no pressure buildup at all was observed, we might conclude that the hydraulic conductivity of the relatively pure halite around C2H03 is less than 10^{-14}m/s. This may be a conservatively high upper bound on the hydraulic conductivity around C2H03, considering the responses observed during testing of the C2H01-B guard zone, which had an interpreted hydraulic conductivity of 1.4 x 10^{-14}m/s (Figure 7-14).

Finley (personal communication) has attempted to measure brine inflow to 10-cm-diameter holes drilled horizontally into map unit 9 from Room D (see Figure 5-1). Over a monitoring period of more than three years, no observable brine inflow to the holes has been detected, providing further indication of small or non-existent permeability in the pure halite of map unit 9.

The simulations discussed above are highly speculative and are only presented in an attempt to give an upper bound on the hydraulic conductivity of relatively pure halite, based on an underlying assumption that map unit 9 has some permeability and pore pressure. When similar hydraulic behavior is encountered in future test holes, additional testing will be performed to try to address questions about the presence or absence of pore pressure and permeability more directly."

All of the testing discussed in this report was performed in intervals where stress redistribution must have occurred as a result of excavation of the WIPP facility. Furthermore, all test intervals except for those of C2H01-C, C2H02, and C2H03 extended no farther than 5.6 m from a room or drift, and were within about two room radii of the openings. Thus, the interpreted hydraulic properties presented in this report may not be representative of undisturbed rock, but may reflect permeability and porosity enhancement and depressurization within the DRZ around the WIPP facility. Possible effects of the DRZ on the observed test responses are discussed below."

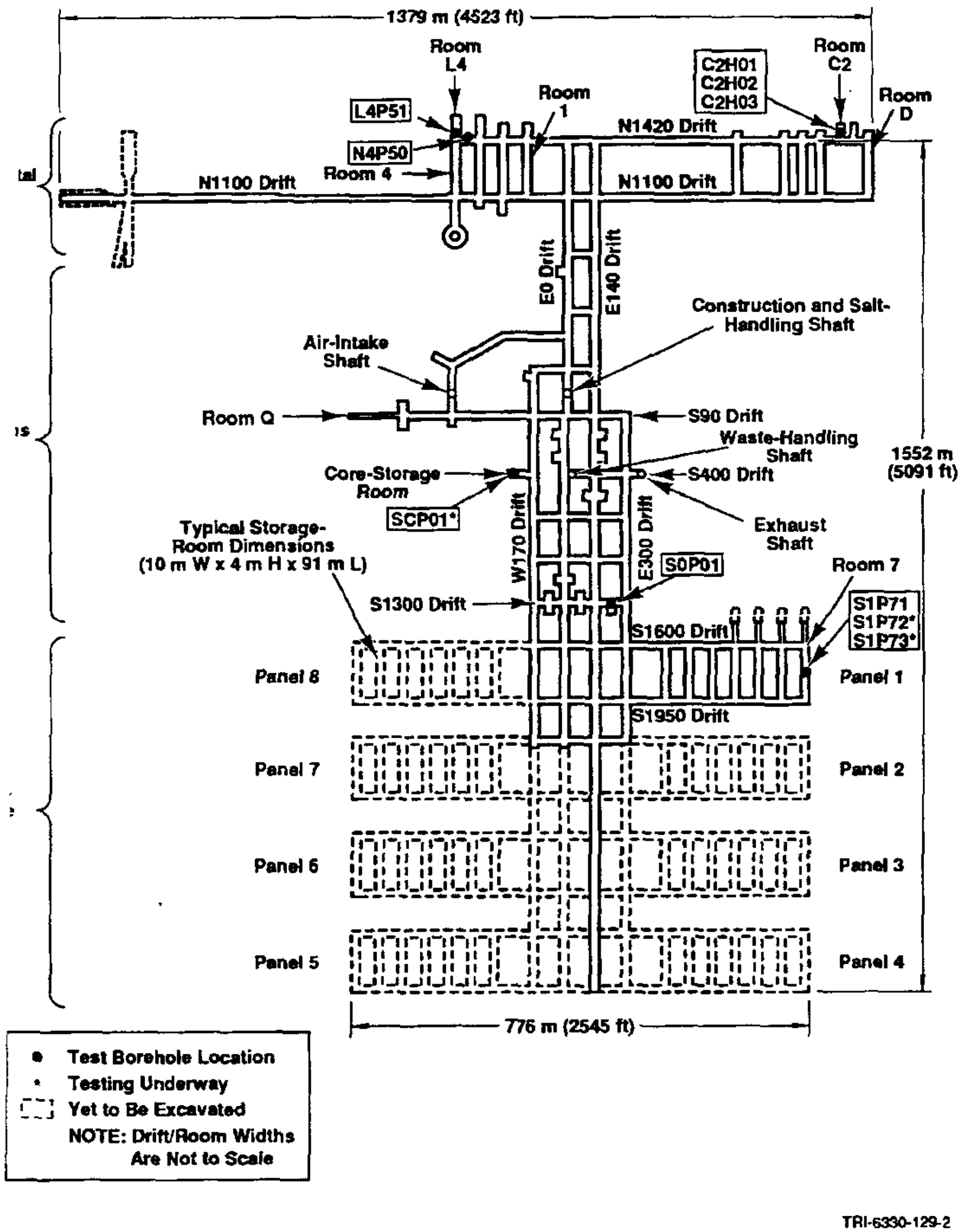


Figure 5-1. Map of the WIPP Underground Facility Showing Test Locations.

Section 8.3 Conclusions, p 131, col 2, para 1;

" The tests discussed in this report have demonstrated that the hydraulic properties of bedded evaporites can be determined from *in situ* hydrogeologic testing. Hydraulic conductivities of evaporites are low (10^{-14} to 10^{-11} m/s) when compared to those of most other water-bearing rock types, but they can be estimated using techniques and equipment specifically designed for low-permeability media. Questions remain, however, as to the nature and degree of interconnected porosity and permeability naturally present in halite. Hydraulic conductivities were found to increase, and formation pore pressures decrease, with increasing proximity to the underground excavations. Whether or not any of the tests can be considered to be unaffected by rock response to the excavations (deviatoric stress) is as yet unknown. This question can probably only be resolved by testing at greater distances from the excavations to establish the distance beyond which hydraulic properties remain relatively constant. A comparison of the hydraulic behaviors observed within and beyond the region influenced by deviatoric stress should provide insight into the mechanisms affecting brine flow through evaporites."

Beauheim, R.L., Meigs, L.C., Saulnier, G.J., and Stensrud, W.A. 1995. Culebra Transport Program Test Plan: Tracer Testing of the Culebra Dolomite Member of the Rustler Formation at the H-19 and H-11 Hydropads on the WIPP Site. On file in the Sandia WIPP Central Files.

1. SUMMARY, p. 1;

" The Culebra Dolomite Member of the Rustler Formation is considered to be the most likely pathway for radionuclide transport to the accessible environment in the event of a breach of the Waste Isolation Pilot Plant (WIPP) repository by inadvertent human intrusion. Evaluation of WIPP's compliance with 40 CFR 191 Subpart B by the WIPP Performance Assessment Computational Support Department of Sandia National Laboratories (SNL) relies in part on a model of radionuclide transport through the Culebra. Modeling of transport through the Culebra requires, first, a conceptual model of the mechanisms and processes governing that transport and, second, quantitative estimates of the parameters required for numerical simulation of those processes. The Culebra Transport Program represents the combined efforts of the SNL Geohydrology (6115) and WIPP Chemical and Disposal Room Processes (6748) Departments to provide the conceptual understanding and data necessary to construct a model for Culebra transport.

Field tracer tests are a major component of the Culebra Transport Program. Tracer tests provide data with which to evaluate different processes affecting transport and to estimate transport parameters. Interpretations of previous tracer tests conducted at the WIPP site (Jones et al, 1992) suggest that the Culebra behaves locally as a double-porosity medium in which advective flow occurs through fractures wile diffusion of solutes from the fractures to the surrounding rock matrix acts to retard solute transport. Using a double-porosity transport model based on these tracer-test interpretations, the WIPP PA Department (1993b) showed that physical retardation arising from matrix diffusion makes the Culebra an effective barrier to release of radionuclides to the accessible environment.

Independent reviewers of the interpretations of the previous tracer tests have questioned the assumption that matrix diffusion was the only mechanism causing physical retardation during those tracer tests, and suggested other processes, such as channelling caused by variations in fracture apertures (causing heterogeneity in permeability) and delayed tracer release from the injection wells, that might have contributed to the observed physical retardation. These other processes might be less effective at retarding transport on the regional scale than matrix diffusion. The data from the previous tests are inadequate to determine the relative contributions of different potential retardation mechanisms, primarily because too few flow paths were tested, only one tracer-injection technique was employed, tracers having different free-water diffusion coefficients were not used, and tests were not repeated at different pumping rates. The previous tests also did not: 1)examine the importance of vertical heterogeneity in the Culebra; 2) address scaling issues (changing transport parameters as a function of transport distance); and 3) provide sufficient data to determine whether variations in transport behavior along different flow paths were due solely to anisotropic permeability in the Culebra or were caused by heterogeneity.

The tracer tests of the Culebra described in the Test Plan are being designed to provide data with which to: 1) demonstrate the importance of matrix diffusion as a physical-retardation mechanism; 2) evaluate the relative importances of different processes causing physical retardation during transport; 3) investigate transport processes at different scales; 4) evaluate the effects of heterogeneity, anisotropy, and layering on transport; 5) quantify important transport parameters; and 6) as an end result, develop a model of transport in the Culebra that can be used by PA and defended with a high level of confidence. An added benefit of the tracer testing is that the long-term pumping associated with the tests will produce transient pressure responses that can be interpreted to define the distribution of transmissivity in the Culebra in the area within which transport is expected to occur in the event of a breach of the WIPP repository by inadvertent human intrusion.

New tracer tests are being planned at two locations, the H-19 and H-11 hydropads. The testing planned at the H-19 hydropad is much more extensive than that to be performed at the H-11 hydropad. The H-19 testing will include a single-well injection-withdrawal (SWIW) test over the lower portion of the Culebra and a convergent-flow multiwell tracer test involving multiple tracer injections, tracer injections over different intervals of the Culebra, tracer injections using different injection techniques, tracers with different tracer-breakthrough and recovery curves that can be used to quantify the amount of matrix diffusion occurring, determine how the different layers within the Culebra interact, and evaluate the effects of anisotropy and heterogeneity on transport on the hydropad scale.

Tracer testing at the H-11 hydropad is focused on a few key issues. This testing will consist of a single-well tracer test in H-11b1 and a two-well convergent-flow tracer test between H-11b3 and H-11b1. Both H-11 tests will be performed over the entire thickness of Culebra. The single-well test should provide additional evidence for the occurrence of matrix diffusion and, in combination with the H-19 single-well test, provide information on the heterogeneity of the Culebra. The two-well test at H-11 will serve to corroborate and quantify the effects of matrix diffusion interpreted from the 1988 tracer test at that location by providing a repeated test at a different pumping rate. Tracers with different free-water diffusion coefficients, if available, will also be used in this test to provide additional evidence for matrix diffusion. An improved tracer-injection tool, which will prevent tracer-laden water from sinking to the bottom of the hole and providing a potential long-term diffusional source of tracer in the wellbore, will help to resolve source-term questions associated with the earlier test.

This Test Plan describes the overall goals and objectives of the tracer test program and the methods that will be employed to achieve them. The plan describes the types of test to be performed, equipment configurations, testing requirements and procedures, data-acquisition systems, data-quality objectives, quality assurance requirements, regulatory requirements, and health and safety concerns."

Blackwell, D.D., Steele, J.L., and Carter, L.S. 1991. "Heat-Flow Patterns of the North American Continent; A Discussion of the Geothermal Map of North America." In Neotectonics of North America, D.B. Slemmons, E.R. Engdahl, M.D. Zoback, and D.D. Blackwell, eds., pp. 423-436. Geological Society of America, Boulder, CO.

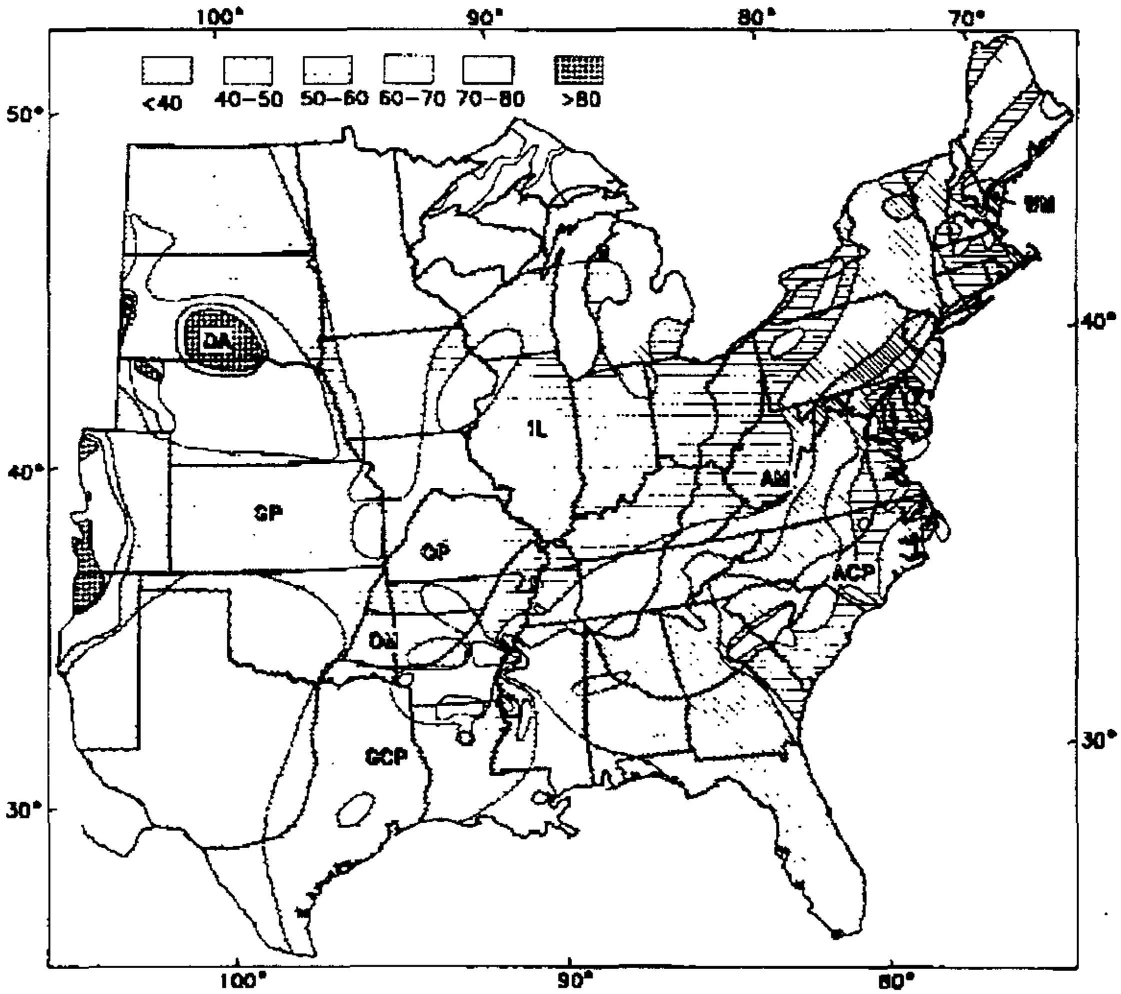


Figure 2. Heat-flow map for the eastern United States. The contours are from the DNAG *Geothermal Map of North America* and are shown at 10-mWm^{-2} intervals. Each band of heat flow is shown by a different pattern. Abbreviations are explained in the text.

Bodine, Jr., M.W. 1978. "Clay-Mineral Assemblages from Drill Core of Ochoan Evaporites, Eddy County, New Mexico." In Geology and Mineral Deposits of Ochoan Rocks in Delaware Basin and Adjacent Areas. G.S. Austin, ed., Circular 159, pp. 21-31. New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.

ABSTRACT, p. 21;

" The ERDA-9 drill hole, Eddy County, New Mexico, was cored for 1,987 ft, from 230 ft below the top of the Salado Formation through the upper 41 ft of the Castile Formation. Clay minerals in 47 insoluble residues include corrensite, random to partially ordered clinochlore-saponite mixed-layer clays, illite, clinochlore, saponite, a tentatively identified talc-saponite mixed-layer clay, serpentine, and talc. Serpentine is restricted to the Castile and lowermost Salado Formations; (?)talc-saponite is confined to some polyhalite beds in and overlying the McNutt potash zone. The salztons (thin argillaceous seams) consist of corrensite, illite, and clinochlore, while the adjacent evaporite strata often contain abundant to random mixed-layer clinochlore-saponite, mixed-layer (?)talc-saponite, or saponite. Chemical compositions of the residues have high Mg-Al atom ratios reflecting abundance of the trioctahedral clays. Mineralogy and chemistry of the assemblages strongly indicate that severe alteration and Mg-enrichment of normal clay detritus occurred in the evaporite environment through brine-sediment interaction. It is further suggested that the relatively immature clays--saponite, mixed-layer (?)talc-saponite, and randomly interstratified clinochlore-saponite--formed later through recrystallization of preexisting trioctahedral clays in response to transient pore fluids; the salztons, impermeable to such fluids, developed a more mature clay assemblage in a static pore fluid environment. The serpentine-saponite residues with their high Mg-Al and Si-Al atom ratios in Castile and lowermost Salado evaporites are indicative of a silica-rich detrital source; the more aluminous clay assemblages with decreased Mg-Al and Si-Al atom ratios in the overlying evaporite strata suggest a substantially more argillaceous detrital source."

INTRODUCTION, p 1, col 1;

" Clay assemblages in core samples from the Salado Formation and the uppermost anhydrites of the Castile Formation from the ERDA-9 drill hole in Eddy County, New Mexico, are highly distinctive. They have unusually extreme Al-Ca-poor and Mg-rich compositions and consist of a variety of abundant trioctahedral clays with subordinate amounts of illite. Although far different from most sedimentary clay assemblages, they do show a marked similarity to clays in marine evaporite rocks from other localities. Their pronounced dissimilarity with clays in normal fluvial or marine sediments strongly suggests that detrital accumulations in the marine hypersaline environment must have been subjected to severe alteration and magnesium enrichment as a result of brine-sediment interaction. It is equally likely that alteration, through reaction with subsequent transient pore fluids, continued long after deposition and burial.

This project is one part of a recently initiated geochemical and mineralogical investigation of silicate assemblages in the Ochoan evaporites of southeastern New Mexico.

The project is not completed, and the conclusions presented in this report are tentative and susceptible to later modifications as additional data become available."

CHEMICO-MINEROLOGIC DISCONTINUITY IN LOWER SALADO FORMATION, p 28, col 2, para 4;

" An abrupt change in the minerology and chemical composition of the EDTA-leach residues occurs about 15 ft above the base of the Salado Formation at a drilling depth of 2,820 ft in the ERDA-9 hole. The contrasting minerologic and chemical features above and below this discontinuity are presented in table 4.

Above the discontinuity through the Cowden Anhydrite, the prevailing minerology in the residues of intercalated rock salts and anhydrites consists of either a dominant mixed-layer clinochlore-saponite variety or saponite alone, with lesser quantities of quartz, feldspar, illite, and clinochlore. Below the discontinuity through 15 ft of the lowermost Salado Formation and the uppermost 30 ft of the Castile Formation, the dominant minerology in the residues from anhydrites and rock salts is a saponite-serpentine association, with other silicates rarely present and never abundant.

The chemical data for the contrasting residues are compatible with their respective minerologies; the residues below the discontinuity show far greater aluminum and silica deficiency than those above (table 4)."

TABLE 4--Mineral Distribution and atom ratios in EDTA-leach residues from ERDA-9:A) the lower Salado Formation from 2,512.5-2,819.3 ft (Cowden Anhydrite to 16 ft above the base of the Salado Formation); B) the lowermost lower Salado and uppermost upper Castile Formation, from 2,820.2-2,876.5 ft (15 ft above the base of the Salado Formation to 25 ft below the top of the Castile Formation). "Random" cl-sap refers to randomly interstratified or slightly ordered clinochlore-saponite mixed-layer clay.

Mineral distribution			Atom ratios		
	A	B		A	B
Samples	11	7	Samples	6	4
Quartz	10	3			
Feldspar	8	1	Mg/Al	2.1	12.
Illite	10	1	Si/Al	4.3	9.9
Clinochlore	10	2	Si/Mg	2.1	0.8
Corrensite	5	--	(Na+K)/Al	0.5	1.3
"Random" cl-sap	3	1	K/NA	0.6	0.5
Saponite	3	4			
Talc	--	1			
Serpentine	--	5			

Borns, D.J. 1987. The Geologic Structures Observed in Drillhole DOE-2 and Their Possible Origins: Waste Isolation Pilot Plant. SAND86-1495. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p. i;

"   The Department of Energy is developing the Waste Isolation Pilot Plant (WIPP) for underground storage of transuranic waste produced by defense-related programs. The WIPP underground storage facility will be located approximately 650 m below the surface within a sequence of evaporites over 1000 m thick. This evaporite sequence is divided into three major units (in descending order): the 100-m-thick Rustler Formation; the 600-m-thick Salado Formation in which the underground facility is placed;the 300-m-thick Castile Formation. After 10 years of geological site-characterization, the major effort of this task is drawing to a close. Still, such questions remain as the origins of evaporite deformation within the Salado and Castile formations. Two miles north of the WIPP site, a stacked sequence of depressions,defined by marker beds in the Salado, was indicated by shallow boreholes. Such structures raise questions regarding the role of dissolution and gravity tectonics at the WIPP site. To investigate these structures, DOE decided to drill hole DOE-2 north of the WIPP site.

At DOE-2, the downward displacement of stratigraphic markers in the Salado confirmed the presence of stacked depressions, which were the primary target of the drilling program. The halitic units between the marker beds were thickened compared to the average section determined from basin-wide drilling. Halitic units in the lower Salado show evidence of recrystallization during deformation and parasitic fold structures. Such deformation structures and thickened halitic units are inconsistent with dissolution within the Salado as a cause of deformation in the basal units of the Salado. The remaining question is whether dissolution occurred in the underlying Castile and resulted in the deformation of the Salado. At drill hole DOE-2 and in nearby deep boreholes, complex structures in the Castile Formation are found. One hundred m or more of halite is expected in an average section of the Castile Formation; however, the only Castile halite section penetrated by DOE-2 is less than 3 m thick. In contrast, markers in the anhydrite units indicate recumbent structures and thickening of the anhydrite units by folding. As a consequence, the Castile Formation is nearly its average thickness, with the folded thickness of anhydrite compensating for the missing halite. The nearby thickening of halite within the Castile, the absence of relic anhydrite laminae in the attenuated halite units, and the high strain fabric of the remaining halite suggest that dissolution was not the dominant process in the Castile. The favored hypothesis for the Castile structures is salt flow in response to gravity inversion of the anhydrite and halite units of the Castile."

Borns, D.J., Barrows, L.J., Powers, D.W., and Snyder, R.P. 1983. Deformation of Evaporites Near the Waste Isolation Pilot Plant (WIPP) Site. SAND82-1069. Sandia National Laboratories, Albuquerque, NM. WPO 27532.

ABSTRACT, p3;

" The Delaware Basin is a broad asymmetric sedimentary trough in southeastern New Mexico and west Texas. Basin subsidence occurred from the Pennsylvanian into the Triassic. The basin also underwent tilting since the early Cenozoic.

Layered evaporite units of Ochoan age in the basin are 1000 m thick. These evaporites are divided into three stratigraphic units (listed in order of increasing age): the Rustler Formation, the Salado Formation, the Castile Formation. These units, especially the Castile, are deformed along portions of the margin of the Delaware Basin and in some areas internal to the basin. In the northern Delaware Basin adjacent to the WIPP site, the term 'Disturbed Zone' (DZ) has been applied to an area in which deformation structures are found in boreholes and from which chaotic seismic reflection data were obtained. The origin and timing of this deformation is considered important for the determination of failure scenarios for the WIPP site. However, the deformation does not present a major hazard to the construction and operational stages of the facility.

Geophysical studies (borehole logging, seismic reflection, and detailed gravity) have covered the DZ areas. Logs show vertical relief in the order of tens to hundreds of meters. Seismic profiles suggest a blocky structure with abrupt offsets and changes in dip between units. This chaotic structure occurs within the Castile Formation, but with little or no deformation exhibited by the overlaying and underlying strata. Changes in seismic character, such as wiggle shapes, imply that unit thicknesses and/or acoustic properties vary. On the periphery of the DZ, seismic profiles indicate salt flowage flexures. Outside the DZ, the seismic time structures appear to be generated by lateral velocity variations. The gravity field is dominated by anomalies originating in lateral density variations within relatively flat-lying strata. Low amplitude, long-wavelength effects of DZ structures cannot be resolved.

Through detailed core description, both meso- and microscopic, fold-styles in the DZ units are separable into distinct stages and sequences of generation. An older sedimentary stage of folding is distinguished from later tectonic folding by microfabric development and opposite senses of asymmetry. The tectonic folding and deformation displays a progressive development of fabrics ending in late-stage fracturing of competent anhydrite units. Petrofabrics reveal synkinematic growth of rotated anhydrite porphyroblasts and stress shadow growth. Microboudinage is also common. Of the possible deformation mechanism for anhydrite and halite, pressure solution appears the most applicable to the DZ. Therefore, an intergranular fluid plays an important role in facilitating deformation under the pressure, temperature, and stress histories of the region.

The following hypotheses of origin of deformation have been considered:

Gravity Foundering

Gravity Sliding

Gypsum Dehydration

Dissolution
Depositional Variations (e.g., thickness)

Of these, gravity foundering and sliding are considered the most probable causes of deformation. However, no hypothesis adequately answers why the deformation has a limited areal distribution. A possible explanation would be areal variations in rock strength caused by variations of intergranular water content. Age and timing of deformation are also crucial. Standard stratigraphic arguments based on superposition may not apply to such a highly incompetent material as halite. Gravity foundering could have happened at any time since deposition including the present; gravity sliding would probably have occurred since basin tilting began in the Cenozoic.

Deformation could be ongoing. However, the strain rates are such ($\approx 10^{-16}s^{-1}$) that deformation would progress slowly relative to the facility's time frame of 2.5 x 10^5 yr. Deformation of Salado units would be minimal (<10m) or nonexistent, but within this time frame, upper anhydrite units of the Castile could fracture and provide the volume for a brine reservoir. Such volumes would be small (<1%) and would require $\approx 10^4$ to 10^6 yr to develop. At these strain rates, fractures that connect the fractured anhydrites of the Castile with the middle Salado could not develop. Deformation should not directly jeopardize the facility over the next 2.5 x 10^5 yr."

p. 79, Col. 2, Para. 2;

" The lateral extent of the DZ is best established from figures 3-6, 3-7, 3-10, and 3-11. These maps show an "area of complex structure" within which the Castile Formation's geologic structures are too complex to map with the seismic technique. This area includes boreholes WIPP 13, WIPP 11, ERDA 6, AEC 7, and is open to the northeast. Bordering this is an area where the Castile Formation horizons show salt flow structures and some faulting. Boreholes AEC 8. WIPP 12, and SCL Fed. No. 1 are in this peripheral region. The outer edge of the mapped flow structures is here taken as the limit of the DZ. This definition is necessarily ambiguous. It includes the anticline at WIPP 12, and may or may not include the anticline in Sec. 19.

The seismically indicated DZ affects primarily the Castile Formation horizons. The underlying Cherry Canyon and Bone Spring horizons have reduced data quality, but are continuous enough to map. As noted below, the irregular seismic time structure on these horizons may be caused by velocity variations within the evaporites. Borehole control supports the interpretation that the DZ structures either do not extend into the Delaware Mountain Group or are very much reduced in amplitude."

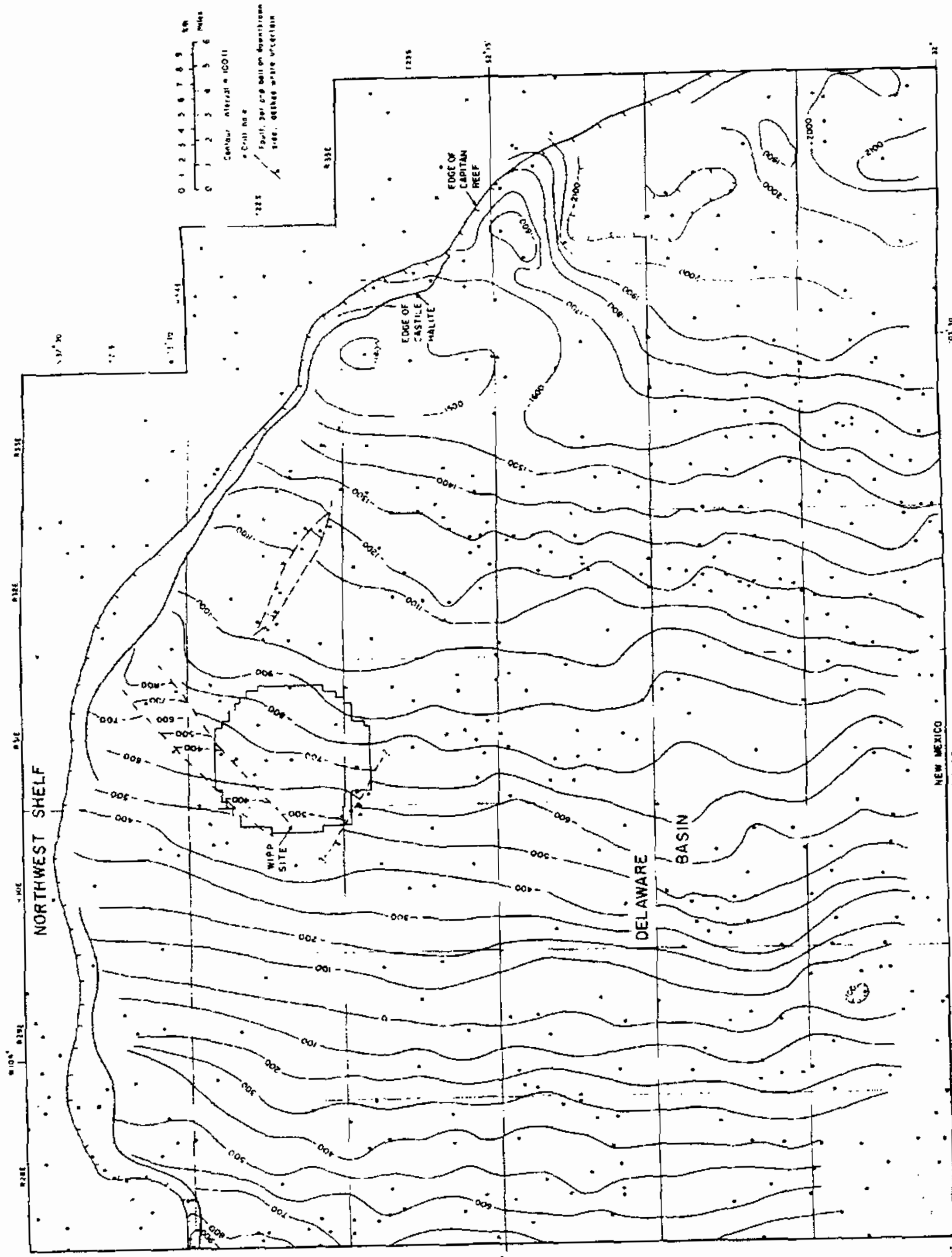


Figure 2-3. Structure Contour Map, Top of Bell Canyon Formation, Northern Part of Delaware Basin

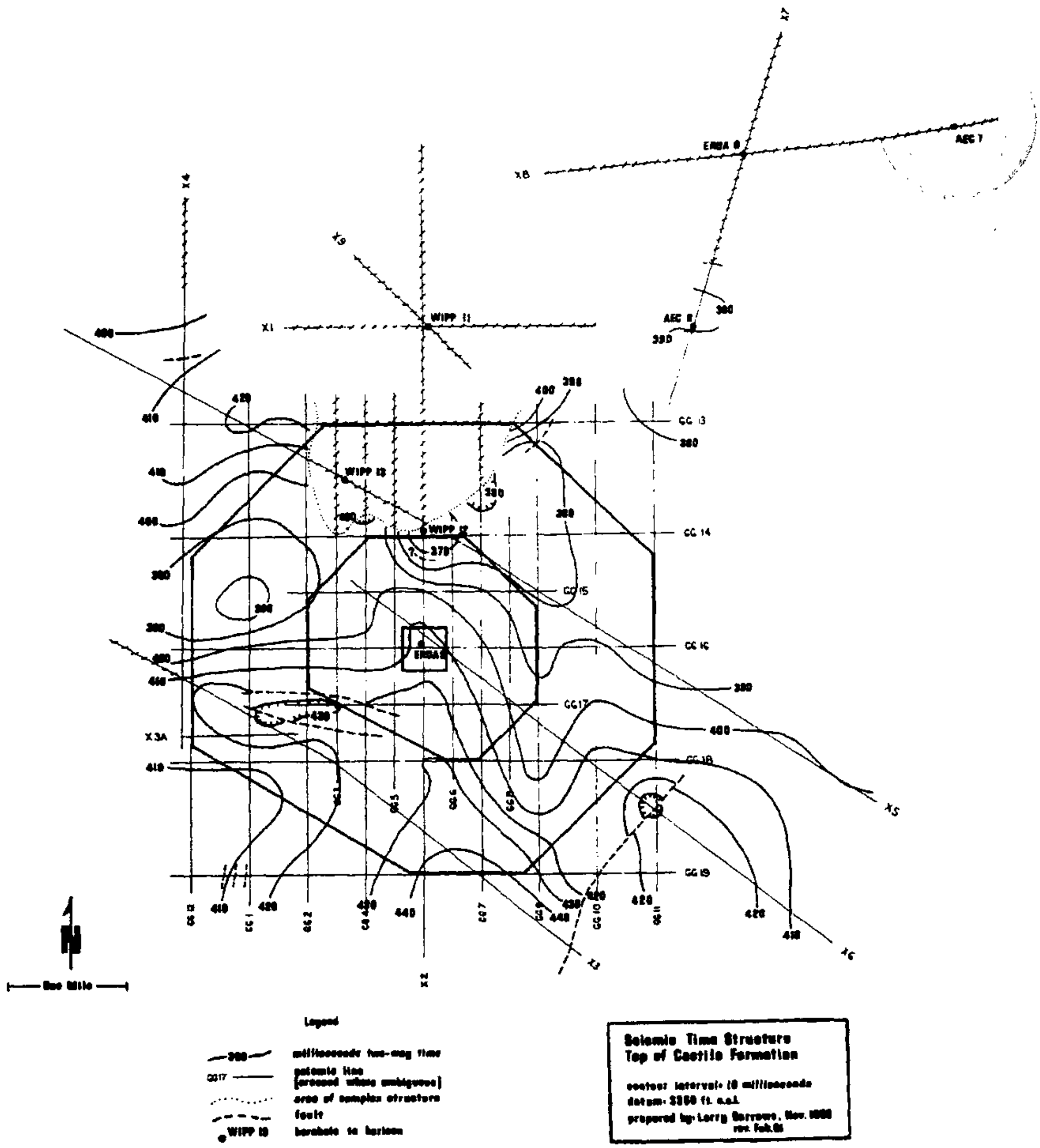


Figure 3-6. Seismic Time Structure – Top of Castile Formation

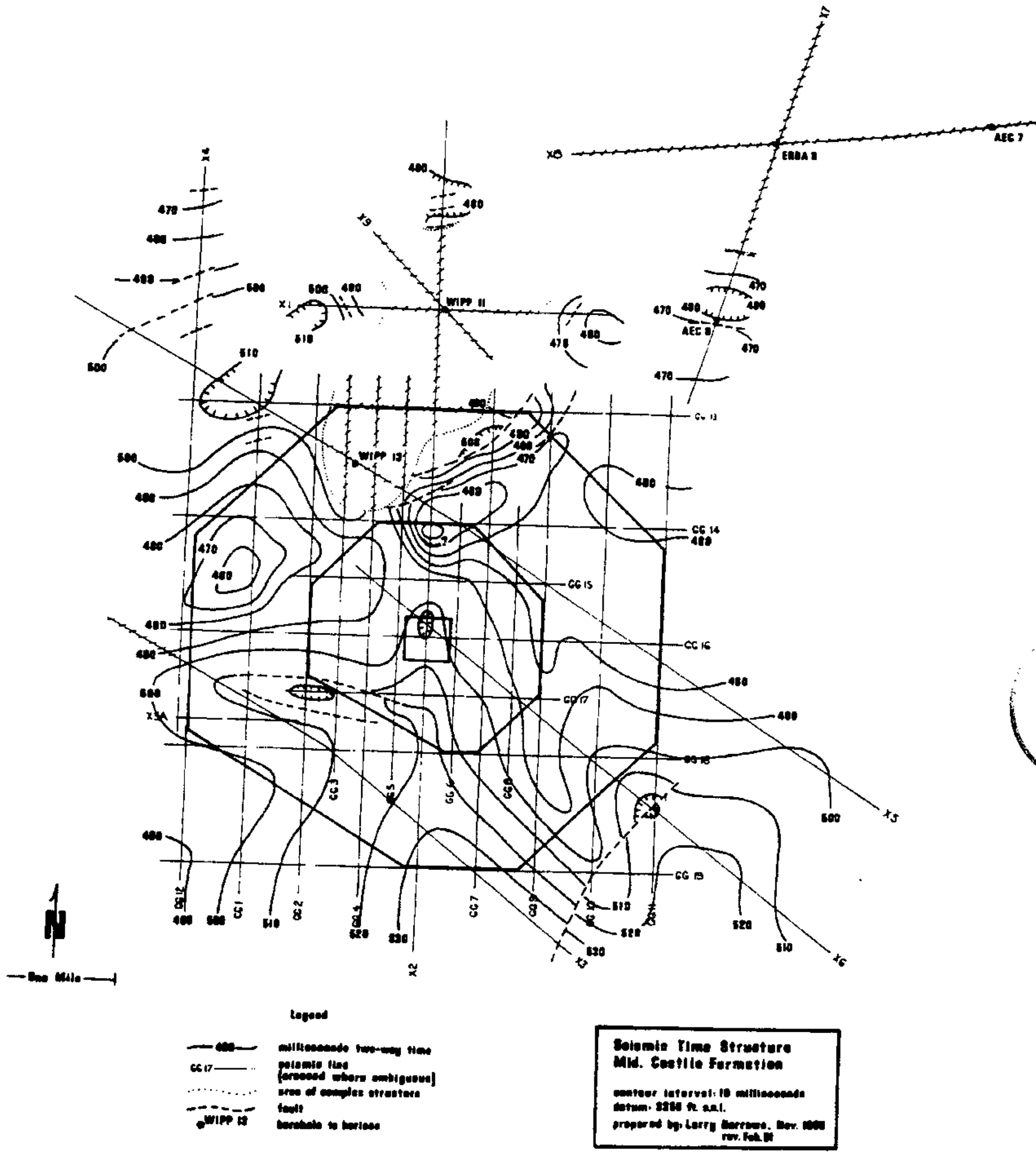


Figure 3-7. Seismic Time Structure – Mid-Castile Formation

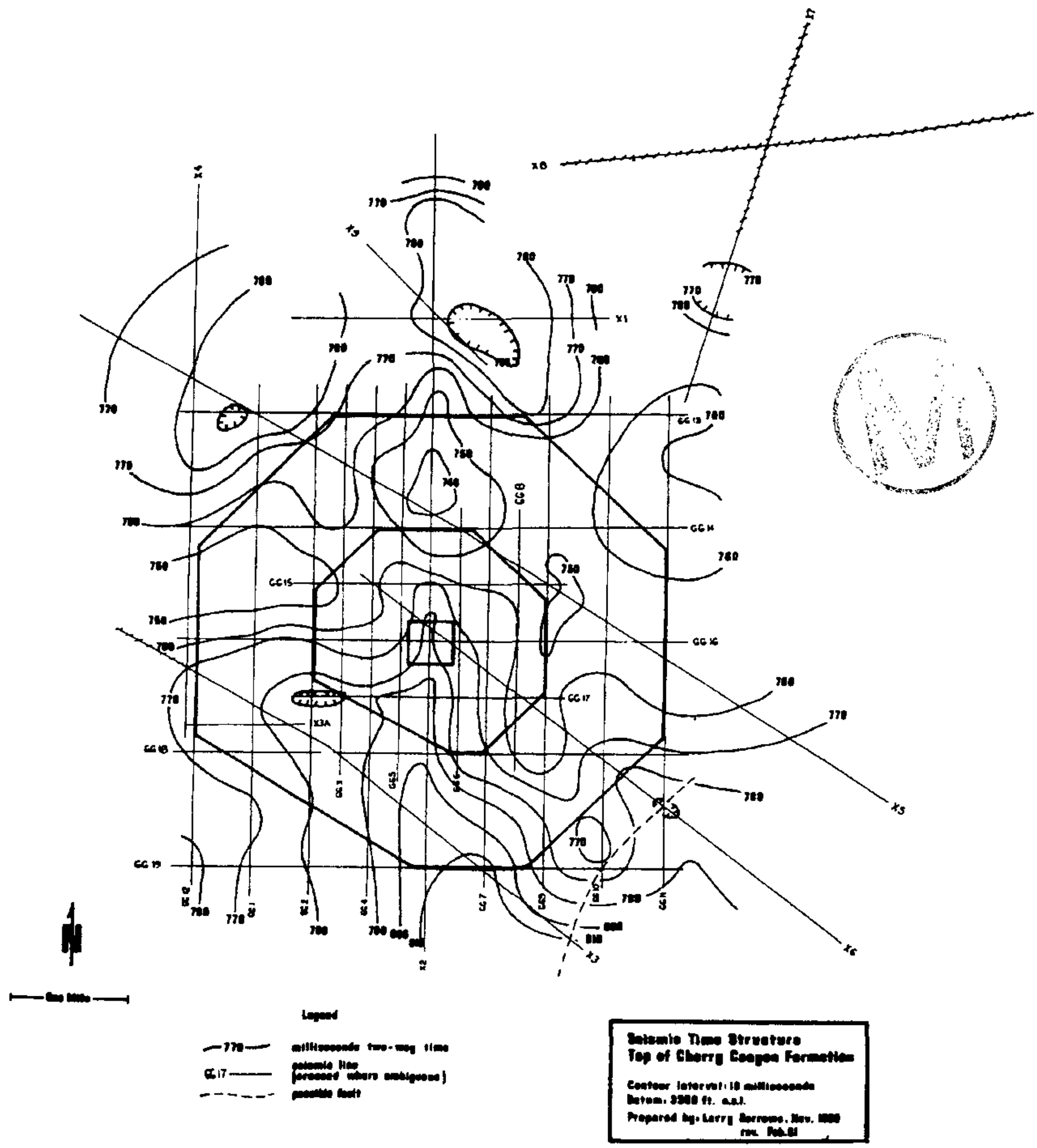


Figure 3-8. Seismic Time Structure – Top of Cherry Canyon Formation

Borns, D.J., 1985. Marker Bed 139: A study of Drillcore from a Systematic Array. SAND85-0023. Sandia National Laboratories, Albuquerque, NM. WPO 24529.

ABSTRACT, p 3;

" In southeastern New Mexico, Marker Bed 139 (referred to in this report as MB139) is one of 45 numbered siliceous or sulfatic units within the Salado Formation of the northern Delaware Basin. MB139 is divided into five zones. Zones I and V are the upper and lower contact zones, respectively. Zone II is a syndepositionally deformed subunit of polyhalitic anhydrite. Zone III is mixed anhydrite and polyhalitic anhydrite, a distinctive pale-green and pink, with subhorizontal fractures. Zone IV consists of interlayered halite and anhydrite without the overprint of polyhalite.

This sequence was transitional between submarine and subaerial. The anhydritic units of MB139 formed in salt-pan or mudflat environments or both. Undulations observed along the upper contact of MB139 are interpreted to result from traction deposits or from reworking of the upper portion of the marker bed during the transition from anhydrite to halite deposition. Zones II and III exhibit soft-sediment deformation and later traces of dewatering; e.g., formation of stylolites. Such deformation is not observed in the halite above MB139 or in Zone V and the halite units below MB139.

A distinctive set of subhorizontal fractures occurs in MB139 in mid-Zone III and, to some extent, in Zone IV. These fractures are partially infilled with halite and polyhalite. Brine occurrences at the mined facility horizon at the Waste Isolation Pilot Plant may be related to these fractures. The fractures formed either in response to stress cycles that were functions of sedimentation and erosion, or in response to deformation in the underlying Castile Formation. The subhorizontal orientation, dominant in the sampling to date, is more consistent with the interplay between stress and sedimentation cycles."

Statement of the Problem, p. 7, col. 2;

" During early development of the underground Waste Isolation Pilot Plant (WIPP) facility, Jarolimek et al (1983) reported that MB139 exhibited and undulatory upper surface in several shafts and vertical boreholes. These undulations were reported to have vertical amplitudes of ~20 in. and wavelengths of 2 to 6 ft.*

The Environmental Evaluation Group (EEG) of the State of New Mexico expressed concern that, since MB139 was a short distance below the facility level (<3 m), these undulations may be evidence of some deformational event that affected the repository level at a stage later than deposition or diagenesis. Jarolimek et al (1983), however, argued that the undulations of the upper surface of MB139 were formed during deposition."

p. 7, col. 2, para. 6;

" As an expression of the work described above, the objective of this report was to assess our understanding of MB139 and to record a systematic drilling program to study MB139."

p. 14, col. 1;

" The **Upper Contact Zone I** displays complex structure and mineralogy. The zone includes a distinctive claystone up to several centimeters thick in which are observed the major undulation structures of interest within MB139. The claystone occurs primarily along the undulatory upper contact of Zone I, with the polyhalitic halite above. The undulations along the upper surface of MB139 are 10 to 50 cm in amplitude and 30 to 100 cm in wavelength. The lower portion of this zone is not as regular in form and content as in the upper portion."

p 18, col 1, para 4, line 15;

" The apparent contradiction between theory and field observation is partly a result of not considering the effects of intergranular fluids and of different mineral mixtures for the evaporite units. The significant observation about the fractures in Zone III is that they are predominantly subhorizontal (>90%) and are partially infilled. The partially infilled nature indicates that these fractures were not formed after excavation of the facility, although their current configuration may be modified by the excavation. The orientation suggests a consistent orientation of the stress field at the time of fracture formation. The textures suggest that fracturing occurred between deposition and excavation. Only a few processes could have produced these fractures:

- Stresses that developed in the Salado and were generated by deformation in the underlying Castile Formation, such as gentle buckling of the Salado over a Castile anticline

- Changes in the overburden pressure coupled to sedimentation and erosion cycles affecting the rock sequence above the marker bed

- Buildup of gas pressures within the unit as a result of decomposition of organic material, whether algal or bacterial"

Borns, D.J. and Shaffer, S.E. 1985. Regional Well-Log Correlation in the New Mexico Portion of the Delaware Basin. SAND83-1798. Sandia National Laboratories,Albuquerque, NM.

ABSTRACT, p 3;

" Although well logs provide the most complete record of stratigraphy and structure in the northern Delaware Basin, regional interpretations of these logs generate problems of ambiguous lithologic signatures and one-hole anomalies. Interpretation must therefore be based on log-to-log correlation rather than on inferrences from single logs. In this report, logs from 276 wells were used to make stratigraphic picks of Ochoan horizons (the Rustler, Salado, and Castile Formations) in the New Mexico portion of the Delaware Basin. Current log correlation suggests that: (1) the Castile is characterized by lateral thickening and thinning; (2) some Castile thinnings are of Permian age; (3) irregular topography in the Guadalupian Bell Canyon Formation may produce apparent structures in the overlying Ochoan units; and (4) extensive dissolution of the Salado is not apparent in the area of the Waste Isolation Pilot Plant (WIPP) site."

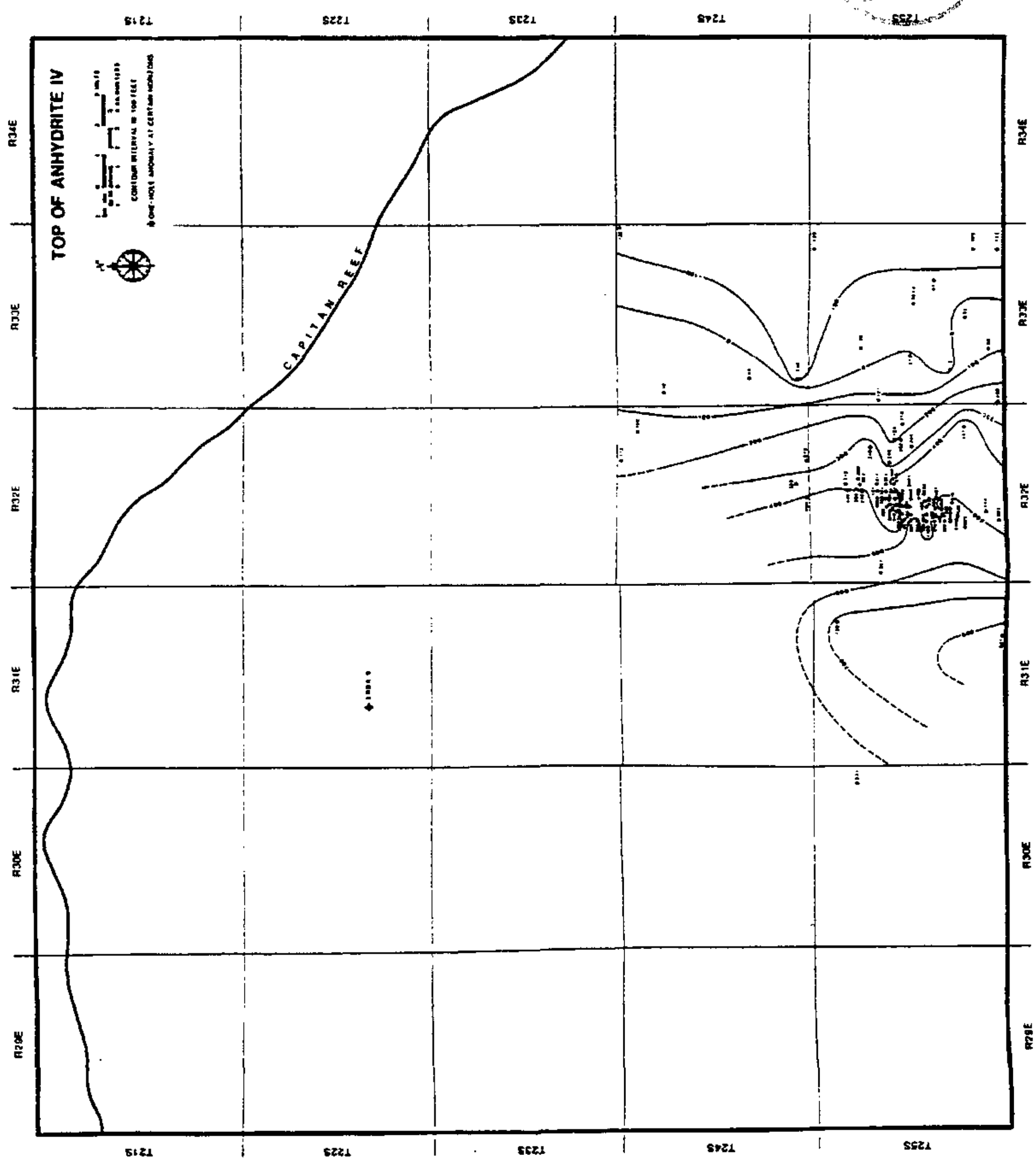


Figure 9. Top of Anhydrite IV (Elevation above MSL in feet)

16

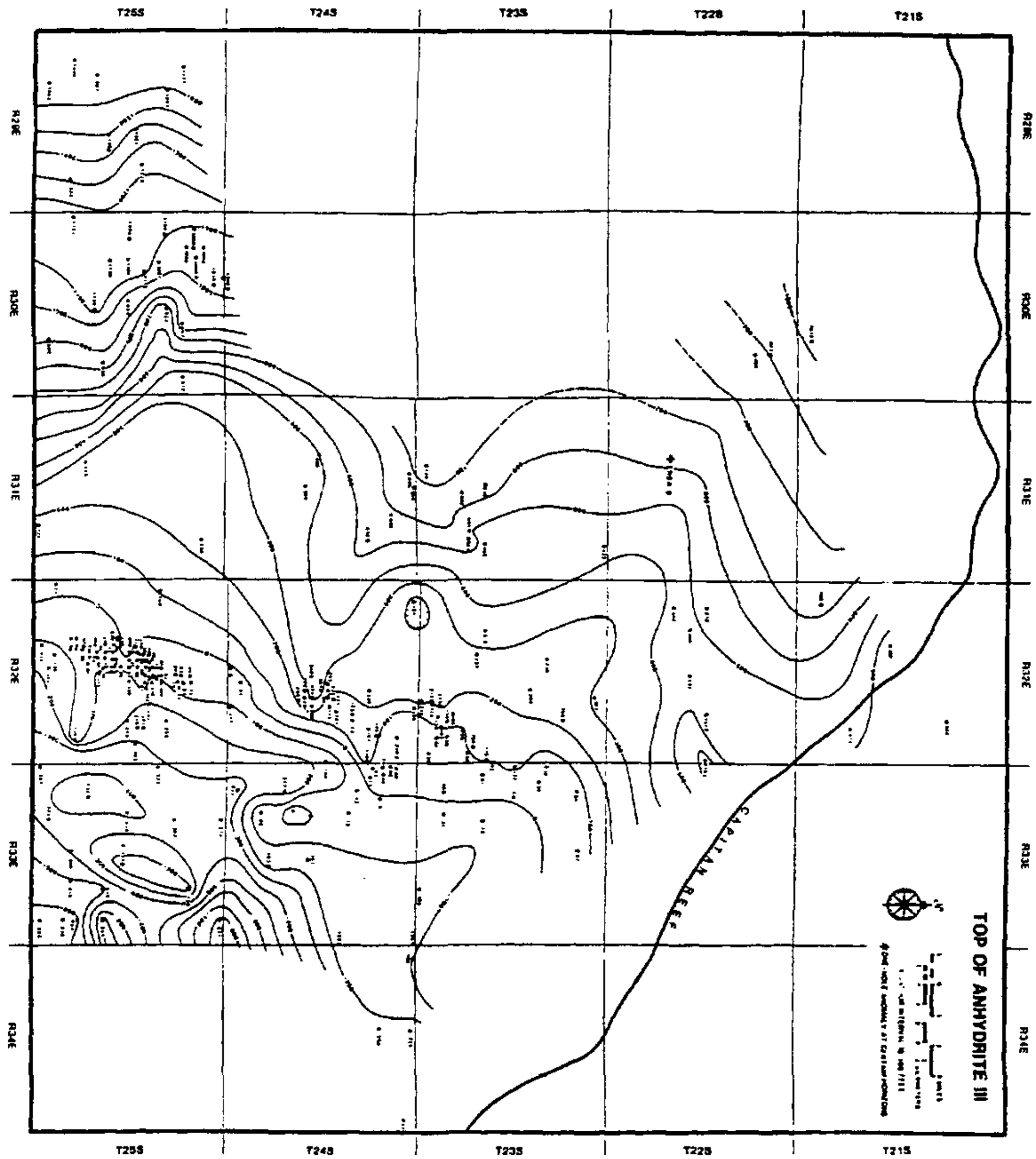
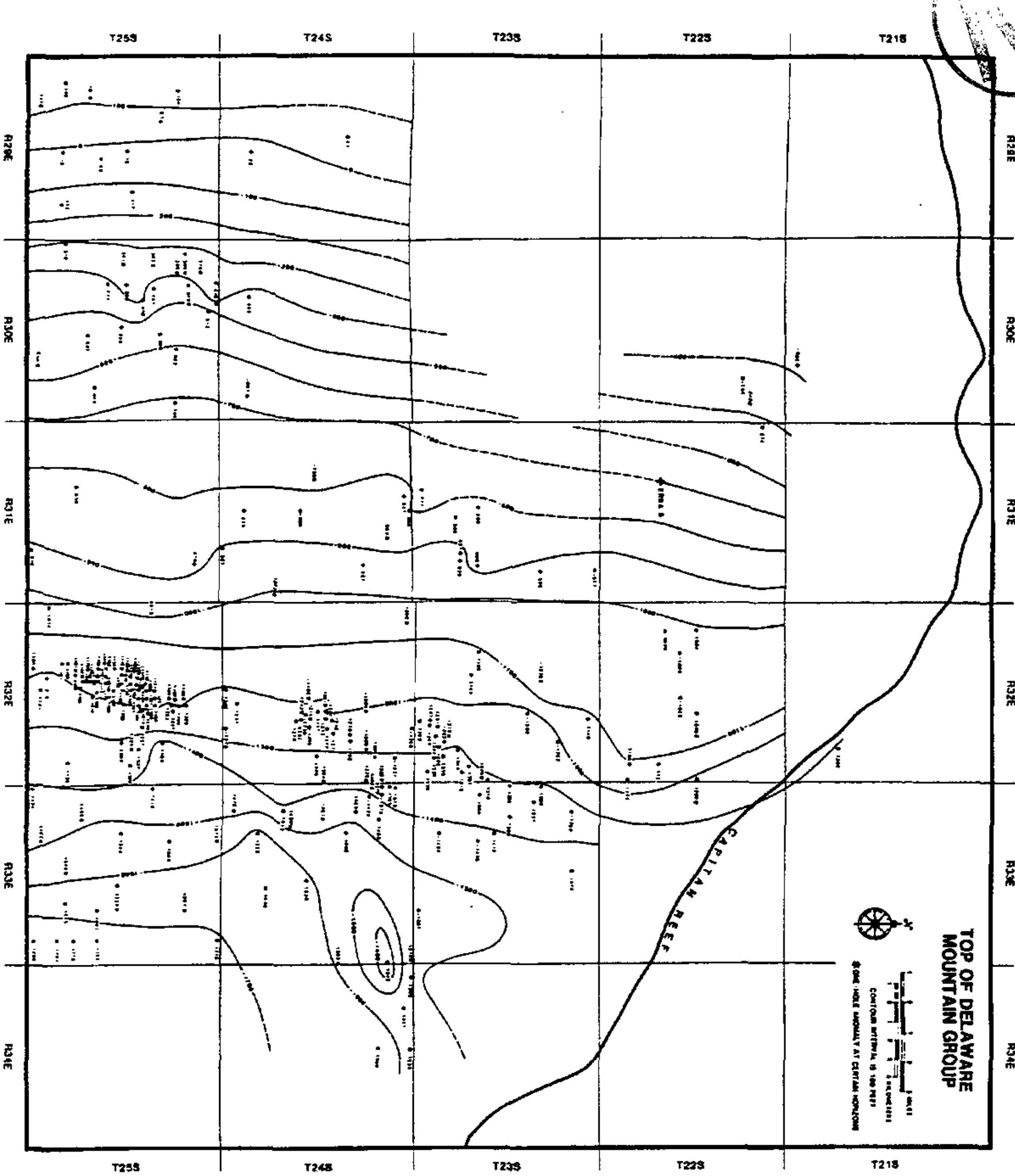


Figure 11 Anhydrite III (Elevation above MSL in feet)

Figure 16. Top of Delaware Mountain Group (Elevation above MSL, in feet)



Poker Lake Anticline, p 44, col 1, para 2;

" Another observation from the dense pack of holes in the Poker Lake area is that the upper surface of the DMG exhibits an uneven topography. Such irregularities can produce apparent flow or dissolution structures in the lower and mid-Castile. However, the depression on the sedimentary surface existed before and during deposition.

Examples have been provided above for (1) the misleading contour extrapolation for one-hole anomalies and (2) the ambiguous nature of certain stratigraphic picks. However, resultant maps (Anderson, 1978; Davies, 1983) have been used as compelling evidence for dissolution and other processes in the Delaware Basin. In the case of the Poker Lake structures, the actual sizes of the anticline and syncline are significantly smaller (6x) in map view, than the structures extrapolated by Anderson (1978) and Anderson and Powers (1978). The remaining smaller structures (one-hole anomalies) can still be attributed to salt flowage and/or dissolution since the Permian."

Conclusions, p 45, col 2, para 4;

". . . Current log correlations suggest the following:

- The Castile is characterized by thickening and thinning. Hence, mass redistribution rather than mass removal is the dominant process.
- Thinning in some lower Castile structures was compensated for by thickened upper Castile and lower Salado sedimentation. This relationship suggests that the synform existed during Permian (Ochoan) sedimentation.
- Irregular topography in the top of the Bell Canyon can produce apparent structures in the overlying Ochoan units.

Anderson (1978, 1981, 1983) has proposed deep dissolutions as a major mechanism of salt removal in the northern Delaware Basin. He suggested that dissolution was marked in two zones, which are linear series of sinks. One zone trends SSE from the Poker Lake structures with a linear extent >30 km; the other zone, which includes San Simon Sink, is a line of troughs overlying the Capitan Reef on the eastern side of the basin. The northern end of Anderson's dissolution structure appears in the southwestern corner of the area covered in Figures 3 through 26. This zone is 20+ km SSW of the WIPP site. It is conceivable that this set of troughs was caused by dissolution, although the mechanism may not be deep dissolution but dissolution related to the ancestral Pecos River (Bachman, 1983). At the scale of resolution for the spacing wells, no continuation is observed of this structure NNE towards the WIPP site.

Locally, Davies (1983) has proposed that finger sands within the Bell Canyon control dissolution; such finger sands have higher transmissivities than do adjacent rock types. These finger sands trend NE. Structure contours do not reflect these sands; nor, in fact, do Anderson's line troughs. Davies has also proposed that a structural depression in the mid-Salado is evidence of deep dissolution two miles north of the WIPP site center as marked by the contour maps of Snyder in Borns et al (1983). The size of this structure is such that it does not appear on maps based on hydrocarbon industry holes. However, DOE has proposed to drill this structure to investigate its origins."

Brausch, L.M., Kuhn, A.K., and Register, J.K. 1982. Natural Resources Study, Waste Isolation Pilot Plant (WIPP) Project, Southeastern, New Mexico. TME 3156. Albuquerque, NM: U.S. Department of Energy, Waste Isolation Pilot Plant. WPO 39094.

Section 1.1.2.1 Potash, p 11, para 2;

" The two separate studies of the economic potential of the potash resources at the WIPP site (U. S. Department of the Interior, 1977; Agricultural and Industrial Minerals, Inc., 1979) used varying approaches and report different results describing the economic attractiveness of the potash resources. Each of these evaluations involved segmenting the ore deposits into distinct blocks of ore and identifying which areas could be economically developed by mining operations. Both studies agree, however, that no economically attractive deposits (i.e., reserves) of sylvite exist within the inner three control zones at the WIPP site and that the majority of the langbeinite reserves are located outside the inner zones (Table 2). The most attractive langbeinite deposits, and the only 'reserves' under current market conditions (USBM Mining Unit B-1), are located north-northeast of the site center in Control Zones III and IV (Figure 5)."

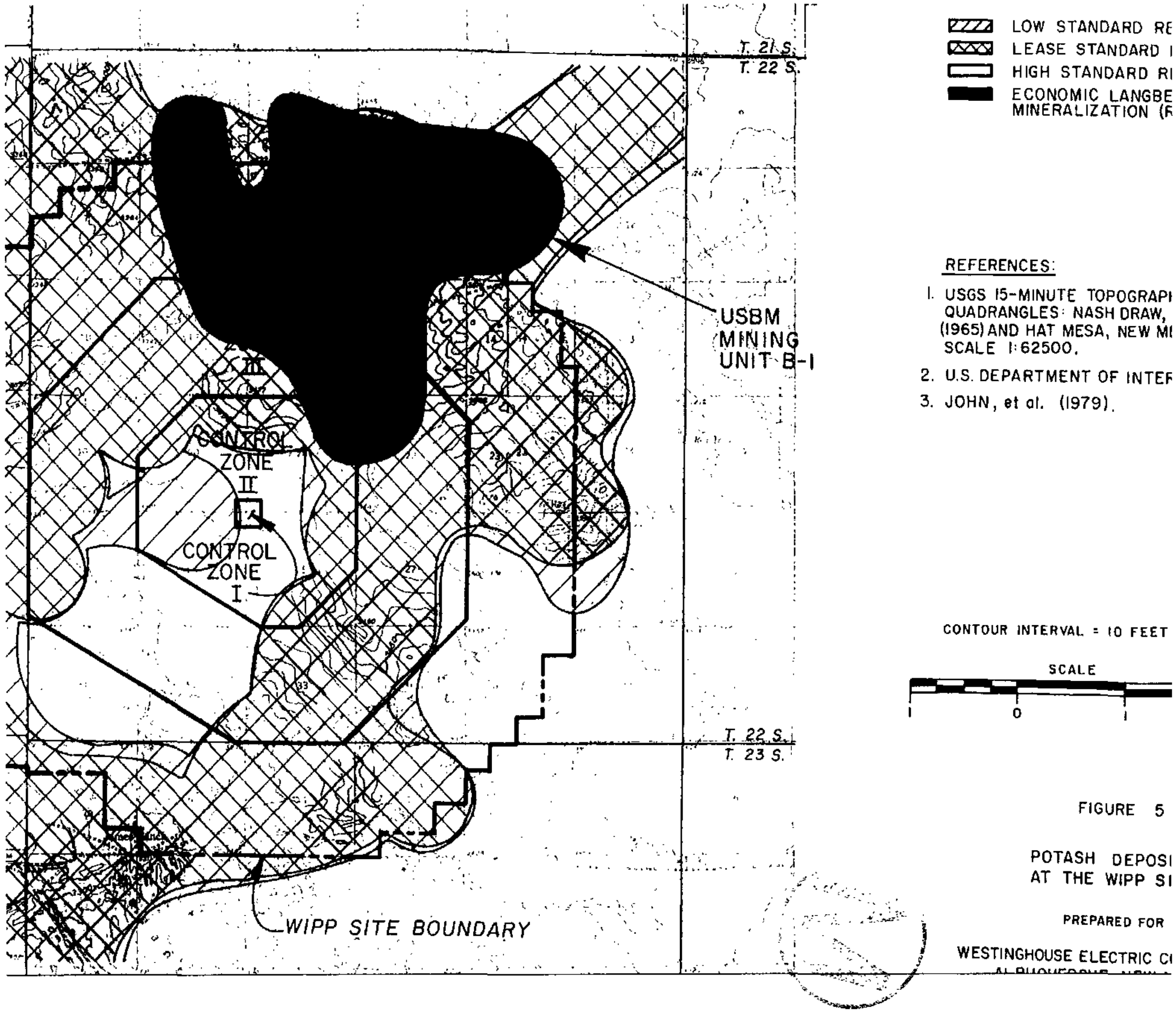


FIGURE 5

POTASH DEPOSI
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Brokaw, A.L., Jones, C.L., Cooley, M.E., and Hays, W.H. 1972. Geology and Hydrology of the Carlsbad Potash Area, Eddy and Lea Counties, New Mexico. Open File Report 4339-1. U.S. Geological Survey, Denver, CO.

ABSTRACT;

" The potash mines of southeastern New Mexico are in a sparsely populated area 15-30 miles east of Carlsbad. Topographic relief is low, surface drainage poor, and collapse features common. The climate is semiarid.

Sedimentary rocks attain thicknesses of more than 20,000 feet and range in age from Ordovician to Quaternary. The area includes the northern end of the Delaware basin and the largely buried Capitan Reef. The basin contains as much as 13,000 feet of Permian strata. The oldest exposed rocks are of Late Permian age, but drilling has provided much data on the buried older rocks. The principle structures are broad gentle features related to late Paleozoic sedimentation: the northern Delaware basin, a shelf north and west of the basin, and a central basin platform to the east. These structures were tilted eastward before Pliocene time, have been inactive since, and now show a general eastward dip of less than 2°.

The salt deposits are in the Late Permian Ochoan Series composed of a thick salt-bearing evaporite lower part (Castile, Salado, and Rustler Formations) and a thin non-salt-bearing upper part (Dewey Redbeds).

The Castile Formation consists largely of interlaminated gray anhydrite and brownish-gray limestone, but includes much rock salt. It is about 1,500-1,600 feet thick along the southern edge of the potash area; it thins northward to about 1,000 feet near the margin of the Delaware basin and tongues out in the southernmost parts of the northwest shelf. All the salt is concentrated in a thick middle member which lies 200-300 ft above the base of the formation.

The Salado Formation, the main salt-bearing unit of the potash area, ranges in thickness from about 1,900 feet in the south to about 1,000 feet in the north. The formation is characterized by thick persistent units of rock salt alternating with thinner units of anhydrite and polyhalite. Thin seams of claystone underlie the anhydrite and polyhalite unit, and there are a few beds of sandstone and siltstone at large intervals. The Salado Formation is divided into three informal units: a lower and an upper salt member, generally free of sylvite and other potassium and magnesium evaporite minerals, and the McNutt potash zone, generally rich in these minerals.

The Rustler Formation mostly anhydrite and rock salt, thins from 300 to 400 feet in the southern part of the area to about 200-250 feet in the northern part. Some dolomite is present in the upper and lower parts of the formation, and thin to thick units of sandstone and shale are interbedded at long to short intervals.

The Dewey Lake Redbeds at the top of the Ochoan Series consist of reddish-brown siltstone and fine-grained sandstone. The formation is 250-550 feet thick in the potash area.

Three main hydrologic units control the ground-water hydrology of the Carlsbad potash mining area: the Pecos River, the water-bearing strata overlying the Salado

Formation, and the Capitan Limestone and other water-bearing strata underlying the Salado. The distribution and development of large dissolution features, particularly in the Nash Draw and Clayton Basin areas, exert a major effect on the occurrence and movement of the ground water. The Pecos River receives nearly all of the ground-water outflow from the area. Most of that outflow reaches the Pecos near Malaga Bend.

The main water-yielding units overlying the Salado Formation are the basal solution breccia zone and the Culebra Dolomite Member of the Rustler Formation, the Santa Rosa Sandstone, and the alluvium. The basal solution breccia zone is the hydrologic unit most significant in the solution of halite from the upper part of the Salado Formation. The easternmost extent of evaporite solution in the potash mining area is roughly at the common boundary between Ranges 30 and 31 E. The formations above the Salado Formation seem to be connected hydrologically and can be considered a single multiple aquifer system. Solution activity and associated collapse, subsidence, and fracturing have increased the overall permeability of the rocks and the interformational movement of water in the aquifer system.

Ground water in the formations above the Salado moves generally southward and southwestward across the potash mining area toward the Pecos River. Although the total amount of ground water discharging to the Pecos River is not known, it has been estimated that 200 gals per minute enter the river from the basal solution breccia zone.

The potentiometric and water-table contours outline a series of ground-water ridges and troughs imposed on the regional southward to southwestward pattern of ground-water movement. A large southwestward-plunging ground-water trough extends from Malaga Bend northeastward roughly through Nash Draw to beyond the mining area in the vicinity of Laguna Plata. Another much smaller trough is east and southeast of the Project Gnome site.

The Salado Formation has an intergranular porosity and permeability that ranges from low to virtually none. Locally, fractures and solution openings impart a spotty formational permeability. In the potash mining area, the Salado Formation is dry except for water in the leached zone at the top of the formation and small pockets of water or water and gas encountered ocassionally during mining.

The Cambrian to Permian sedimentary rocks underlying the Salado Formation contain water of brine composition and are under high artesian pressure. These rocks are not exposed in the potash mining area but lie deeply buried throughout much of southeastern New Mexico and western Texas. In the potash mining area the elevations of the potentiometric surfaces of different zones of these rocks range from a few feet to a few hundred feet above or below the land surface."

p 30;

" The Delaware basin was first defined in Early Pennsylvanian time, when an earlier very broad basin was divided by initial uplift of a large median ridge that became the central basin platform of Permian time. The basin subsided relative to the bounding platform and shelf until Late Permian time, when its history as an active structural feature ended.

The form of the northern part of the basin, as defined by contours on the surface of the Precambrian floor (Foster and Stipp, 1961), is a broad asymmetrical trough, trending north and plunging south. The axis is in central Lea County, roughly parallel to the central basin platform. The eastern slope of the trough rises rapidly to the platform, whereas the western slope is much gentler.

As in any gradually subsiding basin, the older sediments are downwarped in a form like that of the basement floor, and the warping dies out upward in the basin section (fig. 4A). The Late Permian Ochoan rocks and the Triassic rocks exposed in the basin today do not reflect basinwide warping, and their major structural feature is the regional eastward slope mentioned above. This slope is 75-100 feet per mile in proximity to the Gnome site and the southern potash mines.

Disruption of the regional slope of the Ochoan and younger rocks is minor. The vicinity of the Gnome site and the southern mines is apparently representative in its scattering of open folds, domes, and small faults, which may be, in part, of tectonic origin. Deep-seated faults with more than 20 feet of vertical displacement are rare if not absent there (Jones, 1960, p. 16). Near the western edge of the basin and the present upper course of the Black River, Cenozoic tectonism may be involved in a northwest-trending monoclinal flexure. Kelley (1971, pl. 5) showed 600 feet of relief across this monocline on the upper surface of the Bell Canyon Formation. Several minor high-angle faults cutting the Castile Formation in the same part of the basin and two inferred faults at the northwestern edge of the basin (Kelley, 1971, p. 48-51) are most probably products of solution subsidence. Subsurface solution has produced many other minor faults and numerous local flexures in the near-surface rocks, as well as the many sinks and larger depressions. In addition, small surficial domes that are attributed to differential solution of salt or to expansion of anhydrite during hydration are numerous (Vine, 1960)"

Brookins, D.G. 1980. "Polyhalite K-Ar Radiometric Ages from Southeastern New Mexico." In Isochron/West No. 29, pp. 29-31.

p. 29, col. 1;

"   This paper lists four new radiometric K-Ar age determinations for polyhalites from southeastern New Mexico. These data are compared with seven published ages by Brookins and others (1980). The new (nos. 1-4) samples were chosen because they were mixed with halite and sylvite, although the exact halide content could not be determined from x-ray diffratometry. Nor can it be stated with certainty that other halides and-or other evaporite minerals are present or not. The detailed geology, mineralogy, chemistry and precise sample locations are given in SAND (1978). Earlier studies of langbeinite and langbeinite-sylvite mixtures have been reported in this journal by Schilling (1973), and will not be repeated here except to note that a distinct lowering of K-Ar ages with increasing sylvite content was noted. The purpose of this note is to see if similar effects are noted for polyhalites. The K-Ar analyses and age calculations were carried out by Geochron Laboratories, Inc., Cambridge, Mass."

p. 30, col. 1;

"   11. MB76-22 K-Ar

Polyhalite mixed with halite and sylvite, from contact zone of evaporites intruded by lamprophyre dike (Kerr-McGee Potash Mine, Lea County, NM). *Analytical data*: K = 12.14%, $^{*40}Ar$ = 0.01807 ppm $^{*40}Ar/\Sigma^{40}Ar$ = 31.7%. *Collected by*: Marc Bodine, Jr. *Analyzed by*: Geochron Laboratories, Inc.

(impure polyhalite) 21.4 ± 0.8 m.y."

Brookins, D.G. 1981. "Geochronologic Studies Near the WIPP Site, Noutheastern New Mexico." In Environmental Geology and Hydrology in New Mexico. S.G. Wells, and W. Lambert, ed., Special Publication 10, pp. 147-152. New Mexico Geological Society.

ABSTRACT, p. 147;

" The U. S. Department of Energy's Waste Isolation Pilot Plant (WIPP) site is currently being investigated for pilot storage of defense-generated radioactive waste. A critical facet of the overall study is the question whether the rocks have remained closed systems with respect to their bulk chemistry and isotopic composition since formation in the Late Permian as opposed to episodic or more-or-less continuous recrystallization during the post-Late Permian. Early attempts at K-Ar dating of sylvites mixed with other salts yielded inconclusive results, primarily because sylvite is not well suited for K-Ar study because of loss of radiogenic ^{40}Ar. Rb-Sr study of sylvites (Register and Brookins, 1980) yields a 214 $\pm$ 15 m.y.B.P (million years before present) isochron indicating closed system conditions to Rb and Sr since latest Permian or earliest Triassic. Pre-200 m.y.B.P. K-Ar dates have also been determined for pure langbeinites and polyhalites (Brookins and others, 1980a). When mixed with sylvite, age lowering results. The Rb-Sr systematics of eolian clay minerals known to have interacted with the evaporite brine yield a poorly defined isochron of 390 $\pm$ 77 m.y.B.P., but the apparent date does not indicate that the clay mineral-brine interactions were not so severe as to completely rehomogenize Sr isotopes despite the clay mineral alteration. A 34 $\pm$ 1.5 m.y.b.P. lamphrophyre dike intrudes the evaporite sequence some 70 km north of the WIPP Site. Contact effects, including recrystallization of polyhalite, are restricted to within 10 m of the dike. Finally, polyhalite inclusions in one rubble chimney yield a pre-200 m.y.B.P. age indicating no major recrystallization effects due to this disturbance of the evaporite sequence. Collectively, the geochronologic studies argue for pre-200 m.y.B.P. formation of the evaporite minerals and stability of the rocks since that time."

Brookins, D.G. and Lambert, S.J. 1987. "Radiometric Dating of Ochoan (Permian) Evaporites, WIPP Site, Delaware Basin, New Mexico, USA." Scientific Basis for Nuclear Waste Management X, Materials Research Society Symposia Proceedings, Boston, MA, December 1-4, 1986, J.K. Bates and W.B. Seefeldt, eds., Vol. 84, pp. 771-780, Materials Research Society, Pittsburgh, PA.

ABSTRACT, p. 771;

" We have attempted radiometric dating of halide-sulfate salts and clay minerals from the Delaware Basin, New Mexico, USA, as part of geochemical study of the stability of the evaporite sequence at the WIPP (Waste Isolation Pilot Plant--a US DOE facility) site. We undertook this dating to determine: (1) primary age of evaporite genesis or time(s) of recrystallization, (2) if previously undated evaporite minerals (leonite, polyhalite, kieserite) give useful data, and (3) if the detrital clay minerals have been radiometrically reset at any time following their incorporation into the evaporite medium. We have shown earlier that polyhalites can indeed be successfully dated by the K-Ar method, and once corrections are applied for admixed halide minerals, dates of 210-230 Ma for the Delaware Basin are obtained. Rb-Sr isochrons from early stage sylvites-polyhalites-anhydrites yield 220 $\pm$ 10 Ma, even when some sylvites yield lower K-Ar dates due to loss of $^{40}Ar^*$. K-Ar dates on leonites and kieserites are also low due to $^{40}Ar^*$ loss, but their Rb-Sr dates are higher. Detrital clay minerals from the Delaware Basin collectively yield a highly scattered isochron (390 $\pm$ 77 Ma), but samples from a local area, such as the WIPP Site, give a much better age of 428 $\pm$ 7 Ma. These dates show that the interaction between the clay minerals and the evaporitic brines was insufficient to reset the clay minerals Rb-Sr systematics. In a related study, we note that a dike emplaced in the evaporite at 34 Ma had only very limited effect on the intruded rocks; contact phenomena were all within 2 m of the dike. All of our geochemical (radio-metric and trace element) studies of the WIPP site argue for preservation of the isotopic and chemical integrity of the major minerals for the past 200 Ma."

Brookins, D.G., Register, J.K, Jr., and Krueger, H.W. 1980. "Potassium-Argon Dating of Polyhalite in New Mexico." *Geochimica et Cosmoshimica Acta* Vol. 44, No. 5, pp. 635-637.

ABSTRACT, p 635;

" Polyhalite $K_2Ca_2Mg(SO_4)_4 \bullet 2H_2O$, is an important mineral in many evaporites. Although its use for K-Ar dating has never been investigated, our results indicate that it is a very useful mineral for dating events ranging from the time of potash mineralization to any younger events which may have affected the evaporite. Five K-Ar dates on pure polyhalite, including two from included material and from beds distorted by the formation of a rubble chimney, yield dates between 198 and 216 Myp, in good agreement with Rb-Sr dates and the diagenetic age of the potash deposits from the same rocks. Two polyhalites mixed with sylvite gave lower dates (154 and 174 Myr) which is to be expected because of radiogenic ^{40}K loss from the sylvite phase. One polyhalite, formed after the intrusion of a 31 Myr lamphrophyre dike, yielded 21 Myr. Collectively our results indicate that pure polyhalite is satisfactory for K-Ar dating and may provide critical age information in studies of the geologic history of the evaporite sequences."

p 637, col 1, para 3;

" In the Kerr-McGee Potash Mine a lamprophyre dike yields a K-Ar apparent emplacement date of 31 Myr (See SAND. 1978). The evaporite minerals immediately adjacent to this dike have been recrystallized and second generation sylvite, polyhalite, halite and other minerals sometimes fill fractures in the lamprophyre. Because the exposures in the Kerr-McGee Mine have been mined out and are no longer accessible, a sample of very pure polyhalite from this area (See Table 2) was obtained from the New Mexico Institute of Technology (courtesy of Dr. M. Bodine). This sample (No. 8) was free of sylvite and yielded a date of 21.4 $\pm$ 0.8 Myr. in rough agreement with the age of the lamprophyre. If a predike age had been obtained, questions about the use of polyhalite for dating could be raised. The result corresponds well with the established age of the dike. The ages of about 210 Myr for samples one through five provide indirect evidence that the emplacement of the dike was a local event and apparently affected only the contact zones."

Calzia, J.P., and Hiss, W.L. 1978. "Igneous Rocks in Northern Delaware Basin, New Mexico and Texas," In Geology and Mineral Deposits of Ochoan Rocks in Delaware Basin and Adjacent Areas, G.S. Austin, ed., Circular 159, pp. 39 - 45. New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.

p 44, col 1, para 2;

" Since the rate of argon diffusion varies during alteration, it is not likely that analysis of two altered samples would produce: 1) closely similar percentages of radiogenic argon, and 2) calculated age dates that agree within the range of standard deviation. These data suggest that radiogenic argon was not lost during alteration and that igneous dikes east of the Pecos River are early Oligocene (32.2 to 33.9 m.y.) in age."

Cartwright, Jr., L.D. 1930. Transverse Section of Permian Basin, West Texas and Southeastern New Mexico. American Association of Petroleum Geologists Bulletin, Vol. 14,

ABSTRACT, p 969;
" The Permian basin is divided into structural units each of which is characterized by a distinctive stratigraphic section. The Main Permian basin, Central basin platform, and Delaware Mountain basin are included in the transverse section presented in this paper. The strata of the Main Permian basin are divided into the Wichita, Albany, Clear Fork, and Double Mountain groups, the Double Mountain group being divided into the San Angelo, Blaine, Whitehorse-Cloudchief, and Quartermaster formations. The formations of the Main Permian basin are relatively uniform along the strike, but thicken and become more marine basinward.

The Central basin platform is a regional limestone 'high' on which there are pronounced changes in the limestone section penetrated east and west across it. Two explanations of these changes are generally accepted. The first recognizes an extension of the Capitan reef system bordering the Delaware Mountain basin. Back of the reef is a lagoonal facies comprising dolomitic limestone, sandstone, and anhydrite. The second recognizes an older dolomitic limestone known as the 'White lime' on the eroded surface of which there is a heterogeneous deposit of dolomitic limestone, sandstone, and anhydrite known as the 'Brown lime.'

The strata of the Delaware Mountain basin comprise the Bone Springs limestone, the Delaware Mountain sandstone, the Capitan formation, the Lower Castile, the Upper Castile, and Rustler formations. Of special interest are the Capitan, which is a reef phase of the upper Delaware Mountain, and the Lower Castile, which is a peculiar evaporite formation."

Casas, E., and Lowenstein, T.K. 1989. Diagenesis of Saline Pan Halite: ^Comparison of Petrographic Features of Modern, Quaternary and Permian Halites. Journal of Sedimentary Petrology, Vol. 59.

ABSTRACT, p 724;

" Petrographic studies of modern saline pan halites (Saline Valley, CA; Salina Omotepec, Baja California, Mexico) and Quaternary shallow-buried (0-200 m) halites (Saline Valley, CA; Bristol Dry Lake, CA; Searles Lake, CA; Qarhan saline pan, Qaidam Basin, China; Lake Uyuni, Bolivia) show that the diagenetic modification of halite begins contemporaneously with deposition, is most intense within the upper few meters of burial, and is essentially complete within the first 45 m of burial. Halite crusts from modern saline pans that have undergone repeated episodes of flooding, evaporative concentration, and desiccation contain abundant syndepositional diagenetic features. These 'mature' modern halites are dominated by dissolution textures and fabrics (formed during flood stages) and cementation textures (formed during desiccation stages). Interlayered mud beds contain varying amounts of displacive halite crystals.

At shallow burial depths, halites retain many textural features of 'mature' modern saline pan halite. Halites below the first few meters are no longer susceptible to dissolution from floodwaters but continue to be cemented by clear halite. Within the first 10 m of burial, cementation reduces the porosity of halite crusts to less than 10%. The remaining pore spaces are completely filled by burial depths of approximately 45 m. Displacive growth of halite in muds continues at shallow-burial depths and is probably limited to the first few tens of meters of burial depth. The mechanisms for cementation and displacive growth of halite at shallow-burial depths probably include (1) evaporative concentration of groundwater brines and (2) cooling of surface brines when they sink below the sediment surface.

Undeformed halites from the Permian Salado and Rustler Formations of New Mexico contain delicate syndepositional textures and abundant clear halite cements that are comparable to those observed in modern saline pan halites and shallow-buried halites. The Permian halites are interpreted to have undergone a depositional and early diagenetic history similar to the modern and Quaternary analogs.

Complete cementation of saline pan halites at shallow burial depths has important implications for the origin of saline formation waters in sedimentary basins. Parent evaporite brines may not be stored in the pores of halite rocks and later expelled during burial compaction if the rocks are cemented early, and tightly crystallized halite rocks may also impede the downward migration of dense syndepositional brines."

Chugg, J.C., Anderson, G.W., Kink, D.L., and Jones, L.H. 1971. Soil Survey of Eddy Area, New Mexico. Prepared by the U.S. Soil Conservation Service in cooperation with New Mexico Agricultural Experiment Station. For sale by the Superintendent of Documents, U.S. Government Priniting Office, Washington, D.C.

How This Soil Survey Was Made, p 1, col 1, para 5;

" Soil scientists made this survey to learn what kinds of soils are in the Eddy Area, where they are located, and how they can be used. They went into the county knowing they would likely find many soils they had already seen, and perhaps some they had not. As they traveled over the county, they observed steepness, length, and shape of slopes; size and speed of streams; kinds of native plants or crops; kinds of rock; and many facts about the soils. They dug many holes to expose soil profiles. A profile is the sequence of natural layers, or horizons, in a soil; it extends from the surface down into the parent material that has not been changed much by leaching or by roots of plants.

The soil scientists made comparisons among the profiles they studied, and they compared these profiles with those in counties nearby and in places more distant. They classified and named the soils according to nationwide uniform procedures. . . ."

NOTE: Figure 113 is too large and detailed to scan into this document.

Claiborne, H.C. and Gera, F. 1974. Potential Containment Failure Mechanisms and Their Consequences at a Radioactive Waste Repository in Bedded Salt in New Mexico. ORNL-TM 4639. Oak Ridge National Laboratories, Oak Ridge, TN.

ABSTRACT, p 1;

" This report examines potential containment failure mechanisms and estimates their probabilities and consequences, when possible, for a hypothetical waste repository located in bedded salt in southeastern New Mexico.

The preliminary conclusion of this study is that a serious breach of containment for such a repository, either by human action or natural events, is only a very remote possibility and falls into the category of least likely occurrences that affect society.

A sealed repository 600 m underground would be virtually sabotage proof; even the surface burst of a 50-megaton nuclear weapon could not breach the containment. Accidental drilling of bore holes through the disposal horizon could cause relatively minor local contamination.

The mechanism of containment failure with the most serious potential consequences seems to be the impact of a meteorite that produces a crater extending to the disposal horizon. The probability of such a catastrophic meteorite impact was estimated at 1.6×10^{-13} per year. The calculated exposure from the global fallout resulting from such an event would be of the same order of magnitude as that from nuclear bomb tests, provided the impact did not take place during the first few hundred years after closure of the mine. The ejecta falling back into the nearby area would cause a serious and protracted contamination problem. A pathway analysis showed that individuals living exclusively on foodstuffs produced in the contaminated area would be exposed to high radiation doses.

Based on the tectonic activity of the Delaware Basin over the past 200 million years, the probability of faulting through the repository has been estimated at 4×10^{-11} per year; however, the probability that faulting would cause failure of waste containment is only a small but unknown fraction of this value.

Exposure of the waste horizon to the action of ground water by a large fault with a vertical displacement of at least 350 m cannot be proved impossible. However, at least a few hundred thousand years would be required for an offset of 350 m to take place. A more sudden breach of containment could be effected by a large fault that cuts through the disposal zone and hydraulically connects the over- and underlying aquifers. In this case, any water flowing along the fracture zone would be downward into the deep aquifers. Fortunately, the geologic evidence indicates that such a fracture could eventually be healed by plastic flow of the salt beds. Even in the event that the deep aquifers became contaminated, it is extremely unlikely that activity could be brought to the surface because the normal flow velocities in these aquifers are on an order of only a few kilometers per million years.

In view of the hydraulic heads of the various aquifers, it is difficult to visualize circumstances that could result in an upward flow and contamination of the fresh water in the Culebra Dolomite aquifer. The only possibility for the release of radioactive material to the Culebra Dolomite aquifer would appear to be on the basis of a model that permits faulting

and progressive displacement of the disposal horizon until waste contacts the circulating ground water. The contamination of surface aquifers by this mechanism of release could be relatively serious, despite the very long time necessary to produce such a displacement."

3.2.4 Erosion, p. 43, Para. 2;

" Average rates of erosion in the United States, based on recent stream load records, are on the order of a few centimeters per thousand years.[13] Occasionally erosion rates can be higher; for example, small drainage basins or river valleys are known where materials are removed at rates ranging from tens of centimeters up to meters per thousand years.[13]

The selected site for this report is located in the Mescalero plain, a geomorphic surface in southeastern New Mexico situated between the Pecos River on the west and the High Plains on the east. The Mescalero plain has limited relief and is covered by windblown sand over large areas; the surface is usually underlain by a layer of caliche of Pleistocene age.

No significant lowering of the land surface by erosion occurred during Quaternary time as indicated by the existence of the caliche layer. Large depressions are due more to subrosion and subsidence than surface erosion. Small depressions can be formed either by subrosion or wind deflation. Bachman[63] has reviewed removal processes in the Mescalero plain, concluding that the site area underwent very limited erosion and salt dissolution in Quaternary time. A southeast-flowing stream of probable Pleistocene age may have eroded San Simon Swale; the bottom of the swale is 60 to 70 m below the surrounding high land surface.

The surface lowering at one place in Nash Draw has been estimated at 60 m during the past 600,000 years (a rate of 10 cm/1000 years); salt dissolution and subsidence have been responsible for most of the lowering.[63] Based on this estimate, it seems reasonable to assume that, even if a future climate were to favor increased rates of erosion, no disinterment of waste could take place before several million years.

A drastic change in the rate of erosion could be caused by a significant uplift of the area. There is no indication that the Mescalero plain is presently being uplifted. It is obviously impossible to prove that uplift will not occur in the future; however, the known rates of large-scale vertical movements in midcontinental areas indicate that an uplift of 500 m would require several hundred thousand years.[13,64]

On the basis of these considerations it seems reasonable to conclude that erosion, as a potential mechanism of containment failure for waste buried in southeastern New Mexico at a depth of 600 m, can be neglected."

Corbet, T.F. and Knupp, P.M. 1996 The Role of Regional Groundwater Flow in the Hydrogeology of the Culebra Member of the Rustler Formation at the Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico. SAND96-2133. Sandia National Laboratories, Albuquerque, NM.

p. i, para. 1;
1. INTRODUCTION; p. 1, para. 1;
"   This report summarizes a study in which numerical simulation is used to enhance conceptual understanding of the hydrogeology of the Culebra Dolomite in the context of groundwater flow on a regional scale in the vicinity of the Waste Isolation Pilot Plant (WIPP). The WIPP is a potential repository for defense-generated transuranic wastes. The Culebra Dolomite is a member of the Permian age Rustler Formation, a sequence of predominantly evaporate deposits that overlie the Salado Formation. The Salado is a thick bedded salt of Permian age that contains the WIPP and provides the primary containment for the repository. The groundwater flow system in the overlying Permian and Triassic deposits forms a secondary barrier to releases from the repository in the even of a breach of the primary containment. Consequently, an important requirement of the performance assessment of the repository is to characterize long-term groundwater flow in the shallow system. We consider the possibility that patterns of groundwater flow in the shallow system change over thousands of years in response to change climate. Although groundwater flow is simulated in all of the strata above the Salado, this report focuses primarily on flow in the Culebra Dolomite because it is thought to be the most likely pathway for lateral migration of radionuclides to the accessible environment."

p. 3, para. 2;
"   We developed a new numerical code called SECOFL3D, to perform the simulations. The algorithm implements a rigorous treatment of the free-surface and seepage-face boundary conditions (Bear and Verruijt, 1987; Dagan, 1989; de Marsily, 1986) and is designed to be robust even if extremely large contrasts in hydraulic conductivity are present within the model domain. A moving mesh that adaptively deforms so that its upper surface conforms to the moving water table is used to ensure that the entire computational domain remains saturated.

Lateral boundaries of groundwater basins are sub-vertical flow divides that typically coincide with depressions and highs on the land surface. Flow over a region much larger than the WIPP site (Figure 1-1) was simulated in order to have the model boundary coincide with topographic features that are likely to act as groundwater divides over a range of climatic conditions. A series of steady-state simulations was performed to examine the sensitivity of simulation results to assumed values for hydraulic conductivity and recharge rate. Transient simulations provided insight into how patterns of groundwater flow respond to long-term changes in climate. These simulations covered the time period from late in the Pleistocene (14,000 years ago) to 10,000 years in the future.

The simulations results suggest that patterns of groundwater flow in the Culebra in the vicinity of the WIPP are influenced by the hydrology of the entire groundwater basin. Flow rates and directions depend on the position of the water table and heterogeneity in hydraulic conductivity at the basin-scale. Groundwater flow changes with time due to interaction among recharge, movement of the water table, and topography of the land surface."

p. 5, para. 2;

" The simulations also provide information about how flow in the Culebra in the vicinity of the WIPP is coupled with flow in adjacent strata. Vertical leakage across the top of the Culebra is directed downward. The amount of vertical leakage into the Culebra cannot be estimated with confidence because the vertical conductivity of the confining units is not well constrained. Vertical leakage may contribute as little as 5% or more than 50% of the total inflow to the portion of the Culebra that lies within the WIPP-site boundary. All of the outflow from this portion of the Culebra is lateral flow. Therefore, contaminants introduced into the Culebra will travel toward the accessible environment along the Culebra rather than by migrating upward or downward into other units."

p. 103, para. 4;

" We performed mass balances over the reference volumes (defined in the introduction to Section 3) of the more conductive layers. This was accomplished by summing the flow across each face of the reference volumes in order to calculate total flow through each reference volume, as well as the proportions of lateral and vertical inflow and outflow from the reference volumes."

p. 105, para. 1;

" Figures such as 3-46, 3-47, and 3-48 mass balances provide a clear overview of the mass balance but are difficult to interpret quantitatively. To complement these figures, we have included tables in Appendix D that summarize the mass balance data at two simulated times: at the present time (zero years) and at 10,000 years into the future. The total inflow to the Dewey Lake/Triassic rocks, Magenta, and Culebra reference volumes at the simulated present time are 5015, 784, and 2100 cubic meters per year (base case in Table D-1). The inflow rates for these units at 10,000 years are somewhat larger: 16738, 1736, and 3354 cubic meters per year (base case in Table D-4). These numbers show that, in this simulation, most of the flow occurs in the Dewey Lake/Triassic rocks and that more flow occurs in the Culebra than the Magenta."

p. 106, para. 1;

" Table D-2 gives the total flow across the upper surface, lower surface, and sides as a percentage of the total flow through the reference volume at zero years simulation time. For the base-case simulation, 42% of the inflow to the Dewey Lake/Triassic reference volume is from groundwater recharge (i.e., 42% of the inflow to the Dewey Lake/Triassic rocks is across the top). Zero percent of the inflow to the Dewey Lake/Triassic is from upward vertical leakage. In fact, an important aspect of all of the transient simulations performed for this study is that the vertical flow components are directed downward in all layers within the vicinity of the WIPP site. 98% of the inflow to the Magenta reference volume is vertical leakage from the Dewey Lake/Triassic and 30% of the inflow to the Culebra is leakage from the Magenta. All of the outflow from the Culebra reference volume is by lateral flow. Table D-5 provides the same information at 10,000 years."

p. 139, para. 2;

" Within the region of intact strata, the contrast in hydraulic conductivities plays an important role in determining flow patterns. The Dewey Lake and Triassic rocks are more permeable than the anhydrites at the top of the Rustler Formation. Consequently most of the water that recharges the groundwater basin flows only in these rocks above the Rustler. The rest leaks vertically through the upper anhydrites and is available for flow through the rest of the Rustler. Differences in hydraulic head along the base of the Dewey Lake provide the driving force for flow in the Rustler.

Groundwater flow in the Rustler Formation is characterized by very slow vertical leakage through confining units and faster lateral flow in conductive units. Specific discharges (flow rates per unit area) in the Culebra are 2 to 3 orders of magnitude greater than the vertical specific discharges across the top of the Culebra. However, vertical leakage can contribute a significant portion of the total inflow to portions of the Culebra that are extensive enough that the upper surface is very much larger than the area available for lateral flow."

p. 141, para. 4;

" These simulations suggest that, in the vicinity of the WIPP site, vertical flow across the top of the Culebra is directed downward. The amount of vertical leakage into Culebra at this site cannot be estimated with confidence. It contributes a small portion of the total inflow to the Culebra reference volume, perhaps 5% to 10%, if the vertical conductivity of the confining units is 1×10^{-13} m/s or less. However vertical leakage may contribute more than 50% of the total inflow if the conductivity is an order of magnitude larger.

A robust implication of these simulations is that nearly all (greater than 90% in all simulations) outflow from the Culebra reference volume is by lateral flow. Therefore, contaminants introduced into the Culebra will travel toward the accessable environment within the Culebra rather than by leaking upward or downward into other units. This result provides confidence that a flow and transport model that assumes that flow occurs only in the Culebra would include the appropriate release pathways."

Davies, P.B. 1984. "Deep-Seated Dissolution and Subsidence in Bedded Salt Deposits." Ph.D. Thesis. Stanford University, Palo Alto, CA.

Section 2.3.5 Summary, p 175;

" A suite of structure contour maps constructed from available borehole logs confirms the existence of an anomalous, closed, structural depression in the northern portion of the WIPP site. This depression persists through several hundred feet of the middle and upper Salado Formation. The depression is broad and shallow in the upper portion of the section and becomes narrower and deeper in successively lower strata. Isopach maps show that the strongest local variations in bed thickness occur in the lowermost unit and are spatially associated with the structural depression. The salt appears to be anomalously thin in the margin areas.

Physical analyses of salt deformation processes suggest that this structural depression formed as the result of ductile subsidence in response to the localized removal of salt at some lower horizon. Processes capable of removing salt include dissolution of lower Castile salt, dissolution of lower Salado salt, and depletion of Castile salt by gravity driven flow. Deep boreholes in the northern WIPP area and elsewhere in the basin reveal geologic features that are characteristic of each of these processes. Consideration of complex structures in these areas leads to the conclusion that there are potentially significant interrelationships between individual processes and that more than one process may be active in a given area. For example, lower Castile salt dissolution may play a critical role in triggering the gravity foundering process by creating local increase in the deviatoric stress at the quasi-stable Anhydrite II and III density inversions and by causing the influx of a small amount of intergranular saturated brine, thereby decreasing the strength of the salt. Another example of process interrelationships is the potentially important role of lower Castile salt dissolution and gravity foundering in creating vertical and horizontal hydrologic pathways, thereby facilitating lower Salado dissolution.

At the Salado depression in the northern WIPP site, there is insufficient data in the Castile and lower Salado to delineate which processes have been active and what process interrelationships exist. Therefore, either additional subsurface data should be gathered in the lower Salado and Castile, or safety analyses of the WIPP facility should explicitly encompass all possible processes, or both."

Davies, P.B., 1989. Variable-Density Ground-Water Flow and Paleohydrology in the Waste Isolation Pilot Plant (WIPP) Region, Southeastern New Mexico. Open-File Report 88-490. U.S. Geological Survey, Albuquerque, NM. WPO 38854.

ABSTRACT, p 1;

" A series of analyses, including variable-density flow simulations, was used to examine groundwater flow in the vicinity of the Waste Isolation Pilot Plant (WIPP) in the context of the regional flow system. WIPP is an underground repository mined from a thick bedded-salt unit to provide a facility for the disposal of radioactive waste. WIPP is located in southeastern New Mexico. The analyses primarily examined the Culebra Dolomite Member of the Rustler Formation, which is a potential pathway for the transport of radionuclides to the biosphere in the event of a breach of the WIPP repository.

An analysis of the relative magnitude of pressure-related and density-related flow-driving forces indicates that density-related forces are not significant at the WIPP Site and to the west but are significant in areas to the north, northeast, and south of the site. The area to the south is important because it lies along potential transport pathways from the site. In this area, groundwater flow simulations based on equivalent-freshwater head produce very misleading information on predicted flow directions and velocity magnitudes.

A regional-scale, variable-density model of ground-water flow in the Culebra Dolomite Member was developed in which a baseline, approximate steady-state simulation was calibrated to the distribution of equivalent-freshwater heads. The flow field from the baseline simulation, along with long-term brine transport patterns, indicates that flow velocities are relatively fast west of the site and extremely slow east and northeast of the site. In the transition zone between these two extremes, which includes the WIPP Site, velocities are highly variable.

A series of sensitivity simulations was used to analyze boundary effects and vertical flux. These simulations indicate that if the Culebra is as impermeable to the east and northeast of the WIPP Site as geologic conditions indicate, the central and western parts of the region, including the WIPP Site, are fairly well insulated from the eastern and northeastern boundaries and are insensitive to whatever conditions are assumed to be present along these boundaries. A simulation of a 5-meter head increase along the Pecos River boundary indicates that if the Culebra were tightly confined throughout the entire region, approximately 50 percent of any change in river elevation would eventually reach the WIPP Site. Uncertainty in the regional distribution of storage characteristics in the Culebra makes it difficult to accurately predict how long it would take for Pecos-related stresses to propagate through the WIPP region. A series of vertical-flux simulations indicates that as much as 25 percent of total inflow to the Culebra could be entering as vertical flux. These simulations also indicate that if significant volumes of water enter the Culebra vertically, most of the influx must be occurring in the westernmost part of the transition zone adjacent to Nash Draw.

Motivated by recent isotopic and geochemical analyses, a simple cross-sectional model was developed to provide a physically based analysis of the flow system as it may have drained through time following recharge during a past glacial pluvial. Drainage for 20,000 years was simulated using a variety of hydraulic-conductivity distributions for rock units overlying the Culebra. These simulations indicate that the system as a whole drains very slowly and that it apparently could sustain flow from a purely transient drainage following recharge of the system during the Pleistocene. Although these simulation do not prove that this has been the case, they do show that such long-term transient drainage is physically possible. The simulations also indicate that the observed underpressuring of the Culebra in the vicinity of the WIPP site is most likely the hydrodynamic result of the Culebra having a relatively high hydraulic conductivity and being well connected to its discharge area but poorly connected to sources of recharge."

Driving-Force Analysis of the Model Area of Barr and Others (1983), p 35, para 3;
" South of the WIPP site, density-related driving-force components are as much as an order of magnitude larger than the pressure-related driving-force components (fig. 13). The density-related driving-force components are not only much greater in magnitude, but the angle between the two driving-force components is very large, almost 180 degrees in some areas. Because flow simulation based on equivalent-freshwater head ignore the density-related driving-forces, such simulations will produce large errors in predicted flow direction in this area. Flow directions in this area south of the site are important because this area may include flow paths for potential contaminant transport away from the site."

Hydraulic-conductivity distribution, p 110, para 3;
" No hydraulic conductivity data were available for the Dewey Lake Red Beds, which overlie the Rustler Formation. Mercer (1983) indicated that these fine-grained sandstones and siltstones have relatively low hydraulic conductivity. Therefore, a hydraulic conductivity of 10^{-8}m/s, which falls at the low end of the range of typical values for fine-grained sandstones (Morris and Johnson, 1967, p. D18), was used in the standard simulation.

Deal, D.E., and Case, J.B. 1987. Brine Sampling and Evaluation Program Phase I Report. DOE-WIPP 87-008. Westinghouse Electric Corporation, Carlsbad, NM.

ABSTRACT;

" This interim report presents preliminary data obtained in the course of the WIPP Brine Sampling and Evaluation Program. The investigations focus on the brine present in the near-field environment around the WIPP underground workings that is easily moved under existing pressure gradients. Observations began in 1983 and were expanded in 1984 and 1985. Most of the data reported in this document were acquired in the 600 days after January 1, 1985.

Although the WIPP underground workings are considered 'dry,' small amounts of brine are present, probably on the order of 0.1 to 0.5 percent by weight of the surrounding rocks. This amount of brine is not unexpected in rocks of marine sedimentary origin. Part of that brine can and does migrate into the repository in response to pressure gradients, at essentially isothermal conditions. These small volumes of brine have little effect on the day-to-day operations, but are pervasive throughout the repository and may contribute enough moisture over a period of years to affect resaturation and repressurization after sealing and closure.

The inflows occur as 'weeps' on the exposed surfaces and as very small inflows of brine at various locations, most noticeably in holes drilled outward from the underground workings. Over 1400 underground drill holes, most 15 meters or less in length, exist at WIPP. Gas is usually associated with the brine inflows. Gas bubbles are observed in many of the brine occurrences. Gas is also known to exsolve from solution as the brine is poured from container to container.

Measured brine occurrences have inflow rates that range from less than surface evaporation rates to approximately 0.5 liters per day. Most range between a few tenths and a few hundredths of a liter per day. Individual occurrences vary greatly and some drill holes less than a meter apart have brine inflows that contrast dramatically, making the discussion of 'averages' or 'typical occurrences' difficult or misleading. Most occurrences have initial peak inflow rates that decline to steady rates over the observation period. Some have ceased entirely, and a few have increased inflows.

The largest individual production that was measured during this reporting period produced an aggregate of over 235 liters of brine. It was clearly an unusual and exceptional occurrence, and inflow rates for that occurrence have declined over the observation period.

It is clear from these preliminary data that the brine, gas, and salt creep phenomena are intimately associated. Pressure-driven brine inflows that are not the result of brine migration in a thermal gradient may occur at any time a pressure difference exists, including after sealing and closure of the repository. It is likely that the observed inflows into the repository excavations are dominated by the response to transient pressure gradients resulting from the excavation of the repository itself. A component due to regional hydraulic head cannot be ruled out at this time, but if it exists, it appears to be relatively very small.

Investigations of the occurrence and chemistry of the brines are continuing."

Deal, D.E., Case, J.B., Deshler, R.M., Drez, P.E., Myers, J. and Tyburski, J.R. 1987. Brine Sampling and Evaluation Program Phase II Report. DOE-WIPP-87-010. Westinghouse Electric Corporation, Carlsbad,NM.

INTRODUCTION, p 1;

" The Waste Isolation Pilot Plant (WIPP) project is a Department of Energy (DOE) research and development facility constructed to demonstrate the safe disposal of radioactive wastes derived from the defense activities of the United States. The WIPP Project's mission consists of two parts. The first is to demonstrate the safe handling and disposal of transuranic (TRU) waste in bedded salt. The second is to create a research facility for in situ examination of the technical issues related to the emplacement of defense-related radioactive waste in bedded salt.

The WIPP facility is located approximately 42 kilometers east of Carlsbad, New Mexico, in an area known as Los Medanos (Figure 1-1). The underground portion of the facility is located at a depth of approximately 655 meters in the bedded salt deposits of the Salado Formation, part of an evaporite sequence over 1000 meters thick (Figure 1-2). An extensive program of site characterization and validation has been conducted for the past eleven years (1976-1987). The results of these studies are summarized in the WIPP 'Geological Site Characterization Report' (Powers, et al., 1978), the WIPP 'Safety Analysis Report' (U.S. DOE, 1986), the WIPP 'Preliminary Design Validation Report' (bechtel National, Inc., 1983), the WIPP 'Design Validation Final Report' (Bechtel National, Inc., 1986b), and the WIPP 'Results of Site Validation Experiments' (Black, et al., 1983). Additional site investigations are being conducted as part of an ongoing program to further refine the understanding of the site-specific geology. The hydrogeological activities of the Brine Sampling and Evaluation Program (BSEP), as outlined in the Brine Testing Program Plan (Morse and Hassinger, 1985), are part of these investigations. Phase I of the BSEP activities were reported by Deal and Case (1987).

The purpose of the BSEP is to investigate the origin, hydraulic characteristics, extent, and composition of brine occurrences in the excavations for the WIPP repository in the Salado Formation. Although considered dry workings, brine is observed to weep from exposed surfaces in the repository horizon and seep into drill holes in the underground excavations.

These brine occurrences become visible shortly after excavation or drilling. The more noticeable occurrences that have been observed for more than three years produced brine at the rate of a few tenths or a few hundredths of a liter per day.

Although individual occurrences are small and not particularly noticeable on a day-to-day basis, they are pervasive throughout the repository (Deal and Case, 1987). Over a period of months and years they may contribute enough moisture to merit consideration from the standpoint of long-term repository performance. During present operations, virtually all of the moisture entering the workings from the host rock is evaporated and removed in the air that is circulated by the underground ventilation system. The assessment and understanding of the brine occurrences becomes especially important when considering what their long-term impacts might be on operations during the demonstration and retrieval period and the rates of resaturation and repressurization of the excavations after closure of the facility.

The data presented in this report are a continuation and update of studies that began in 1983 (Black, et al., 1983; TSC-D'Appolonia, Part II, 1983; and Alcorn, 1983), formalized by Morse and Hassinger,(1985), and previously reported in the Brine Sampling and Evaluation Phase I report (Deal and Case, 1987). Users should consult Deal and Case (1987) for background information, detailed descriptions of the data gathering and analysis procedures, and the cautions that should be exercised when using the data presented herein."

Deal, D.E., Abitz, R.J., Belski, D.S., Case, J.B., Crawley, M.E., Deshler, R.M., Drez, P.E., Givens, C.A., King, R.B., Lauctes, B.A., Myers, J., Niou, S., Peitz, J.M., Roggenthen, W.M., Tyburski, J.R., and Wallace, M.G. 1989. Brine Sampling and Evaluation Program, 1988 Report. DOE-WIPP-89-015. Carlsbad, NM: Westinghouse Electric Corporation.

Executive Summary, p. E-1;

"   The data presented in this report are the result of Brine Sampling and Evaluation Program (BSEP) activities at the Waste Isolation Pilot Plant (WIPP) during 1988. These activities, which are a continuation and update of studies that began in 1982 as part of the Site Validation Program, were formalized as the BSEP in 1985 to document and investigate the origins, hydraulic characteristics, extent, and composition of brine occurrences in the Permian Salado Formation, and seepage of that brine into the excavations at the WIPP. Previous BSEP reports (Deal and Case, 1987; Deal and others, 1987) described the results of ongoing activities that monitor brine inflow into boreholes in the facility, moisture content of the Salado Formation, brine geochemistry, and brine weeps and crusts. The information provided in this report updates past work and describes progress made during the calendar year 1988.

During 1988, BSEP activities focused on four major areas to describe and quantify brine activity: (1) monitoring of brine inflow parameters, e.g., measuring brines recovered from holes drilled upward from the underground drifts (upholes), downward from the underground drifts (downholes), and near-horizontal holes; (2) characterizing the brine, e.g., the geochemistry of the brine and the presence of bacteria and their possible interaction with experiments and operations; (3) characterizing formation properties associated with the occurrence of brine, e.g., determining the water content of various geologic units, examining these units in boreholes using a video camera system, and measuring their resistivity (conductivity); and (4) modeling to examine the interaction of salt deformation near the workings and brine seepage through the deforming salt."

Deal, D.E., Abitz, R.J., Belski, D.S., Clark, J.B., Crawley, M.E., and Martin, M.L. 1991a. Brine Sampling and Evaluation Program, 1989 Report. DOE-WIPP-91-009. Carlsbad, NM: Westinghouse Electric Corporation.

INTRODUCTION, p 1-1;

" The Waste Isolation Pilot Plant (WIPP) project is a Department of Energy (DOE) research and development facility established to demonstrate the safe disposal of defense generated radioactive wastes in the United States. The WIPP Project's mission consists of two parts: (1) to demonstrate the safe handling and disposal of transuranic (TRU) waste in bedded salt, and to create a research facility for in situ examination of the technical issues related to the emplacement of defense related radioactive waste in bedded salt.

The WIPP facility is located approximately 42 kilometers east of Carlsbad, New Mexico (Figure 1-1). The underground portion of the facility is located approximately 655 meters below the surface in the Salado Formation, an evaporite sequence over 1000 m thick (Figure 1-3). An extensive program of site characterization and validation has been conducted for the past 13 years (1976-1989). Initial studies are summarized in the WIPP 'Geological Site Characterization Report' (Powers and others, 1989) and the WIPP 'Preliminary Design Validation Report' (Bechtel National, Inc., 1983). Additional site investigations are being conducted as part of an ongoing program to refine the understanding of the site-specific geology. The hydrogeological activities of the Brine Sampling and Evaluation Program (BSEP) are part of these investigations.

The purpose of the BSEP is to investigate the origin, hydraulic characteristics, extent, and composition of brine in the Salado Formation excavations at the WIPP repository horizon. Although the repository horizon is considered dry, brine is observed to weep from exposed surfaces and seep into drillholes placed in the underground excavations. Brine studies began in 1982 as part of the Site Validation Program (Black and others, 1983), and was formalized in 1985 (Morse and Hassinger, 1985). The data presented in this report are an update of studies previously reported (Deal and Case, 1987; Deal and others, 1987; Deal and others, 1989). To facilitate a better understanding of the presented data, readers should consult those previous reports. Detailed descriptions of the data gathering and analytical procedures, and the cautions that should be exercised when using the data presented herein are given in these earlier reports.

Activities in 1989 provide information on the amount of brine that flows into the underground (Section 2.0), the geochemical properties of the brine (Section 3.0), and the hydrologic properties of the zone of macrofractures that develop beneath the excavations as those excavations age (Section 4.0). Other than Section 4.0, this report is an update of the 1988 Brine Sampling and Evaluation Program report (Deal and others, 1989) and further substantiates the observations and conclusions therein.

This report constitutes a permanent quality assurance record and will be retained as such as provided for in the quality assurance sections of the geotechnical Engineering Program plans and procedures."

Deal, D.E., Abitz, R.J., Myers, J., Case, J.B., Martin, M.L., Roggenthen, W.M., and Belski, D.S. 1991b. Brine Sampling and Evaluation Program 1990 Report. DOE-WIPP 91-036. Prepared for U.S. Department of Energy by IT Corporation and Westinghouse Electric Corporation. Westinghouse Electric Corporation, Waste Isolation Division, Carlsbad, NM.

EXECUTIVE SUMMARY, p XV;

" The data presented in this report are the result of Brine Sampling and Evaluation Program (BSEP) activities at the Waste Isolation Pilot Plant (WIPP) during 1990. When excavations began in 1982, small brine seepages (weeps) were observed on the walls. These brine occurrences were initially described as part of the Site Validation Program. Brine studies were formalized in 1985. The BSEP activities document and investigate the origins, hydraulic characteristics, extent, and composition of brine occurrences in the Permian Salado Formation and seepage of that brine into the excavations at the WIPP. The brine chemistry is important because it assists in understanding the origin of the brine and because it may affect possible chemical reactions in the buried waste after sealing the repository. The volume of brine and the hydrologic system that drives the brine seepage also need to be understood to assess the long-term performance of the repository.

After more than eight years of observations (1982-1990), no credible evidence exists to indicate that enough naturally occurring brine will seep into the WIPP excavations to be of practical concern. The detailed observations and analyses summarized herein and in previous BSEP reports confirm the evidence apparent during casual visits to the underground workings--that the excavations are remarkably dry."

4.2.3 Model Input Parameters, p. 4-4, para. 4, second line;

" A determination was made of the moisture content of the Salado salt at the WIPP (Deal and others, 1989) that showed that the facility horizon is about 1.56 percent brine by volume (0.6 percent by weight), which must occupy that much pore space."

5.2 Origin of the Brine, p. 5-3, para. 2, 7th line;

" Estimates of the amount of fluid-inclusion brine range from 0.22 weight percent (Black and others, 1983) to 0.6 weight percent (Stein, 1985) and are clearly a minor portion of the WIPP host rocks."

5.7 Further Investigations, p. 5-13, para 3, first bullet;

" Clay samples have been collected from the WIPP underground and are being subjected to laboratory testing. Preliminary results indicate that the clay is quite wet and may contain 20 percent or more by volume. After quantification, this work will be reported in the BSEP 1991 annual report. ..."

DOE (U.S. Department of Energy), 1980. Final Environmental Impact Statement, Waste Isolation Pilot Plant, DOE/EIS-0026, Vols. 1 and 2, Office of Environmental Restoration and Waste Management, Washington, D.C.

p 1-2, Section 1.2.1 1980 WIPP FEIS

" The 1980 WIPP Final Environmental Impact statement (FEIS) and the associated public review and comment period provided environmental input for the DOE's initial decision to proceed with the WIPP (DOE, 1980). The significance of impacts associated with the various alternatives was assessed. For the selected alternative, a two-phased approach to development was proposed: 1) a site and preliminary design validation (SPDV) program, as discussed in Subsection 8.2.1 of the FEIS, and 2) full construction, as discussed in FEIS Subsection 8.2.2. The durations of key WIPP activities are shown in Figure 1.1.

The 1980 FEIS presented an analysis of the environmental impacts of a number of alternatives for demonstrating the safe disposal of TRU waste. The alternatives considered include:

- Alternative 1. No action. A research and development facility to demonstrate safe disposal of TRU waste would not be developed and post-1970 TRU waste would continue to be retrievably stored.

- Alternative 2. Developing the WIPP at the Los Medanos site in southeastern New Mexico.

- Alternative 3. Disposing of stored TRU waste in the first available repository for high-level radioactive waste.

- Alternative 4. Delaying a decision on the site for a WIPP until at least 1984 to allow for investigation of alternative sites.

Alternative methods and geologic media for TRU waste disposal were also considered but rejected in the FEIS. The alternative methods included burial in deep ocean sediments, emplacement in deep drillholes, transmutation, and ejection into space. The alternative geologic media included igneous, volcanic, and argillaceous rocks.

The DOE's Record of Decision, published January 28, 1981 (46 FR 9162), announced the DOE's selection of Alternative 2: to proceed with the phased development of the WIPP at the Los Medanos site in southeastern New Mexico. . . ."

Volume 1, Section 1.3 The Los Medanos Site, p 1-3, para 5, line 1;

" The site is in the north-central part of the Delaware basin, a region in which evaporation in a shallow sea deposited about 3600 feet of evaporites during the Permian period 280 to 225 million years ago. A repository at this site would be built in nearly pure salt in the Salado Formation, itself almost 2000 feet thick, with a mined disposal level 2150 feet below the surface."

Volume I, Section 7.1.1, Climate, p. 7-3;

" The climate of the region is semiarid, with generally mild temperatures, low precipitation and humidity, and a high evaporation rate. Winds are mostly from the southeast and moderate. In late winter and spring, there are strong west winds and dust storms. During the winter, the weather is often dominated by a high-pressure system situated in the central portion of the Western United States and a low-pressure system located in north-central Mexico. During the summer, the region is affected by a low-pressure system normally situated over Arizona.

Temperatures are moderate throughout the year, although seasonal changes are distinct. Mean annual temperatures in southeastern New Mexico are near 60°F (Eagleman, 1976). In the winter (December through February) nighttime lows average near 23°F and average maximums are in the 50s. The lowest recorded temperature at the nearest class A weather station in Roswell was -29°F, in February 1905. In the summer (June through August), the daytime temperature exceeds 90°F approximately 75% of the time. The highest recorded temperature at Roswell was 110°F, in July 1958.

Precipitation is light and unevenly distributed throughout the year, averaging 11 to 13 inches. Winter is the season of least precipitation, averaging less than 0.6 inch of rainfall per month. Snow averages about 5 inches per year at the site and seldom remains on the ground for more than a day at a time because of the typically above-freezing temperatures in the afternoon. Approximately half the annual precipitation comes from frequent thunderstorms in June through September. Rains are usually brief but occasionally intense when moisture from the Gulf of Mexico spreads over the region."

Volume I, Section 7.1.3, Aquatic Ecology, p. 7-9, para. 4;

" The combination of high salinity, elevated concentrations of heavy metals, and salt-tolerant and marine fauna makes the lower Pecos a unique river system."

Volume 1, Section 7.3.1 Summary, p 7-17, para 7, line 1;

" Analysis of risk from vibratory ground motion at the surface shows that the greatest ground acceleration expected to occur once in 1000 and 10,000 years are less than or equal to 0.06g and 0.1g, respectively. The probabilities of higher values depend mainly on assumptions about the seismic potential of the area near the site."

Volume 1, Section 7.3.2, Regional Geology, p. 7-21, para. 8;

"Physiography and geomorphology

The WIPP site is in the Pecos Valley section of the southern Great Plains physiographic province, a broad highland belt sloping gently eastward from the Rocky Mountains and the Basin and Range province to the Central Lowlands province (Figure 7-10). The Pecos Valley section itself is dominated by the Pecos River Valley, a long north-south trough 5 to 30 miles wide and as much as 1000 feet deep in the north. The valley has an uneven rock- and alluvium-covered floor with widespread solution-subsidence features, the result of dissolution in the underlying Upper Permian rocks. The terrain varies from plains and lowlands to rugged canyonlands, including such erosional features as scarps, cuestas, terraces, and mesas. The surface slopes gently eastward, reflecting the underlying rock strata. Elevations range from more than 6000 feet in the northwest to about 2000 feet in the south (Powers et al., 1978, pp. 3-3ff).

The Pecos Valley section is bordered on the east by the Llano Estacado, a virtually uneroded plain formed by river action. The Llano Estacado is part of the High Plains section of the Great Plains physiographic province. Few and minor topographic features are present in the High Plains section, formed when more than 500 feet of Tertiary silts, gravels, and sands were laid down in alluvial fans by streams draining the Rocky Mountains. In many areas the nearly flat surface is cemented by a hard caliche layer.

To the west of the Pecos Valley section are the Sacramento and the Guadalupe Mountains, part of the Sacramento section of the Basin and Range province. The Capitan escarpment along the southeastern side of the Guadalupe Mountains marks the boundary between the Basin and Range and the Great Plains provinces. The Sacramento section has large basinal areas and a series of intervening mountain ranges.

The main geomorphic features bearing on the region are the Pecos River drainage system, the Mescalero plain, a karst terrain, and wind-erosion 'blowouts.' The Pecos River system has evolved from the south, cutting headward through the Ogallala sediments and becoming entrenched sometime after the middle Pleistocene. It receives almost all the surface and subsurface drainage of the region; most of its tributaries are intermittent because of the semiarid climate. Most of the ground surface east of the Pecos River Valley lies in the Llano Estacado, a poorly drained eastward-sloping surface covered by gravels, wind-blown sand, and caliche that has developed since early to middle Pleistocene time. The surface locally has a karst terrain containing superficial sinkholes, dolines, and solution-subsidence troughs, from both surface erosion and subsurface dissolution. The site lies near a caliche- and sand-covered drainage divide separating two major and actively developing solution-erosion features: Nash Draw to the west and San Simon Swale to the east."

7.3.6 Seismology, p 7-48;

" The purpose of the seismic studies is to build a basis from which to predict the ground motions that the WIPP repository might be subjected to both in the near and in the distant future. The concern about seismic effects in the near future, during the operational period, pertains mainly to the design requirements for surface and underground structures to withstand levels of ground motion much greater than those expected during this period. The concern about effects occurring over the long term, after the repository has been decommissioned and sealed, pertains more to relative motions (faulting) within the repository and possible effects on the integrity of the salt beds and/or shaft seals.

In this discussion, all intensities are based on the modified Mercalli intensity scale (Wood and Neuman, 1931). Most of the magnitudes were determined by the New Mexico Institute of Mining and Technology or described in the Geological Characterization Report

(Powers et al., 1978, pp. 5-10ff).

Seismic history

Seismic data are presented here in two time frames, before and after the time when seismograph data for the region became available.

The earthquake record in southern New Mexico dates back only to 1923, and seismic instruments have been in place in the State only since 1961. Sanford and Toppozada (1974) have examined various records to determine the seismic history of the area within 180 miles of the site. Their results for the period before 1961 are given in Table 7-3. With the exception of the weak shock in 1926 at Hope, New Mexico, and the shocks in 1936 and 1949 felt at Carlsbad, all known shocks before 1961 occurred to the west and southwest of the site and more than 100 miles away.

Since 1961, instrumental coverage has become comprehensive enough to locate most of the moderately strong earthquakes (local magnitude >3.5) in the region. Instrumentally determined shocks that occurred within 180 miles of the site since 1961 are listed in Table 7-4 and shown in Figure 7-21. Their distribution may be biased by the fact that seismic stations were more numerous and were in operation for longer periods north and west of the site.

Except for the activity southeast of the site, the distribution of epicenters since 1961 differs little from that of shocks before that time. There are two clusters, one associated with the Rio Grande Rift on the Texas-Chihuahua border and another associated with the Central Basin platform in Texas near the southeastern corner of New Mexico. This latter activity was not reported before 1964. It is not clear from the record whether earthquakes were occurring in the Central Basin platform before 1964, although local historical societies and newspapers tend to confirm their absence before that time.

A station operated for 10 months at Fort Stockton, Texas, indicated many small shocks from the Central Basin platform. Activity was observed at the time the station opened on June 21, 1964. Shurbet (1969) suggested that this activity is related to the injection of water underground for oil recovery. The suggestion has merit in that the Central Basin platform is an old structure (Early Permian), with no surface indication of having been rejuvenated, and in that enormous quantities of water have been injected. In one of the oil fields, the Ward-Estes North operated by the Gulf Oil Corporation, the cumulative total of water injected up to 1970 was over 1 billion barrels. Accounting for 42% of the water injected in Ward and Winkler Counties, Texas, the quantity is three times the total injected in all the oil fields of southeastern New Mexico in the same period. The known hydrocarbon resources nearest the site are two gas wells approximately 3 miles to the southwest of the center of the site. Water injection has not been used in this region to stimulate gas production. The nearest oil fields in the Delaware basin, where secondary recovery might be attempted, are 7 miles from the site. Water-injection operations would be prohibited within the site during the period of administrative control. After the closing of the repository, seismicity induced by water injection would not produce enough ground displacement to jeopardize the repository.

The strongest earthquake on record within 180 miles of the site was the Valentine, Texas, earthquake of August 16, 1931 (event 4 in Table 7-3). Coffman and von Hake (1973) estimate it to have been of magnitude 6.4 (modified Mercalli intensity of VIII). The Valentine earthquake was 130 miles southwest of the site. Its modified Mercalli intensity at the site is estimated to have been V; this is believed to be the highest intensity felt at the site in this century.

In 1887, a major earthquake occurred in northeast Sonora, Mexico. Although about 335 miles west-southwest of the site, it is indicative of the size of earthquakes possible in the eastern portion of the Basin and Range province, west of the province containing the site. Sanford and Toppozada (1974) estimate its magnitude to have been 7.8, and Coffman and von Hake (1973) list it as VIII-IX in modified Mercalli intensity. It was felt over an area of 0.5 million square miles (as far as Santa Fe to the north and Mexico City to the south); fault displacements near the epicenter were as large as 26 feet (Aguilera, 1920).

Local observations

From April 1974 to October 1978, 420 events identifiable as local and regional earthquakes (within about 210 miles) were recorded by a station (CLN) 4 miles from the center of the site (see Appendix J). For 159 of the 420 events, the epicenters were identified and magnitudes determined (Table 7-4). Nine tentative locations were also determined. These seismic patterns are similar to those of the preinstrumental data.

Local earthquakes. Any seismic activity at or near the site is of great interest. Three events (July 26, 1972; November 28, 1974; and January 19, 1978) have been instrumentally recorded within 35 miles of the WIPP site. Seismic events become more numerous with distance.

The nearest event to the WIPP site occurred on January 19, 1978, about 10 miles northeast of station CLN. its magnitude was 2.3, and the event does not appear to have been related to human activity.

The other two nearby events (July 26, 1972, and November 28, 1974) had magnitudes of 2.8 and 3.6, respectively, and both were about 25 miles to the northwest. At both times, rockfalls and ground cracking were reported at an active potash mine. To determine whether the two epicenters coincided. They were about 6 miles apart. Thus the two events cannot both have been caused by the mine. Moreover, the earthquake had too much energy to have been caused by the rockfall. In the absence of additional seismic data on these events, seismic risk at the site should be estimated on the assumption that both were natural (Caravella and Sanford, 1977).

Seismic risk

Maps of the position and intensity of recorded earthquakes are useful in evaluating the probability of an earthquake at a given site. To increase their usefulness, the historical data have been supplemented with field geologic data.

Several researchers have divided the United States into zones of earthquake risk. The standard estimate is that of Algermissen (1969). According to this estimate, the site is located in seismic risk zone 1, where only minor damage to structures is to be expected, corresponding to a modified Mercalli intensity of V to VI. Earlier, Richter (1959) had placed the region within a seismic zone where the probable maximum intensity would be VIII. Sanford and Toppozada (1974) considered the site to be either on the boundary of zones 2 and 3 or within zone 2, depending on whether earthquakes in the Central Basin platform are found to be natural or induced by human activity.

One desires not only an estimate of the largest seismic motions possible at a site but also an estimate of their probability. Such an estimate has been made for the WIPP site, starting with an analysis of the recurrence rates of earthquakes in nearby active areas.

Earthquakes in the Central Basin platform. The Central Basin platform is a structural feature less than 30 miles east of the site, adjacent to the Delaware basin. Instrumental studies have shown the Central Basin platform to be much more active than would be expected from its stable tectonic setting. Primarily for this reason, a seismographic station array was established in Kermit, Texas, late 1975. During the period from November 1975 to July 1977, 407 local events were detected and 135 located with array data.

The Central Basin platform has been active since at least mid-1964. It has been the most active seismic area within 180 miles of the site in the number of events, but not in magnitude of events. The data imply that seismic activity is equally likely to occur anywhere along the Central Basin platform, without any clear relationship to small-scale structural details such as pre-Permian buried faults. Attempts have been made to relate this seismicity to the injection of water for the recovery of oil. Such a relationship has not been unequivocally established, but the lack of evidence for a tectonic origin suggests this correlation.

Sanford et al. (1978) calculated the apparent recurrence rates for earthquakes on the Central Basin platform. The distribution of minor shocks implied a recurrence rate of every 10,000 years for earthquakes of the size of the 1887 Sonoran event. There is no evidence that such earthquakes have occurred (fault scarps 25 miles long would be expected from shallow quakes such as these, with displacements of perhaps 10 feet; they are not found). To explain this discrepancy, three possible explanations have been advanced:

1. Crustal movement has only recently resumed on the Central Basin platform.
2. The structure of the Central Basin platform imposes a limit on the possible magnitude of earthquakes.
3. The minor shocks observed were caused by human activity.

The first explanation may not be absolutely discarded. However, it is extremely unlikely that a structure such as the Central Basin platform, which has exhibited no tectonic movement for about 200 million years, should be tectonically reactivated so recently that no surface manifestations are observed. The calculated recurrence rates previously discussed indicate a large event every 10,000 years; no surficial evidence has been found to confirm such events. The first explanation is not reasonable given the information now available. The third explanation, which seems best supported by the evidence, means that the seismic activity in the Central Basin platform is not natural and should be not be used for assessing tectonic stability over the long term. The second explanation is used for assessing tectonic stability over the long term. The second explanation is used in the analysis presented here. It is more conservative in that it assumes natural causes (which is probably not the case), but with an upper limit to the magnitude of an earthquake on the Central Basin platform. This assumption would be consistent with natural earthquakes in a region where the geology does not indicate large recent events.

The method of Cornell (1968) was used to estimate seismic risk at the site (Powers et al., 1978, pp.5-32ff). Three source regions suggested by Algermissen and Perkins (1976) were used: the Rio Grande rift, the Central Basin platform, and the remainder of the area within 180 miles of the WIPP site (site source zone). The analysis used Sanford's recurrence relationships (Sanford et al., 1976, 1978). On the basis of the earthquake of 1887, an upper limit of 7.5 was set on the magnitude of earthquakes in the Rio Grande rift.* On the basis of the largest earthquake observed so far (magnitude 3.2) and considering the uncertainties in causative mechanisms, the upper magnitude limit for the Central Basin platform was set at 5 and 6 in separate calculations. The largest earthquake so far observed in the remaining region (the site source zone) was of magnitude 3.6; from this, and from the absence of any indication of Holocene local faulting, the upper magnitude limit for the site region was set at 4.5 and 5 in separate calculations. The depth of earthquakes in the site source zone was assumed to be 3 miles.

The Cornell method expresses seismic risk as the probability per year that a specific acceleration will be reached or exceeded. The probabilities calculated for the WIPP site are shown in Figure 7-22.

Figure 7-22 shows the separate contributions to these totals of each of the three sources regions with each of the assumed upper magnitude limits. The contribution of the Rio Grande rift source zone to the total seismic risk at the site is small at all acceleration levels. Curves A and B and curves C and D indicate the total combined acceleration for the various combinations of upper magnitude limits indicated above.

From Figure 7-22 the accelerations that would be experienced at the site from earthquakes in the three source zones separately are as follows for two levels of probability:

Source zone	Upper limit magnitude	Acceleration g for probability (per year) 10^{-8}	10^{-6}
Rio Grande rift	7.5	0.14	0.09
Central Basin platform	6.0	0.17	0.15
Central Basin platform	5.0	0.07	0.07
Site source zone	5.0	>0.3	0.23
Site source zone	4.5	0.21	0.17

The total seismic risk is controlled by earthquake probabilities in one of these source zones, depending on the acceleration level considered. The relationships are shown below.

	Upper limit magnitude		Controlling zone	
Rio Grande rift	Central Basin platform(CBP)	Site source zone (SSZ)	High acceleration	Low acceleration
7.5	5	4.5	SSZ	SSZ
7.5	6	4.5	SSZ	CBP
7.5	5	5.0	SSZ	SSZ
7.5	6	5.0	SSZ	CBP

Thus assumptions about the seismic properties of the area around and beneath the site (site source zone) are important in estimating seismic accelerations at the WIPP site and the potential for faulting through the repository after its closure. The possibility of faulting at the site of a magnitude that could significantly affect its integrity is extremely low."

7.3.7 Energy and Mineral Resources, page 7-64, para 6;
"Methods used to determine potash reserves at the WIPP site

Two separate studies were conducted for the DOE by the U.S. Bureau of Mines (USBM, 1977) and Agricultural and Industrial Minerals, Inc. (AIM, 1979) to determine what portion of the potash resources at the WIPP site is economic and may be considered to be reserves. Both studies started with the basic grade and thickness data provided by the USGS, and the USBM study was available for use by AIM. However, the two studies used different concepts for the development of the potash reserves and evaluated processing difficulties independently. The AIM approach, which may more nearly resemble the perspective of a potash operator, results in lower reserve estimates. However, because estimates of reserves and the associated economics are subject to uncertainty and because the USBM report gives a higher estimate of reserves, most table presented here will use USBM reserve estimates. The AIM report also estimated potash resources in the Carlsbad district and in the United States to allow comparison with the WIPP-site resources, and their values will be used in these comparisons. It should also be noted that local potash operators question the economic feasibility of mining the WIPP reserves.*

The USBM method of determining to what extent the deposits could be profitably mined and thus considered reserves consisted of designing conceptual models for exploiting the deposits. Models ranged from new mines and refineries to mines that merely send the new ore to existing refineries. Shaft locations were selected to minimize underground development and allow the richest ore beds to be mined first. The latter is important to the quick recovery of invested capital.

Costs were either estimated or, when available, matched to known cost experience at nearby mines. All costs, including construction, were used in discounted cash-flow analysis to determine the market price for refined products guaranteeing a 15% rate of return on invested capital. Federal, State, and local taxes and royalties were taken into account.

In all, the USBM prepared 12 different conceptual plans (which it has termed mining units) for exploiting the potash deposits in the WIPP site. Of these, eight were fully evaluated and four discarded because of complex problems related to the enrichment of raw ore.

Results of the potash-reserve determination

The full findings of the reserve evaluation have been reported (USBM, 1977; AIM, 1979), and the USBM estimates are summarized in Table 7-8. The eight mining units that were conceived and then costed are listed in the approximate order in which they would rank as potentially minable. Only the 48.46 million tons in mining units B-1 (Figure 7-25) within the site were classified as reserves by the USBM study. This is much less than would be classified as reserves by the USGS. The USGS used the potash grade and thickness parameters of the most efficient producers in the district. These minimum ore standards, excluding all other minability parameters, include all material in the WIPP site with a minimum cutoff grade of 4% K_2O as langbeinite or 10% K_2O as sylvite in a thickness of 4 feet.

The USBM used criteria consistent with industry practice in preparing economic-feasibility studies. In calculating potash-ore reserves, it used a method based on engineering design and economic-analysis procedures, including discounted cash flow, to determine the tonnage of minable potash ore that will yield a 15% rate of return on the total capital investment. Only economically recoverable ore is included in the USBM reserve estimates.

Under the USBM criteria, only mining unit B-1 meets the 1977 market prices current at the time of the study: \$42 per ton of muriate, \$84 per ton of "sulfate" (K_2SO_4), and \$48 per ton of langbeinite. This particular reserve consists of langbeinite, mostly in ore bed 4 in the northern portion of the site. (Restriction of mining within the WIPP site would not render uneconomic the remainder of mining unit B-1 outside the site.)

Unit A-1 does not meet the market-price requirements; however, the market price of muriate has exceeded \$52 per ton in the recent past, at which point the A-1 deposit would be considered a marginal, or "nearly economic," deposit. (Average market prices for October 1979 were \$58.37 per ton of muriate, \$42-44 per ton of langbeinite, and \$56.14 per ton of all sulfate products: USGS Conservation Division, Monthly Mining Report, Roswell, New Mexico.) The A-1 deposit consists of sylvite contained in ore bed 10 and located on the west side of the site.

Methods used to determine the hydrocarbon resources at the WIPP site

The New Mexico Bureau of Mines and Mineral Resources (NMBM&MR) conducted hydrocarbon-resource study in southeastern New Mexico under contract to the Oak Ridge National Laboratory (Foster, 1974). The study included an area of 1512 square miles (Figure 7-26). At the time of that study, the proposed repository site was about 5 miles northeast of the current site. The NMBM&MR evaluation included a more detailed study of a four-township area centered on the old site; the present site is in the southwest quadrant of that area (Figure 7-26).

The resource evaluation was based both on the known reserves of crude oil and natural gas in the region and on the probability of discovering new reservoirs in areas where past unsuccessful wildcat drilling was either too widely spread or too shallow to have allowed discovery. All potentially productive zones were considered in the evaluation; therefore, the findings may be used for determining the total hydrocarbon resources at the site. A fundamental assumption in this study is that the WIPP area has the same potential for containing hydrocarbons as the much larger region in which the study was conducted and for which exploration data are available. Whether such resources actually exist can be satisfactorily established only by drilling at spacings close enough to give a high probability of discovery.

Results of the hydrocarbon-resource evaluation

Table 7-9 summarizes the findings of the NMBM&MR hydrocarbon evaluation as the potential resource of hydrocarbons that probably exist under a square mile (640 acres) with the typical geologic and stratigraphic section of that region. The New Mexico Bureau of Mines and Mineral Resources examined an area of 967,680 acres (1512 square miles). The hydrocarbon resources under the site are then estimated as the proportion of the total in the 29.625 square miles of the site (Table 7-10).

The hydrocarbon-resource quantities given in Table 7-10 are equivalent to potash-resource-quantity estimates in that both relate to the quantity of what is present, and not to its economic value or recoverability. Because the hydrocarbon-resource evaluation relies on statistical probability, it is not as accurate as the potash-resource evaluation. The potash resources were actually drilled and assayed, while the hydrocarbon resources were estimated by projecting historical drilling success into an untested area. Site-selection requirements dictated that the inner zones be free of deep holes (i.e., oil and gas test holes)."

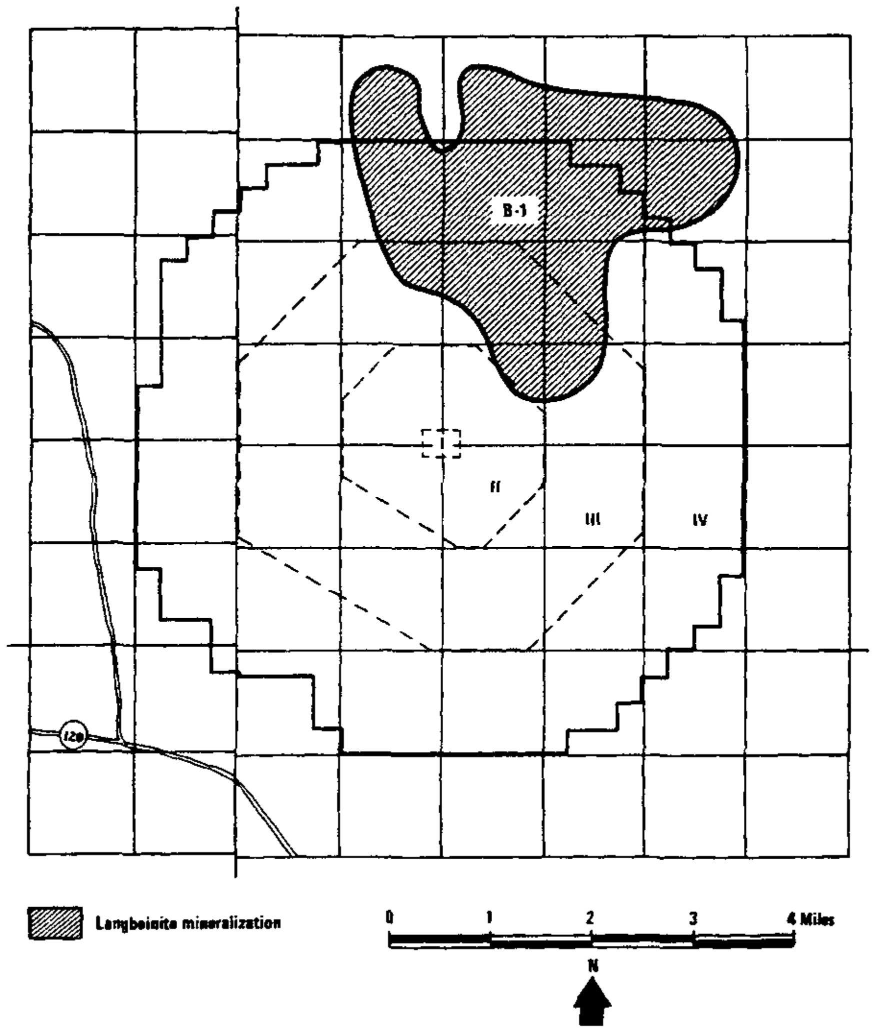


Figure 7-25. Economic langbeinite mineralization in mining unit B-1. (After USBM, 1977).

7.4.1 Surface-Water Hydrology, p 7-79, para 4;

" The maximum recorded flood on the Pecos River near Malaga occurred on August 23, 1966, with a discharge of 120,000 cubic feet per second (cfs) and a stage elevation of about 2938 feet above mean sea level (USGS Station No. 08406500). The minimum surface elevation of the WIPP site is approximately 300 feet above the elevation of this maximum historical flood elevation."

7.4.1 Surface-Water Hydrology, p 7-80, para 2;

" More than 90% of the mean annual precipitation at the site is lost by evapotranspiration. Table 7-15 shows the mean monthly temperature at Artesia, the mean monthly pan evaporation at Lake Avalon, and the mean monthly rainfall at Carlsbad. On a mean monthly basis, evapotranspiration at the site greatly exceeds the available rainfall; however, intense local thunderstorms may produce runoff and percolation. Water-infiltration rates in the local sand dunes are probably similar to the 1.6-inch-per-hour intake rate of Harkey sandy loam (75% sand) near Carlsbad (Blaney and Hanson, 1965)."

7.4.1 Surface-Water Hydrology, Local surface-water hydrology,p 7-83, para 1;
" The drainage area of the Pecos River at this location is 19,000 square miles (Figure 7-29). A few small creeks and draws are the only westward-flowing tributaries of the Pecos River within 20 miles north or south of the site. (A low-flow investigation has been initiated by the USGS within the Hill Tank Draw drainage area, the most prominent drainage feature near the WIPP site. The drainage area is about 4 square miles, with an average channel slope of 1 to 100, and the drainage is westward into Nash Draw. Two years of observations showed only four flow events. The USGS estimates that the flow rate for these events was under 2 cubic feet per second.) The Black River (drainage area 400 square miles) joins the Pecos from the west about 16 miles southwest of the site. The Delaware River (drainage area 700 square miles) and a number of small creeks and draws also join the Pecos along this reach. The flow in the Pecos River below Fort Sumner is regulated by storage in Lake Sumner, Lake McMillan, Lake Avalon, and several other smaller irrigation dams."

8.7.5 Airborne Effluents, p 8-36, para 3;
"<u>Emissions from fuel combustion</u>

There will be three principal sources of emissions from the combustion of diesel fuel: the emergency-power system, the surface handling equipment, and the underground handling equipment. In addition, an oil-fired drier may be required to dry the salt stored on the surface for backfilling the repository. Table 8-9 shows the calculated annual emissions. The calculations were based on emission factors published by the U.S. Environmental Protection Agency (EPA, 1977) and on the following assumptions: The emergency-power diesel-generator plant, with an installed capacity of about 10,000 horsepower, will be used 1% of the time (88 hours per year). The diesel-powered surface handling equipment (about 3400 horsepower) will be used about 10% of the time during one work shift each day. The underground salt-handling equipment (about 560 horsepower) will be used about 40% of the time during one work shift each day. The salt drier (approximately 30 million Btu per hour, using about 800,000 gallons of fuel per year) will be used during one work shift each day after mining has ceased."

Table 8-9. Estimated Annual Emissions from the Combustion of Diesel Fuel[a]

Pollutant	EPA emission factor (g/hp-hr)	Total (lb/yr)
	EMERGENCY POWER PLANT	
Carbon monoxide	3.03	5,870
Hydrocarbons	1.12	2,170
Nitrogen oxides	14.00	27,100
Sulfur dioxide	0.93	1,800
Particulates	1.00	1,940
	SURFACE HANDLING EQUIPMENT[b]	
Carbon monoxide	2.62	5,730
Hydrocarbons	0.85	1,860
Nitrogen oxides	14.9	32,600
Sulfur dioxide	0.89	1,950
Particulates	0.78	1,710
	UNDERGROUND HANDLING EQUIPMENT[b]	
Carbon monoxide	2.62	3,780
Hydrocarbons	0.85	1,220
Nitrogen oxides	14.9	21,500
Sulfur dioxide	0.89	1,280
Particulates	0.78	1,120
	MINED-SALT DRIER[c]	
Carbon monoxide	5.0[d]	4,000
Hydrocarbons	1.0[d]	800
Nitrogen oxides	22.0[d]	17,600
Sulfur dioxide	71.0[d]	56,800
Sulfur trioxide	1.0[d]	800
Particulates	2.0[d]	1,600

[a]Based on factors published by the EPA (1977).
[b]Emission rates based on one 8-hour work shift per day.
[c]Emission rates based on one 8-hour work shift per day after mining has ceased or decommissioning decision has been made.
[d]Units of pounds per 1 thousand gallons of fuel consumed.

9.2.1 Biophysical Environment, p 9-14, para 3;

"Biological resources

Adverse impacts on biological resources are expected to be slight for the following reasons (Appendix H, Section H.5):

1. No proposed natural areas are present on or animals are known to inhabit the site or the vicinity of the site; nor are any critical habitats known to exist on or near the site.

2. No endangered species of plants or animals are known to inhabit the site or the vicinity of the site; nor are any critical habitats known to exist on or near the site.
3. Water requirements for the site are low.
4. The land contains soil types and vegetation associations that are common throughout the region.
5. Access in the form of dirt roads is already available throughout the area; therefore, recreational use of the area is not likely to increase significantly.

Planned mitigation measures (Section 9.6) will prevent unnecessary damage to plants and animals in areas that might be affected by fugitive dust and dispersed salt. The removal of land from rangeland habitats during construction will produce other effects on biological resources; the acreages to removed are listed in Table 9-1.

During the SPDV program and repository construction, a total of 49 and 192 acres, respectively, will be cleared of vegetation from the shinnery oak, senecio, sage-brush, yucca, mesquite, and broom snakeweed vegetation types. All vegetation and wildlife in this area will be removed for the duration of the project. Environmental studies conducted at nearby potash mines indicate that vegetation adjacent to the mined-rock (salt) pile will be reduced or eliminated (Appendix H, Section H.5). It is probable that, in small areas near the pile, enough material will be deposited to cause adverse effects, and some vegetation may be lost. However, a 1978 field examination around a mined-rock pile at the site of Project Gnome, an underground nuclear explosion carried out in 1961 9 miles from the WIPP site, found no identifiable salt-related stress on any of the vegetation in the area with the single exception of a mesquite tree growing on one end of the pile itself (Intera, 1978). There is thus some evidence that the local vegetation may be able to adapt to a more saline environment than it is now experiencing.

In addition to the areas that will be cleared of vegetation, 18 and 710 acres of existing vegetation will be disturbed, respectively, for rights-of-way corridors during the SPDV program and repository construction. For the complete repository, 112 acres of rights-of-way will be covered with roads and railroads (Table 9-1). Creosote bush may invade the roadway and railroad and thrive there, providing cover in these corridors. Much of the land cleared during construction will revert to natural vegetation. Although some of the removed plant species may remain absent from the rights-of-way for years, the impact is considered minor because the removed species are very common in the region.

Impacts on wildlife from construction can be classified as follows:

1. Direct mortality of nonmobile species, such as small and burrowing mammals, ground-nesting birds, reptiles, and insects.
2. Displacement of mobile species (including game species and birds) by the loss of habitat and human intrusion (visibility of people and increased noise levels).
3. Increased competition and stress among species in adjacent areas.
4. Direct loss of species from road kills and poaching.

No unique species or populations have been identified at the site, and the loss of individuals of the species present is not significant to the overall ecology of the site area.

The environmental impact of corridors has been studied by ecologists for a relatively short time, and concepts are still in the formative stages. A number of impacts can be expected from the construction of rights-of-way. Some raptor deaths may be caused by electrocution on utility lines, but the lines will be designed to minimize such occurrences (Bulletin 61-10 of the Rural Electrification Administration). Although some negative effects (increased animal mortality, inhibition of animal movements) should be expected when the roads are built, roadways often have a positive effect on local biota by increasing the diversity of habitats. Corridors provide habitat that may favor the establishment of small-mammal communities differing in composition from surrounding communities. Animals adapted to open areas may appear in the new communities, and transient species may be able to outcompete residents.

Right-of-way construction will frighten and displace the larger and more mobile wildlife inhabitants. This disturbance is attributed not only to habitat removal but also to an increase in the visibility of people and frequent sharp increases in ambient noise levels. The displaced species will migrate to adjacent undisturbed habitats and may temporarily cause an ecological imbalance or stress condition in local adjacent habitats, resulting in a loss of most of the displaced organisms. The highly mobile game species present at the site, the mule deer and the pronghorn, while displaced, are not expected to suffer any significant losses in their local population because the area of disturbance will be small when compared to the normally large ranges of these species. Bird populations, on the other hand, may benefit from right-of-way corridors (Anderson et al., 1977). The increased habitat diversity (the "edge effect") increases the densities of some bird species. Summer residents have sometimes increased in density at the apparent expense of year-round residents."

Table 9-14. Significance of the Resources and Reserves at the WIPP Site.

Deposit	WIPP site	Region	United States	World
RESOURCES[a]				
Sylvite (at lease grade)				
Quantity, millions tons ore	88.5	4260	8500	850,000
Percentage at WIPP site		2.1	1.0	0.010
High grade	54.0			
Low grade	133.2			
Langbeinite (at lease grade)				
Quantity, millions tons ore	264.2	1140	No estimate available	
Percentage at WIPP site		23		
High grade	77.6	(21.5		
Low grade	351.0	as K_2O)		
Crude oil				
Quantity, million barrels	37.50	1915	200,000	Not
Percentage at WIPP site		2.0	0.019	available
Natural gas				
Quantity, billion cubic feet	490	25,013	855,000	Not
Percentage at WIPP site		2.0	0.057	available
Distillate				
Quantity, million barrels	5.72	293	Not available	
Percentage at WIPP site		2.0		
RESERVES[b]				
Sylvite[c]				
Quantity, million tons K_2O	3.66	106	206	11,206
Percentage at WIPP site		3.4	1.8	0.033
Langbeinite[d]				
Quantity, Million tons K_2O	0.92[d]	9.3	9.3	Not
Percentage at WIPP site		10	10	available
Crude oil				
Quantity, million barrels	Nil	471.7	29,486	646,000
Percentage at WIPP site		0	0	0
Natural gas				
Quantity, billion cubic feet	44.62	3865	208,800	2,520,000
Percentage at WIPP site		1.15	0.021	0.0018
Distillate				
Quantity, million barrels	0.12	169.1	35,500	Not
Percentage at WIPP site		0.07	0.0003	available

[a]Data sources: Hydrocarbons, Foster (1974) for the site and region; potash salts, John et al. (1978) for the site and region; Brobst and Pratt (1973) for U.S. oil and gas and the world resources of sylvite.

[b]Data sources: Hydrocarbons, Keesey (1979) for the site, American Petroleum Institute (1978) for the region, the United States, and the world; potash salts, U.S. Bureau of Mines (USBM, 1977).

[c]The U.S. Bureau of Mines (USBM, 1977) does not consider any sylvite to be commercial today. However, one bed (mining unit A-1) of sylvite was marginal and has been added to the reserve list.

[d]Estimated from the AIM (1979) study. The USBM estimate for the WIPP site is 4.41 million tons K_2O equivalent, but no comparable USBM estimate is available for the entire district.

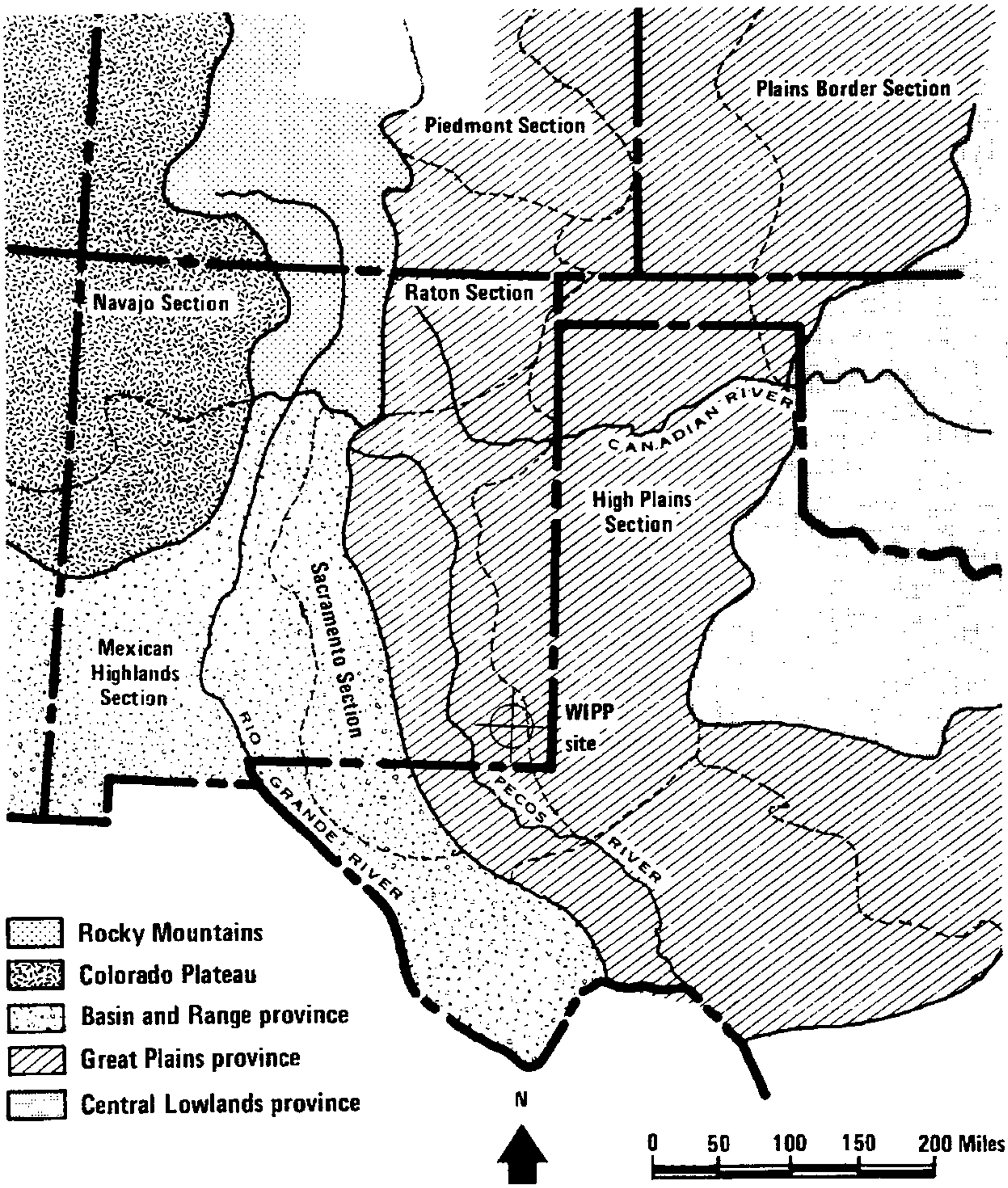
9.2.3.5 Significance of the Hydrocarbon Resources, p 9-26;

" Table 9-14 puts the hydrocarbon resources into perspective. While the quantities of hydrocarbons that may exist under the site are large, they account for only 2.0% of the crude oil, 2.0% of the natural gas, and 2.0% of the distillate that could exist in the region. (The region is here defined as the area studied by the New Mexico Bureau of Mines and Mineral Resources. That area contains 967,700 acres, or 1512 square miles, versus only 18,960 acres, or 29.625 square miles, for the site.) On a national basis, the expected crude oil at the site accounts for only 0.019% and natural gas for only 0.057% of U.S. resources."

Section 9.7.2.2 <u>Effects of Subsidence</u>, p 9-152, para 1,2, line 3;

" In Nash Draw subsidence on the order of 200 feet are suspected to have created vertical interconnections between water-bearing strata in the Rustler Formation. Hydrologic testing has not yet determined whether this is true, but the possibility remains that to a lesser extent, because of the smaller subsidence, interconnections may also appear over the repository. Water from the Magenta and the Culebra aquifers might then be introduced to the top of the Salado salt. That by itself would have little significance because of the 1200 feet of slat intervening between the top of the salt and the disposal level. At worst, pathways for water intrusion similar to those postulated in scenarios 2 or 4 (Section 9.7.1.3) might be initiated. It has been noted that the radiation doses produced as a consequence of these scenarios are much lower than doses from natural background radiation. Therefore subsidence, even when extrapolated to an extreme, would not significantly affect public health and safety. Furthermore, water has not flowed into the local potash mines in spite of much more severe subsidence than the repository will experience.

Investigations of subsidence continue. A first-order level-line survey line was laid out in 1978 to establish baseline elevations at the site and to monitor subsidence over certain active potash-mining operations. These field observations will help in developing a better understanding of the subsidence processes and in providing data for testing models. Other studies are now investigating the effects of subsidence on the surface, on the rock column and on the aquifers.".



Adapted from Fenneman (1931).

Figure 7-10. Physiographic provinces and sections.

Deal, D.E., Abitz, R.J., Myers, J., Martin, M.L., Milligan, D.J., Sobocinski, R.W., Lipponer, P.P.J., and Belski, D.S. 1993. Brine Sampling and Evaluation Program, 1991 Report. DOE-WIPP-93-026. Carlsbad, NM: Westinghouse Electric Corporation.

Executive Summary, para 2;

" During nine years of observations (1982-1991), evidence has mounted that the amount of brine seeping into the WIPP excavations is limited, local, and only a small fraction of that required to produce hydrogen gas by corroding the metal in the waste drums and waste inventory. The data through 1990 is discussed in detail and summarized by Deal and others (1991). The data presented in this report describes progress made during the calendar year 1991 and focuses on four major areas: (1) quantification of the amount of brine seeping across vertical surfaces in the WIPP excavations (brine weeps); (2) monitoring of brine inflow, e.g., measuring brines recovered from holes drilled downward from the underground drifts (downholes), upward from the underground drifts (upholes), and from subhorizontal holes; (3) further characterization of brine geochemistry; and (4) preliminary quantification of the amount of brine that might be released by squeezing the underconsolidated clays present in the Salado Formation."

Moisture Contents of Clay in the Salado Formation., p. x, Para. 1;

" Clay samples from the WIPP underground were tested in the laboratory to determine how much brine could be squeezed out of them if they were compacted under lithostatic loading. Approximately 25 to 29 percent brine by volume is available. Preliminary calculations indicate that there is enough brine available in the clay within a meter or two of the excavations to account for the observed brine weeps."

4.3.1. Brine Available from Clay Consolidation, p. 4-2, Para. 3;

" The assumption that moisture in the Salado Formation is associated with clays is made for the following reasons. The amount of moisture driven from the WIPP rock samples by heating to 95°C varies directly with the clay content (Deal and others, 1989, Section 4.1). Borehole conductivity studies (Deal and others, 1989, Section 4.2) also show a direct correlation between conductivity, clay content, and moisture, allowing moisture content to be calculated from conductivity. Observations in the WIPP excavations consistently record that patches of moisture often extend downward from the lithologic unites that have the most clay (Deal and others, 1991, Section 2.2.2)."

p. 4-4, Para. 1;

" The volumetric brine content of pure clay can be calculated using the following equation

$$\text{Volumetric Brine Content (\%)} = \text{Brine Mass (\%)} \times \frac{\text{Density of Clay}}{\text{Density of Brine}}$$

(after Hillel, 1980)

where

Brine mass = 12.35 percent
Brine density = 1.22
Range of clay density = 2.5 to 2.9.

The calculated volumetric brine contents of pure Salado clay is shown in Table 4-2, ranging between approximately 25 and 29 percent, with most likely values near 26 or 27 percent."

DOE (U.S. Department of Energy). 1995. Brine Sampling and Evaluation Program, 1992-1993 Report and Summary of BSEP Data Since 1982. DOE-WIPP-94-011, Carlsbad, NM: Westinghouse Electric Corporation.

NOTE: The above listed document was not available for inclusion in the Reference Expansion as of the printing date. Page changes will be provided as the above document becomes available for inclusion.

Domski, P.S., Upton, D.T., and Beauheim, R.L. 1996. Hydraulic Testing Around Room Q: Evaluation of the Effects of Mining on the Hydraulic Properties of Salado Evaporites. SAND96-0435. Sandia National Laboratories, Albuquerque, NM. WPO 37380.

ABSTRACT; p. 1, para. 1;

" Room Q is a 109-m-long cylindrical excavation in the Salado Formation at the Waste Isolation Pilot Plant (WIPP) site. Fifteen boreholes were drilled and instrumented around Room Q so that tests could be conducted to determine the effects of room excavation on the hydraulic properties of the surrounding evaporite rocks. Pressure-buildup and pressure-pulse tests were conducted in all of the boreholes before Room Q was mined. The data sets from only eight of the boreholes are adequate for parameter estimation, and five of those are of poor quality. Constant-pressure flow tests and pressure-buildup tests were conducted after Room Q was mined, producing eleven interpretable data sets, including two of poor quality. Pre-mining transmissivities interpreted from the three good-quality data sets ranged from 1 x 10^{-15} to 5 x $10^{-14} m^2/s$ (permeability-thickness products of 2 x 10^{-22} to 9 x $10^{-21} m^3$) for test intervals ranging in length from 0.85 to 1.37 m. Pre-mining average permeabilities, which can be considered representative of undisturbed, far-field conditions, were 6 x 10^{-20} and 8 x $10^{-20} m^2$ for anhydrite, and 3 x $10^{-22} m^2$ for halite. Post-mining transmissivities interpreted from the good-quality data sets ranged from 1 x 10^{-16} to 3 x $10^{-13} m^2/s$ (permeability-thickness products of 2 x 10^{-23} to 5 x $10^{-20} m^3$). Post-mining average permeabilities for anhydrite ranged from 8 x 10^{-20} to 1 x $10^{-19} m^2$. These values are thought to have been only slightly, if at all, affected by excavation of Room Q. Post-mining average permeabilities for halite ranged from 2 x 10^{-23} to 5 x $10^{-20} m^2$, and are thought to reflect varying degrees of excavation response. Pore pressures decreased by several MPa after mining at all boreholes for which reliable pre- and post-mining comparisons are possible, except for one borehole at which no change was observed. The changes in hydraulic properties and pore pressures that were observed can be attributed to one or a combination of three processes: stress reduction, changes in pore connectivity, and flow towards Room Q. the effects of the three processes cannot be individually quantified with the available data."

Eager, G.P. 1983. Core from the Lower Dewey Lake, Rustler, and Upper Salado Formation, Culberson County, Texas. In Permian Basin Cores, R.L. Shaw and B.J. Pollen, eds., P.B.S.-S.E.P.M. Core Workshop No. 2, pp. 273–283. Permian Basin Section, Society of Economic Paleontologists and Mineralogists, Midland, TX.

INTRODUCTION, p 273;

" Seven hundred and twenty feet of continuous Upper Permian core is displayed by Texasgulf, Inc. The formations cored include the lower portion of the Dewey Lake, the Rustler, and the upper portion of the Salado. This core was obtained by Texasgulf, Inc., as part of a sulphur exploration program. The depth of the core is from 37 feet to 757 feet. It is located in the SE¼, Section 5, PSL, Block 45 (12 miles southwest of Orla) Culberson County, Texas (Fig. 1). Gamma ray and neutron logs are included (Fig. 2) so that the lithology can be compared to the geophysical response. All depths are reported in feet.

The core is presented to give Delaware Basin geologists a 'hands-on' look at the strata that comprise the 'overburden' and troublesome drilling zones through which they must drill to reach the deeper oil-bearing horizons. The Rustler Formation may have reservoir potential."

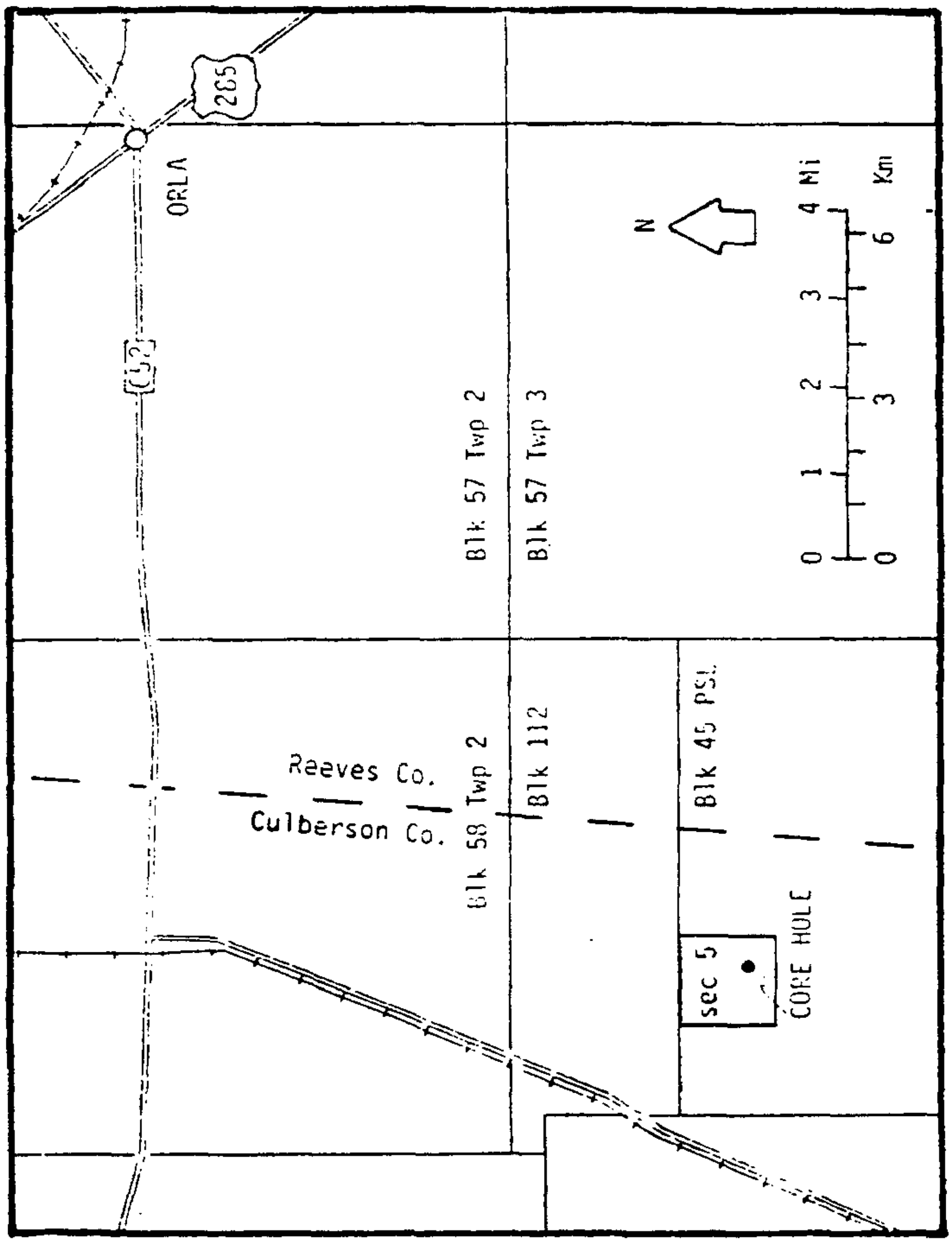
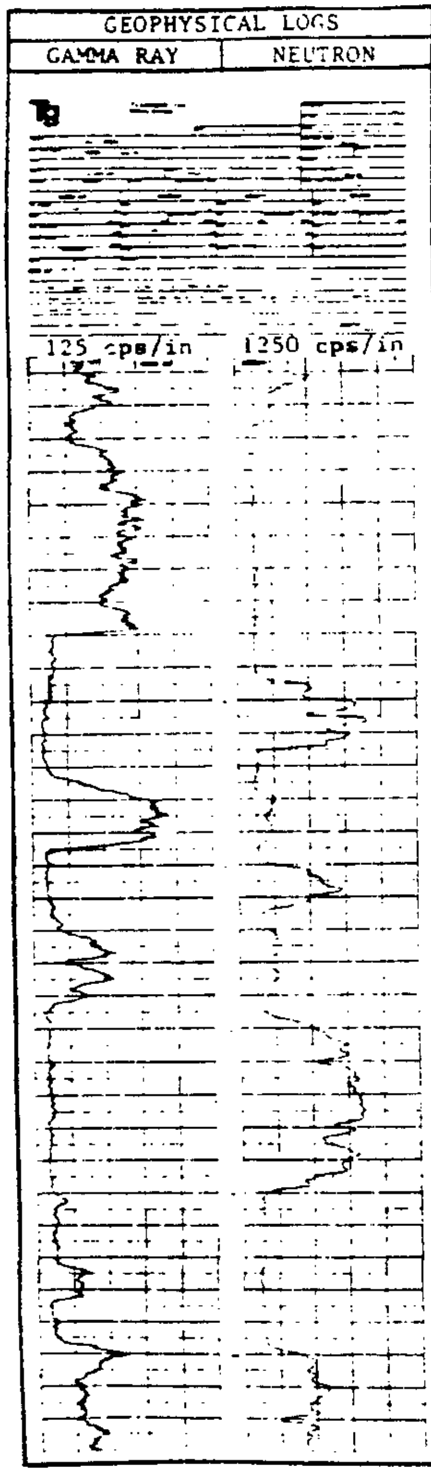


Figure 1.--Map showing the location of the Texasgulf Inc. sulphur core test.



FORMATION ABBREVIATIONS

Pdl	Permian Dewey Lake Formation
Prf	" Rustler Fm, Forty-niner Mbr
Prm	" " " Magenta Mbr
Prt	" " " Tamarisk Mbr
Prc	" " " Culebra Mbr
Prl	" " " Lower gyp-mdst mbr
Prs	" Rustler Fm, Siltstone mbr
Ps	Permian Salado Formation

DEPTH FT	DEPTH M	CSNG	FM	DESCRIPTION
0	0	7"	NR	0.0- 37.0 No Record
50		4"	Pdl	37.0- 79.6 Siltstone, muddy
100			Prf	79.6- 94.7 Gypsum 94.7-115.8 Anhydrite 115.8-127.2 Gypsum 127.2-144.3 Mudstone 144.3-150.0 Gypsum 150.0-163.2 Anhydrite 163.2-169.8 Gypsum
150	50	HCQ	Prm	169.8-190.7 Dolomite, gypsiferous
200 250			Prt	190.7-196.3 Gypsum 196.3-249.5 Anhydrite 249.5-272.5 Gypsum 272.5-281.5 Mudstone with gypsum 281.5-297.3 Gypsum
300 330	100		Prc	297.3-330.0 Dolomite

Figure 2A.--Geophysical logs of Texasgulf core hole, surface to 330.0 feet.

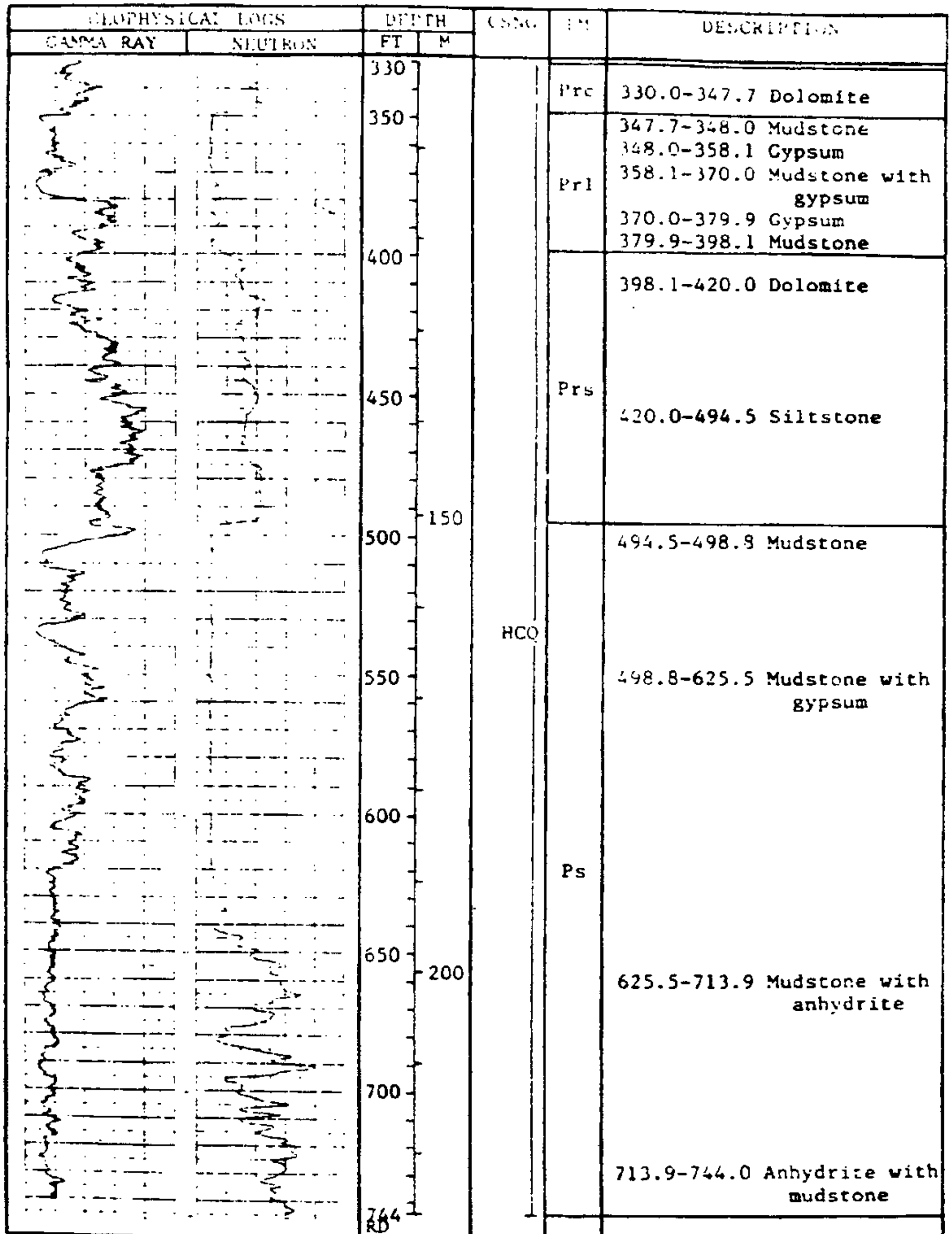


Figure 2B.--Geophysical logs of Texasgulf core hole, 330.0 to 744.0 feet.

Earth Technology Corporation. 1988. Final Report for Time Domain Electromagnetic (TDEM) Surveys at the WIPP Site. SAND87-7144. Albuquerque, NM: Sandia National Laboratories.

EXECUTIVE SUMMARY, p ii;

The Earth Technology Corporation was contracted by Sandia National Laboratories to perform a time domain electromagnetic (TDEM) survey at the WIPP site for the purpose of mapping the depth of occurrence of brine pockets and layers. The impetus for the geophysical survey was that pressurized brine had been encountered in drill holes in the Castile Formation immediately underlying the bedded salts of the Salado Formation in which the waste storage panels are mined. TDEM is a geophysical technique that determines layering in the subsurface from surface resistivity measurements. Because brine layers and pockets have low resistivities compared to the bedded salts of the host rock, they are good targets for electrical exploration.

Most of the measurements (36 out of 38) were located in a 1.5 by 1 km grid directly over the waste storage panels. Two measurements were made next to drill holes WIPP #12 and DOE #1 to validate the interpretation of the geophysical survey. Also, one drill hole (ERDA #9) at the northern boundary of the survey grid was used for calibration.

The results of the survey can be summarized as follows:

- The geoelectric sections derived from the TDEM measurements compare well with geologic and geophysical data of the three drill holes. At WIPP #12 the occurrence of brine at a depth of about 800m (2600 ft.) is clearly seen in the TDEM data.

- The results of the TDEM survey over the waste storage panels show the first occurrence of brine at depths corresponding to the Castile Formation in portions of the area and to the Bell Canyon Formation in the rest of the area, some 400 to 600 m below the mined depth of the waste storage panels in the Salado formation. There is no evidence in the data for brine pockets in the Salado or other formations over the waste storage panels.

Only one sounding was made near drill hole WIPP #12 for the purpose of calibration. Since the center loop TDEM surveys conducted correlate well with drill holes and other geologic data, it is recommended that the areal extent of the brine pocket encountered at WIPP #12 be mapped by surveying a grid centered on WIPP #12."

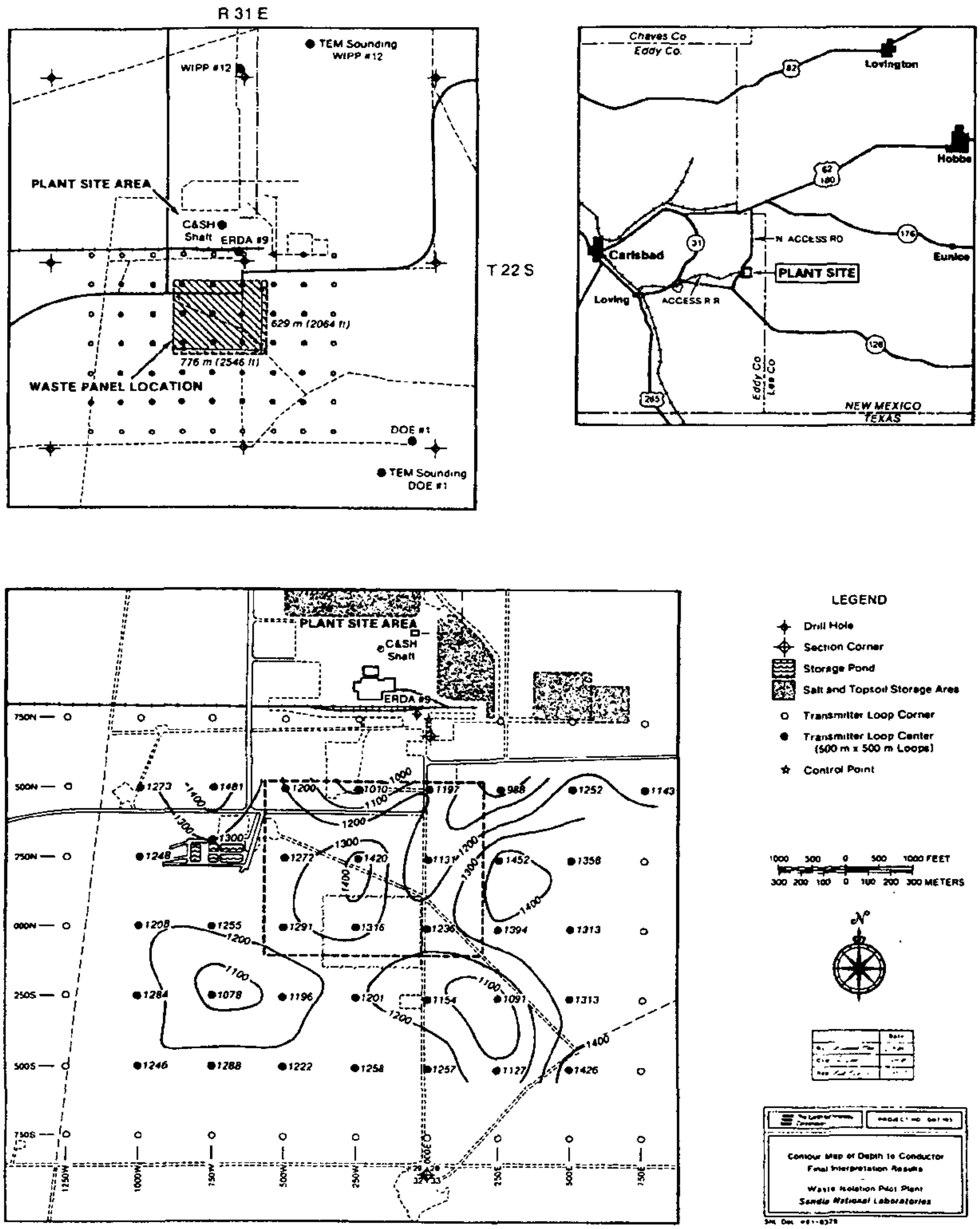


Figure 1-1. TEM Sounding Locations and Waste Panel Location

Elliot Geophysical Company. 1976. A Preliminary Geophysical Study of a Trachyte Dike in Close Proximity to the Proposed Los Medaños Nuclear Waste Disposal Site, Eddy and Lea Counties, New Mexico. Elliot Geophysical Company, Tucson, AZ.

" A long linear magnetic feature that has been geologically interpreted as a dike of Tertiary age has been well known by petroleum and potash explorations for many years. This long linear feature strikes approximately N 50° E across the northwestern part of the Delaware basin in southeastern New Mexico. This structural feature has been intercepted by many petroleum exploratory wells and potash test drill holes and it or related material outcrop in several areas south-southwest of the Carlsbad Caverns.

The trace of this dike is located approximately nine miles northwest of the Los Medaños Nuclear Waste Disposal Site that is currently under investigation. At this distance, the dike itself may possibly present a geologic hazard to the selection of Los Medaños as a viable site for a nuclear waste disposal pilot plant. Further, the dike may be, as is often the case, part of a swarm of en echelon dikes and, therefore, a parallel dike or dikes could exist closer to or beneath the Los Medaños site, and , therefore, a definite geologic hazard to site selection would be present. As a result, it seems pertinent to study this dike in detail in order to ascertain its possible significance, genetic origin, age, and any signs of structural movement in the last several million years. In that this dike is only exposed in one area, a long way from the Los Medanos site, then geologic study by itself cannot adequately define some of the parameters of interest. Fortunately, the dike material has relatively strong magnetic properties and, therefore, the dike can be mapped and studied in part, at least, by geophysical techniques. . . ."

EPA (U.S. Environmental Protection Agency). 1988. "40 CFR Parts 124, 144, 146 and 148 Underground Insertion Control Program: Hazardous Waste Disposal Injection Restrictions; Amendments to Technical Requirements for Class I Hazardous Waste Injection Wells, and Additional Monitoring Requirements Applicable to All Class I Wells." Federal Register, Vol. 53, 28188, July 26, 1988.

p. 210, para. 1;

" ACTION: Final Rule.

SUMMARY: The Environmental Protection Agency (EPA) is today promulgating its approach to implementing the statutorily mandated prohibitions on the underground injection of hazardous waste. This action is being taken in response to amendments to the Resource Conservation And Recovery Act (RCRA) enacted through the Hazardous and Solid Waste Amendments of 1984 (HSWA). In addition, the Agency is promulgating amendments to the existing Underground Injection Control (UIC) Regulations as they pertain to hazardous Waste injection.

Today's notice codifies at 40 CFR Part 148, for those hazardous wastes that are disposed in Class I hazardous waste injection wells, the directly applicable sections of Part 268, the Agency's regulatory framework for implementing the land disposal restrictions (51 FR 40572 et seq. November 7, 1986)."

Section II, p. 237, para. 4;

" Summary of Today's Rulemaking: Response to Comments, Part 148. H. Information To Be Submitted in Support of Petitions--Section 148.21. Several commenters objected to the requirement that, "All waste and environmental sampling, test and analysis data shall be accurate and reproducible and performed in accordance with quality assurance standards." They noted that in many cases, petitions will be based on information gathered during the drilling of the well--information which cannot be reproduced in accordance with procedures specified long after the drilling occurred. These commenters also noted that much of the data relied upon for characterizing the regional geology will be obtained from operations which are conducted by entities other than the petitioner. These commenters believed that the net effect of this requirement would be to prohibit the use of vast amounts of data. The geologic descriptions would therefore be less accurate, they contended.

The Agency agrees. Excluding historical data or information which might have been gathered off-site by methods not consistent with certain prescribed procedures may be counterproductive. The purpose of @@ 148.21 (a) (5) and (6) should be to allow the use of such data, but assure that its limitations are accounted for in a petition review. Accordingly, EPA will require that only measurements pertaining to the waste or that result from testing performed to gather data for the petition demonstration comply with prescribed procedures. The Agency believes, however, that the concerns about the accuracy of geologic data are addressed more appropriately by requiring that the demonstration identify and account for limits on data quality rather than by excluding data from consideration. Again, @ 148.21(b), as revised, requires precisely such consideration. Therefore, the demonstration in @ 148.20

as promulgated, will allow the use of existing data."

EPA (U.S. Environmental Protection Agency). 1993. 40 CFR Part 191 Environmental Radiation Protection Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Waste; Final Rule. Federal Register, Vol. 58, No. 242, pp. 66398-66416, December 20, 1993, Office of Radiation and Indoor Air, Washington, D.C. WPO 39133.

PREAMBLE: SUMMARY;

" The U.S. Environmental Protection Agency (EPA) is promulgating amendments to the environmental standards for the disposal of spent nuclear fuel, high-level and transuranic wastes (40 CFR 191.15 and Subpart C).

EPA originally promulgated these standards in 1985 pursuant to the Agency's authorities and responsibilities under the Nuclear Waste Policy Act of 1982, as amended, the Atomic Energy Act of 1954, as amended, and §2(a)(6) of Reorganization Plan No. 3 of 1970 (5 USC app. 1). In 1987, following a legal challenge, the U.S. Court of Appeals for the First Circuit (hereinafter referred to as 'the First Circuit' or ' the court') remanded subpart B of the 1985 standards to the Agency for further consideration. *Natural Resources Defense Council, Inc. v. United States Environmental Protection Agency*, 824 F.2d 1258 (1st Cir. 1987). Recently enacted legislation, (Pub. L. 102-579) known as the Waste Isolation Pilot Plant Land Withdrawal Act (WIPP LWA), however, reinstates the 1985 disposal standards except 'the 3 aspects of §§191.15 and 191.16 of such [standards] that were subject of the remand ordered' by the First Circuit. The WIPP LWA directs EPA to expedite issuance of final disposal standards and specifies that such regulations shall not be applicable to the characterization, licensing, construction, operation, or closure of any site required to be characterized under §113(a) of Public Law 97-425, the Nuclear Waste Policy Act of 1982."

STATUTORY AND REGULATORY BACKGROUND;

" The WIPP Land Withdrawal and Nuclear Waste Policy Acts

As noted above, today's action responds to the directive in section 8 of the WIPP LWA that EPA conduct a rulemaking to issue certain radioactive waste disposal regulations at 40 CFR Part 191, subpart B. The EPA initially promulgated subpart B in 1985 (50 FR 38084 (Sept. 19, 1985)), but those regulations were subsequently vacated in whole as part of a remand order issued by the First Circuit in 1987 (discussed further above and below). See *NRDC v. EPA*, 824 F.2d 1258 (1st Cir. 1987).

Section 8(a)(1) of the WIPP LWA reinstates those portions of subpart B except §§191..15 and 191.16 (which were the bases of remand by the First Circuit). Accordingly, section 8(a)(2)(A) of the WIPP LWA exempts the requirements at 40 CFR 191.15 (individual protection) and 191.16 (ground-water protection) from the statutory reinstatement. Section 8(b)(2) addresses these non-reinstated provisions by directing the EPA promulgate final regulations. Today's action responds to that directive by revising the individual protection requirements in 40 CFR 191.15, discussed above, and by adding new ground-water protection standards as 40 CFR part 191, subpart C (discussed below)."

§191.27. Effective date: p. 66415, col. 3;
"Appendix A to Part 191--Table for Subpart B

9.Appendix B is redesignated as Appendic C to part 191 and the heading is revised as follows:

Appendix C to Part 191--Guidance for Implementation of Subpart B."

50 FR 38088, p. 38088, col. 2;

" Appendix B--Guidance for Implementation of Subpart B

[Note: The supplemental information in this appendix is not an integral part of 40 CFR Part 191. Therefore, the implementing agencies are not bound to follow this guidance. However, it is included because it describes the Agency's assumptions regarding the implementation of Subpart B. This appendix will appear in the Code of Federal Regulations]"

. . .

" Scope of Performance Assessments.

Section 191.13 requires the implementing agencies to evaluate compliance through performance assessments as defined in § 191-12(q). The Agency assumes that such performance assessments need not consider categories of events or processes that are estimated to have less than one chance in 10,000 of occurring over 10,000 years. Furthermore, the performance assessments need not evaluate in detail the releases from all events and processes estimated to have a greater likelihood of occurrence. Some of these events and processes may be omitted from the performance assessments if there is a reasonable expectation that the remaining probability distribution of cumulative releases would not be significantly changes by such omissions."

EPA (U.S. Environmental Protection Agency). 1996. 40 CFR Part 194: Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations; Final Rule. Federal Register, Vol. 61, No. 28, pp. 5224-5245, February 9, 1996. Office of Radiation and Indoor Air, Washington, D.C. In NWM Library as KF70.A35.C751. 1996 (Reference).

SUMMARY, p. 5224, col. 1;

" The Environmental Protection Agency (EPA) is promulgating criteria for determining if the Waste Isolation Pilot Plant (WIPP) will comply with EPA's environmental radiation protection standards for the disposal of radioactive waste. If the Administrator of the EPA determines that the WIPP will comply with the standards for disposal, then the Administrator will issue to the Secretary of Energy a certification of compliance which will allow the emplacement of transuranic waste in the WIPP to begin, provided that all other statutory requirements have been met. If a certification is issued, EPA will also use this final rule to determine if the WIPP has remained in compliance with EPA's environmental radiation protection standards, once every five years after the initial receipt of waste for disposal at the WIPP. This rulemaking was mandated by the WIPP Land Withdrawal Act of 1992. EFFECTIVE DATE: These regulations are effective April 9, 1996."

p. 5238, col. 2;

" §194.14. Content of compliance certification application.

Any compliance application shall include:

(a) A current description of the natural and engineered features that may affect the performance of the disposal system. The description of the disposal system shall include, at a minimum, the following information:

(1) The location of the disposal system and the controlled area;

(2) A description of the geology, geophysics, hydrogeology, hydrology and geochemistry of the disposal system and its vicinity and how these conditions are expected to change and interact over the regulatory time frame. Such description shall include, at a minimum:

(i) Existing fluids and fluid hydraulic potential, including brine pockets, in and near the disposal system; and

(ii) Existing higher permeability anhydrite interbeds located at or near the horizon of the waste.

(3) The presence and characteristics of potential pathways for transport of waste from the disposal system to the accessible environment including, but not limited to: Existing boreholes, solution features, breccia pipes, and other potentially permeable features, such as interbeds.

(4) The projected geophysical, hydrogeologic, and geochemical conditions of the disposal system due to the presence of waste including, but not limited to, the effects of production of heat or gases from the waste."

Foster, R.W. 1974. Oil and Gas Potential of a Proposed Site for the Disposal of high-Level Radioactive Waste. BNL/SUB-44231/1. Ridge National Laboratory, Oak Ridge, TN. Available fro NTIS. NTIS Accession number: ORNL/SUB-4423-1.

NOTE: Figure 3 from this document is too large to be scanned for this document.

INTRODUCTION, p. 1;

" This study was in part funded by the Atomic Energy Commission under Contract No. AT-(40-1)-4423. Terms of this contract as they involve this particular study, are restated here so that reviewers may be aware of the basic aims of the project.

Project I - Evaluate the Petroleum Potential of the Proposed Radioactive Waste Disposal Site: Initial studies to be completed by February 15, 1973, will involve the development of pertinent information related to the location of a favorable site for coring of the Salado Formation and underlying rocks somewhere within Ts. 22-23 S., [Ts. 21-22 S.] , Rs. 31-32 E.

Evaluation of petroleum potential of the above-mentioned townships will include all rocks from the surface to the Pre-Cambrian [Precambrian] basement with emphasis on the deeper horizons. This study will include all wells in the area, and pertinent structural, lithologic and isopach data for the proposed disposal site. Necessary regional interpretation of these strata will be conducted and will include existing fields, wells, secondary recovery operations, areas of salt water disposal, production data, and pressures. In addition, the 1961 report by Foster and Stipp showing basement configuration in southeastern New Mexico will be revised. . . ."

p 9, para 2;

" Based on isotopic dating, Muehlberger (1964) considered the grouping of the Texas craton too broad and abandoned the use of this term. He introduced Central Basin platform terrane for an area including but not restricted to the structural Central Basin platform. Ages of Precambrian rocks in southeastern New Mexico vary considerably (Wassenburg, et. al., 1962, and Muehlberger, et. al., 1964, 1966, and 1967). The Panhandle Volcanic terrane has an age of approximately 1.14 by, and the Central Basin platform terrane, two distinct ages of 1.17 and 1.35 by. The older rocks are located primarily on the northwestern shelf and are similar in age to the intrusive events of central and northeastern New Mexico. The younger rocks dated from granite and a gneiss suggest an association with the Panhandle Volcanic terrane. The rhyolite to the west of the map area, although not dated, is similar to rhyolite of the Franklin Mountains and possible Pump Station Hills. The Franklin Mountains rhyolite has a maximum age of about 0.97 by (Denison and Hetherington, 1969) somewhat younger than the Panhandle Volcanic terrane.

Ordovician System

Rocks of Cambrian age are not believed to be present in this area. The west-east transgressive overlap of Cambrian/Ordovician sediments onto the Precambrian surface has been well documented for many years. The Bliss Sandstone in the Franklin Mountains of west Texas, is in part of Cambrian age, but is thought to be entirely Early Ordovician in the Sacramento Mountains of New Mexico. Conglomerate and sandstone at the base of the Ordovician section in the subsurface of southeastern New Mexico are sometimes called Bliss Sandstone, particularly in the western part of the Delaware basin. These rocks probably correlate with the Ordovician part of the Bliss.

Barnes, et.al. (1959) have shown that the Gorman Formation of the Ellenburger Group overlies the Precambrian in the area of the Central Basin platform, and locally is as thin as 100 feet in parts of Lea County. Elsewhere in southeastern New Mexico the older Tanyard formation overlies Precambrian. This indicates a greater relief on the Precambrian surface on parts of the Central Basin platform. Areas suggestive of island chains consisting of Precambrian rocks, in the Early Ordovician seas have been noted in other parts of southern New Mexico and west Texas (Kottlowski, et. al., 1973)."

p. 18;

"

Silurian/Devonian Systems

Rocks of Silurian and Devonian ages in southeastern New Mexico have been rather poorly defined. The standard usage includes the Woodford Shale and an underlying carbonate sequence referred to as Silurian, Devonian, or Siluro/Devonian. Locally rocks presumed to be of Silurian age have been separated into the Fusselman Dolomite and Upper Silurian. The difficulty in separating the carbonate sequence has been discussed by numerous geologists. Gibson (1965) used the term Hunton terrane for the carbonate sequence because of the varied terminology in the Permian basin. McGlasson (1967) suggested that the carbonate rocks in the Delaware basin of New Mexico are restricted to Fusselman and Upper Silurian with rocks of Devonian age found only at the southern end of the Central Basin platform in Lea County. Lacking any justification from the present work for specific formational designations for the carbonate sequence, the common oil-field usage of Siluro/Devonian is followed although modified to the more acceptable Silurian/Devonian. Included, however, is a brief description of the derivation of the Fusselman Formation."

p. 24;

"

Mississippian System

Rocks assigned to the Mississippian in this report include a series of limestone referred to simply as Mississippian limestone, and an overlying shaly interval called the Barnett Shale. This follows the general oil-field usage in southeastern New Mexico. The top and base of the Mississippian limestone can be easily recognized, in most cases, in well samples and from mechanical logs. Where some doubt might exist as to the top and base it becomes only a question of a few tens of feet. Because of this, reported scout tops usually are quite reliable. The contact between the Barnett Shale and overlying Pennsylvanian rocks is less reliable. For this report a distinctive 'kick' on mechanical logs that could be traced throughout the Study area, was used as the base of the Pennsylvanian. From sample studies this kick seems to represent a thin sandstone. For most wells this top for the Barnett coincides with the consensus of data reported for southeastern New Mexico. Chester is sometimes used for the Barnett and an overlying section of shale and sandstone here included with the Pennsylvanian. Lower Mississippian also is used occasionally for the Mississippian limestone of this report."

p. 25, para. 3;

" At the reference section locality (fig. 9) the Mississippian includes 540 feet of light-yellowish brown limestone, locally containing fairly abundant chert, and minor gray shale. The barnett consists of 80 feet of brown, in part silty shale."

p. 31, para. 2;

" Meyer's classification was not used in this report because most of these terms are not commonly used in the literature of southeastern New Mexico or in completion reports for specific wells. Above the Morrow oil-field usage is Atoka or sometimes Bend, Strawn, Canyon, and Cisco. Only in a few cases are attempts made to differentiate the Cisco and Canyon intervals; these, as in this report, being included in the Wolfcamp. Hills (1963), in contrast to the interpretation of Meyer, indicates Strawn underlying Wolfcamp in the Delaware basin of New Mexico. In well completion reports the top of the Strawn is picked fairly consistently. The Atoka may be picked at the top of the sandstone included here as the Strawn, at the top of the first sandstone in the Atoka of this report, or coinciding with the usage of this report. The Morrow top may be the same as used here or be as high as the uppermost sandstone in the Strawn interval."

p. 35, para. 4;

" Silver and Todd (1969) have reported that the upper part of the Wolfcamp in the northern part of the Delaware basin is characterized by shale and micritic limestone. In general this lithologic description is adequate for the upper part for the Wolfcamp in the Study area of this report. In the reference section (fig. 14) the Wolfcamp consists of interbedded carbonate and shale including considerable dolomite and minor sandstone. To the south, where a much thicker section is present, the lower part consists mostly of shale. The increase in limestone to the north suggests approach to a shelf margin facies."

p. 39, para 2;

" The Bone Springs was originally referred to by Blanchard and Davis (1929) and later defined by King (1942). At the type locality in the Delaware Mountains, West Texas, the unit consists mostly of limestone with a few members of shaly limestone and shale. Two members have been named; Victorio Peak Limestone and overlying Cutoff Shale. These intervals underlie the Brushy Canyon Formation of the Delaware Mountain Group. The Victorio Peak and Cutoff members crop out in the Guadalupe Mountains of New Mexico (Boyd, 1958).

As noted by King (1942) and Silver and Todd (1969) the Bone Spring facies of the Delaware basin is markedly different than in the outcrop sections to the west. A typical basinal section of the Bone Springs was drilled in the reference well (fig. 16). The interval consists of a thick, partly cherty, limestone at the top, underlain by alternating units of sandstone and limestone. The three very fine-to-fine-grained sandstone intervals are referred to simply as the first, second, and third Bone Spring sands. The lower most 'third sand' is also called the Dean sand. Shale is a minor constituent of the Bone Springs but limestone beds are commonly argillaceous. The lithologic sequence as shown in the reference well is quite uniform throughout the Study area with minor variations in thickness of members. The shelf-margin carbonates, consisting of reefs or banks that limit the areal extent of the Bone Springs basinal facies to the west, north, and east are not present in this area.

The thickest sections of the Bone Springs occur in the western part of the Study area (fig. 17). The interval, in the area of thickest accumulation of sediments ranges from 3,300 to 3,500 feet. At an angle to this north-south depositional axis there is a northeast trending area where 3,000 to 3,300 feet of sediments were deposited. This is an area where a comparatively thin section of Wolfcamp rocks is present although it follows the structural axis of the Delaware basin. The Bell Lake structure remains evident in rather abrupt thinning of the Bone Springs interval onto this pre-Wolfcamp formation high. In the Pilot area the Bone Springs Formation ranges from 2,900 feet to over 3,400 feet in thickness."

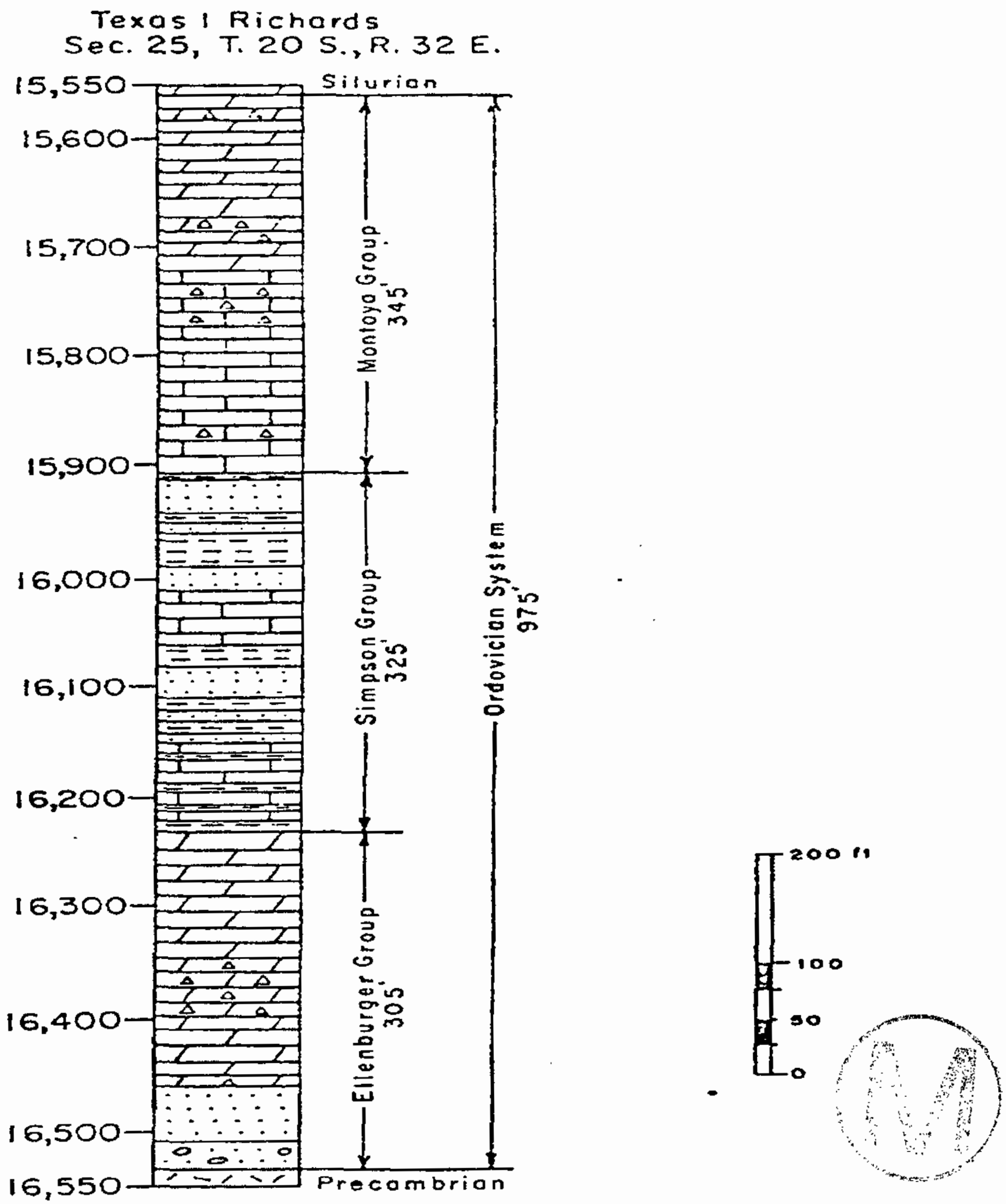


Fig.4 Ordovician reference section

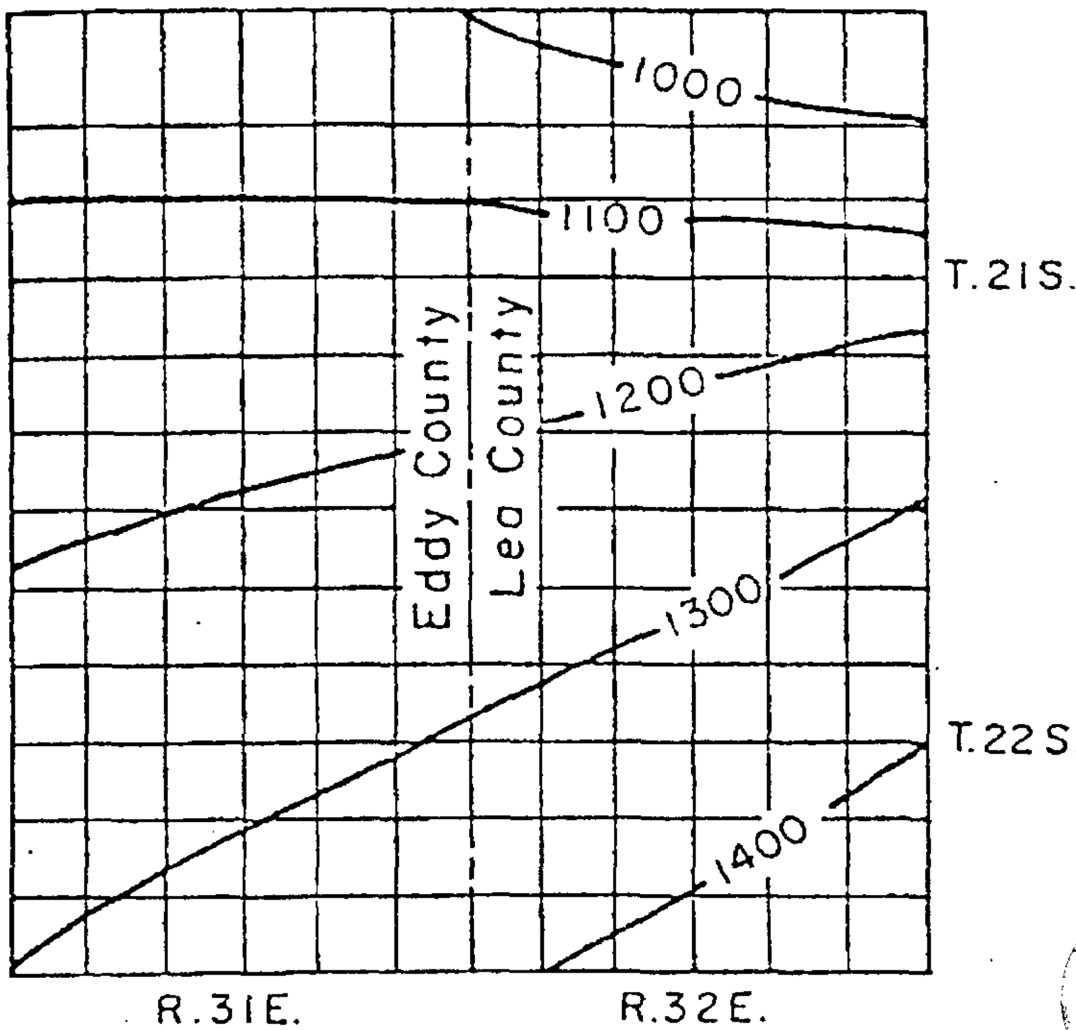


Fig.5 Isopach map: Ordovician

Contour interval: 100 feet 0 2 4 miles

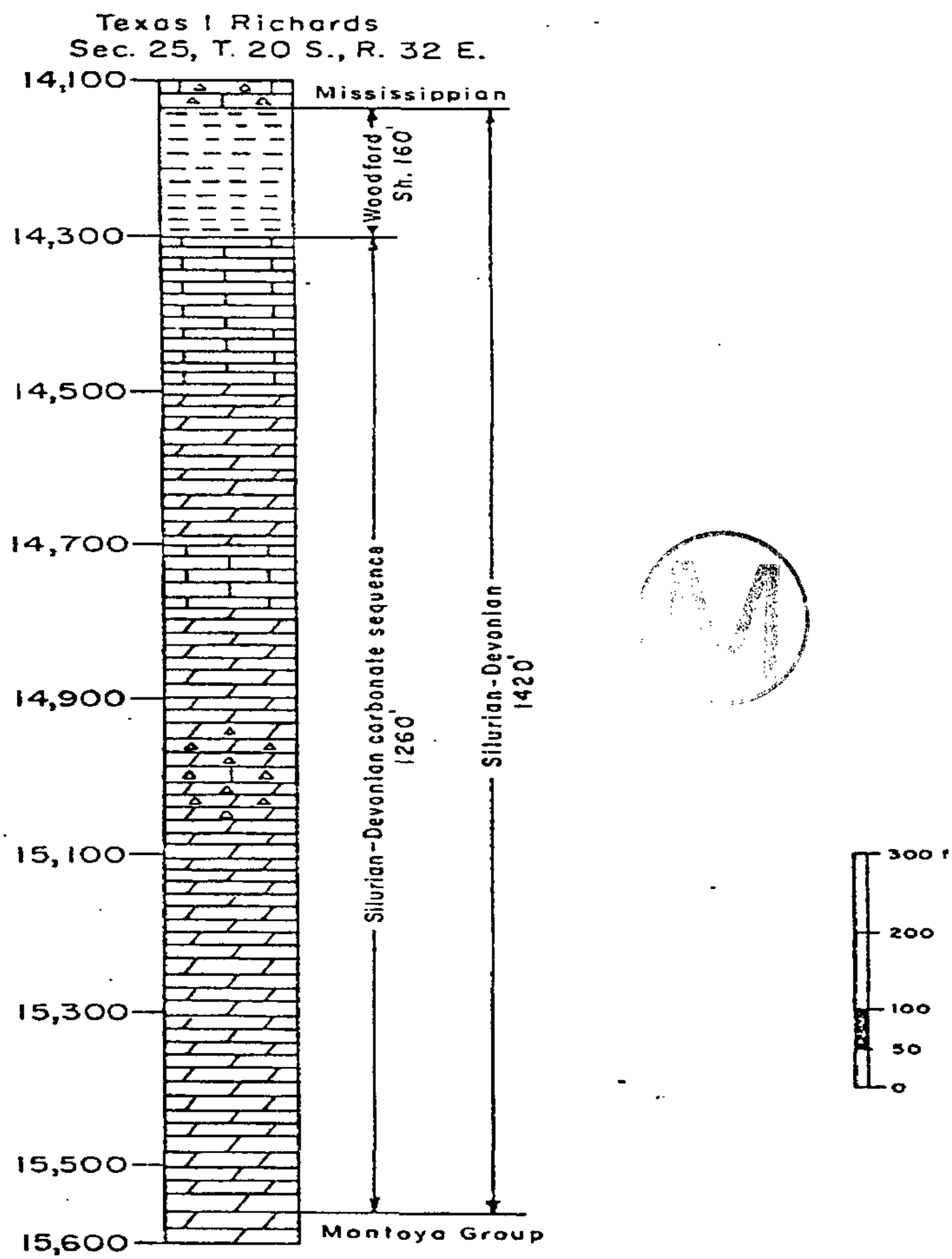


Fig.6 Silurian/Devonian reference section

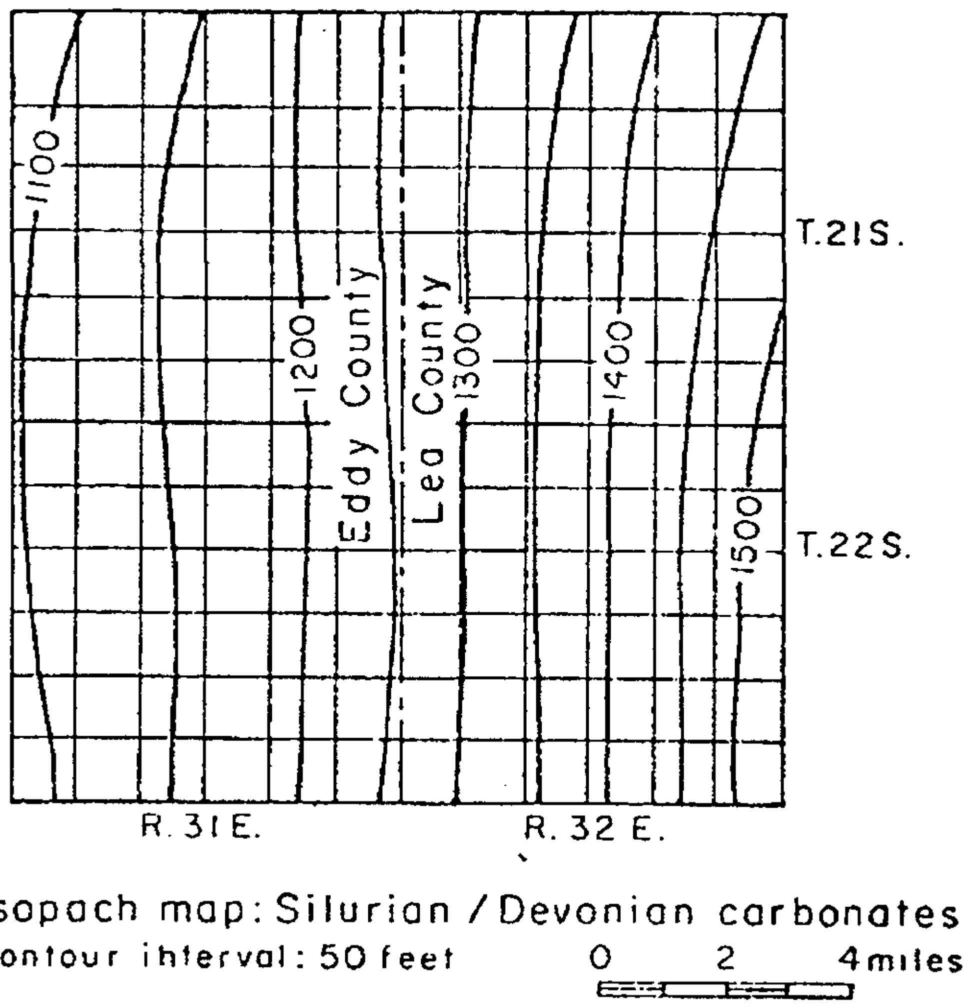


Fig. 7 Isopach map: Silurian / Devonian carbonates
Contour interval: 50 feet

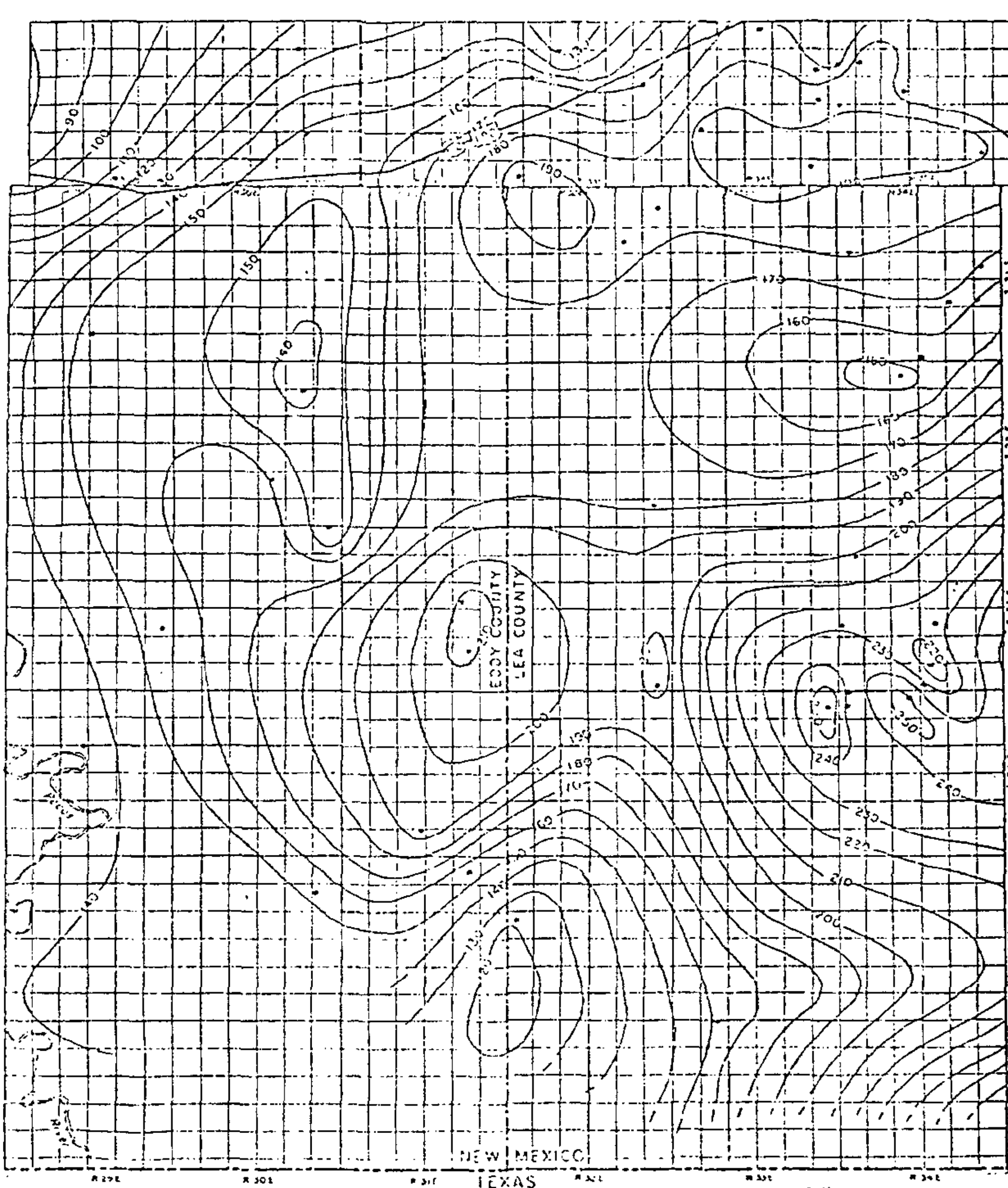


Fig. 8 Isopach map: Woodford Shale

Contour interval: 10 feet

0 5 10 miles

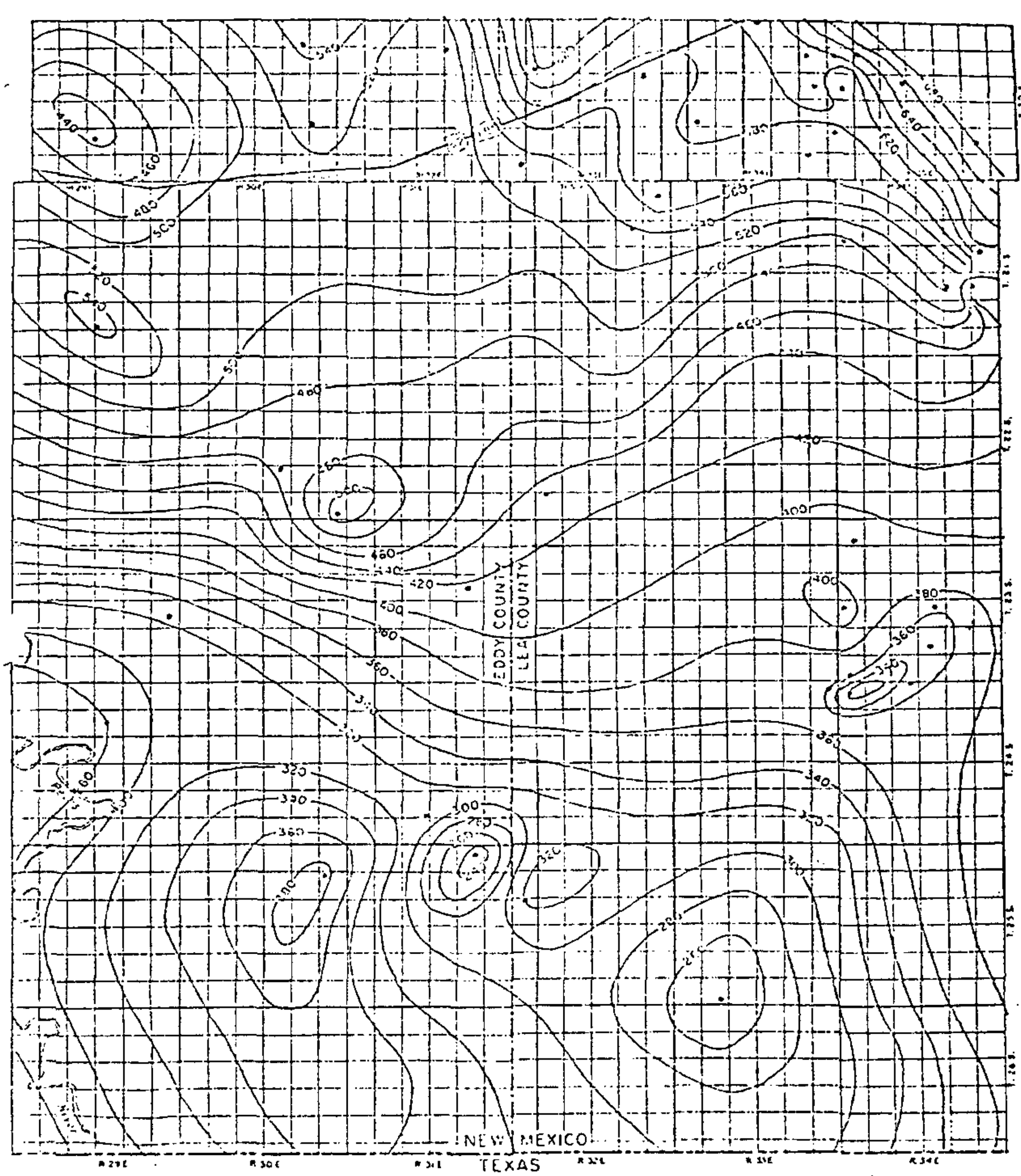


Fig.10 Isopach map: Mississippian carbonates
Contour interval: 200 feet
0 5 10 miles

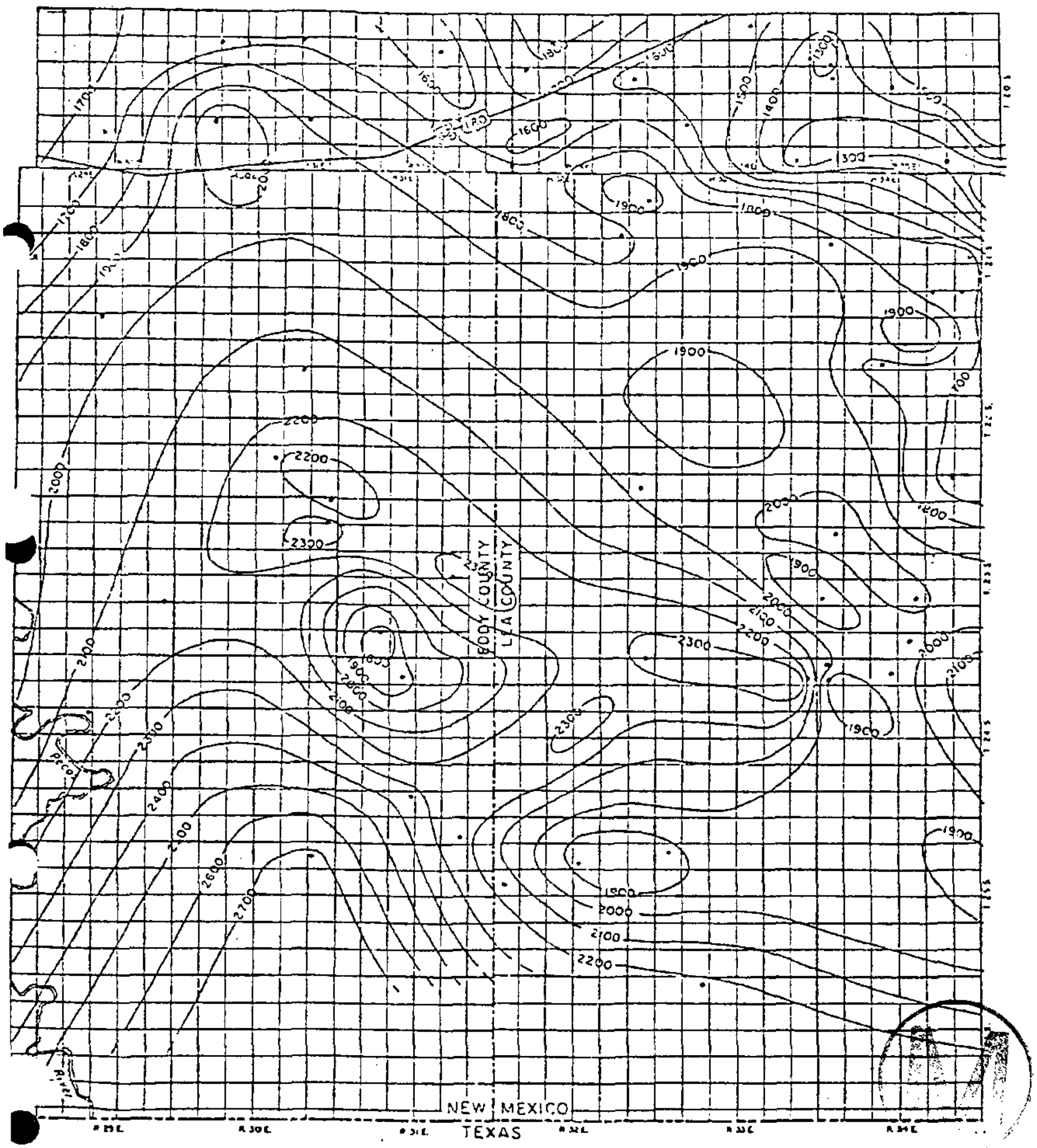


Fig.13 Isopach map: Pennsylvanian
0 Contour interval: 100 feet 10 miles

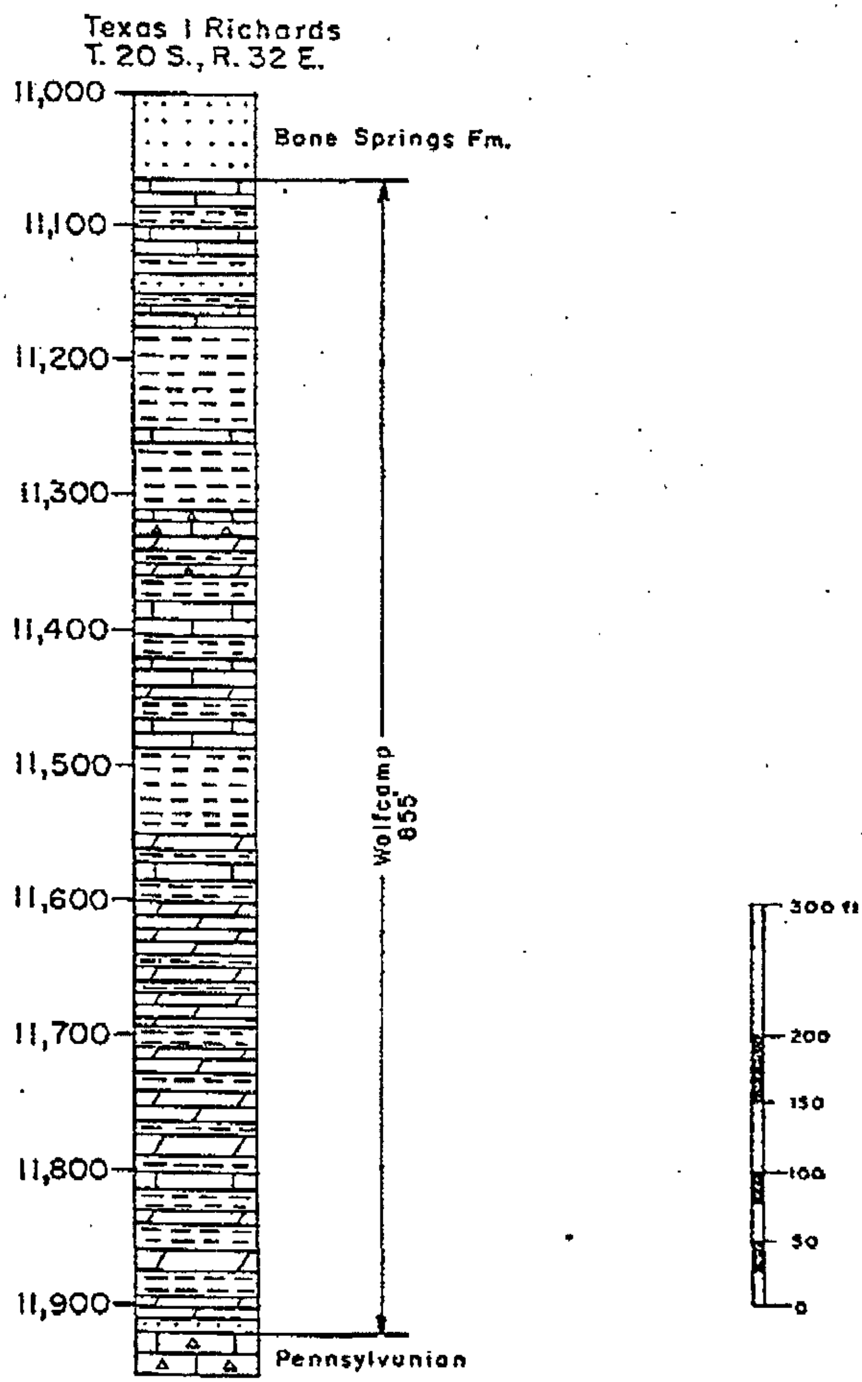


Fig. 14 Wolfcamp reference section

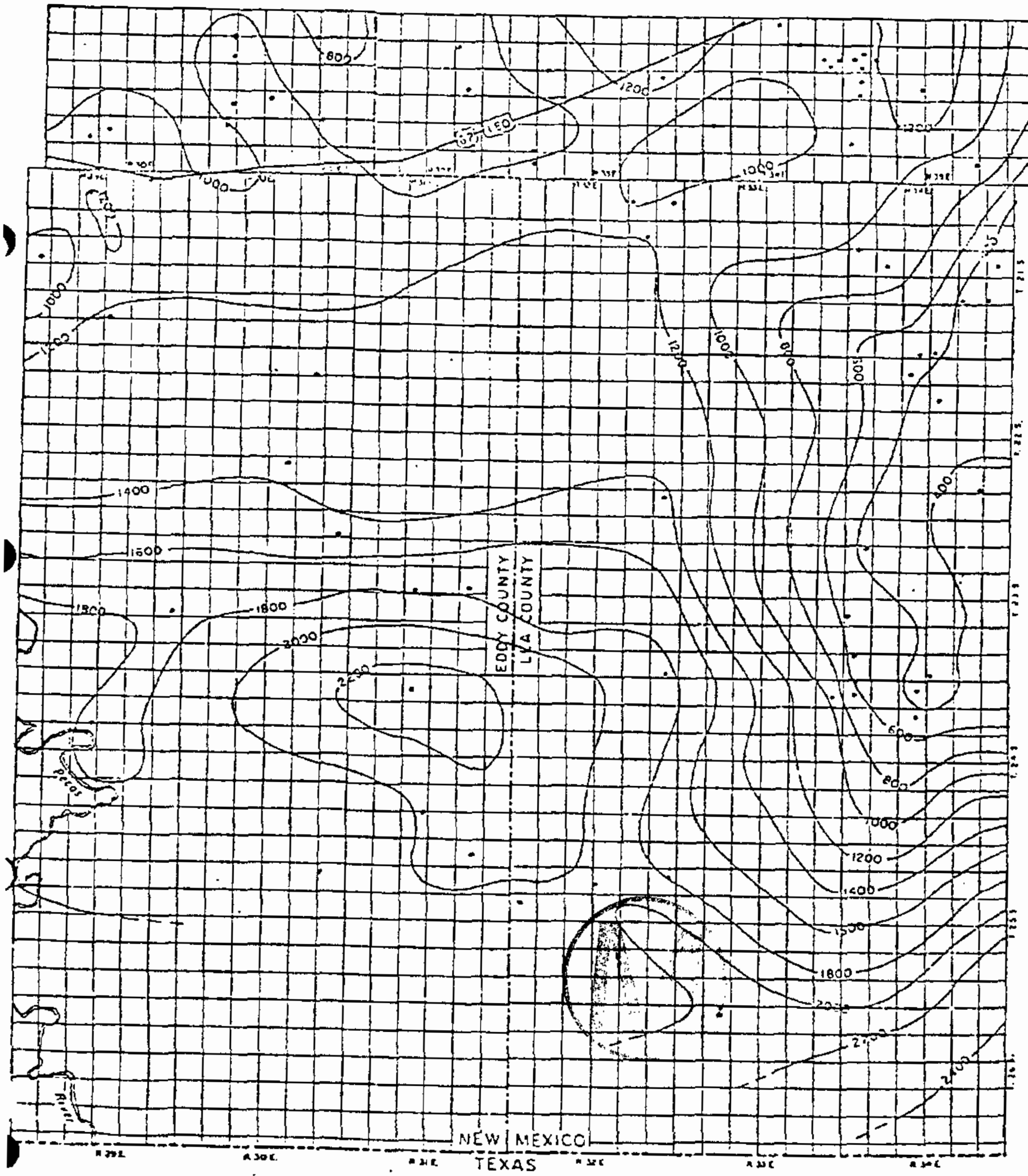


Fig.15 Isopach map: Wolfcamp
Contour interval: 200 feet
0 5 10 miles

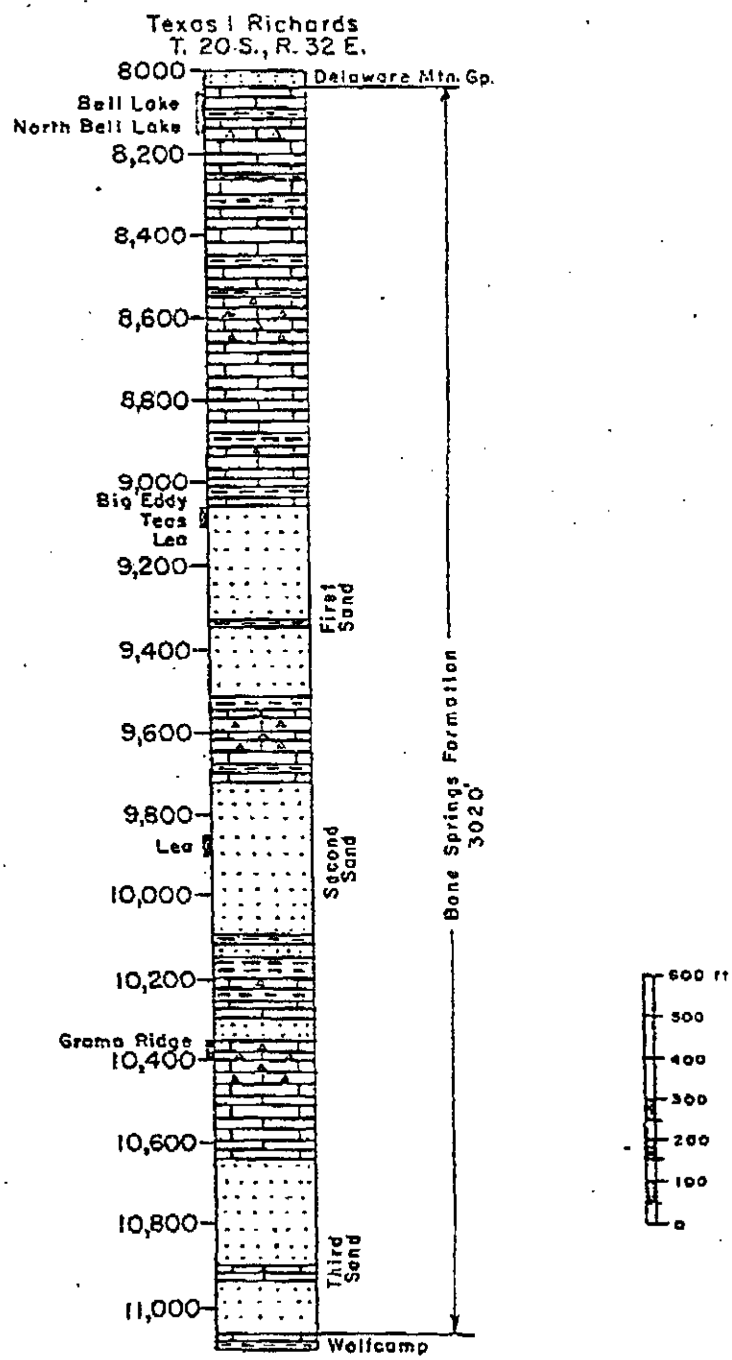


Fig. 16 Bone Springs Formation reference section showing stratigraphic position of Study area fields.

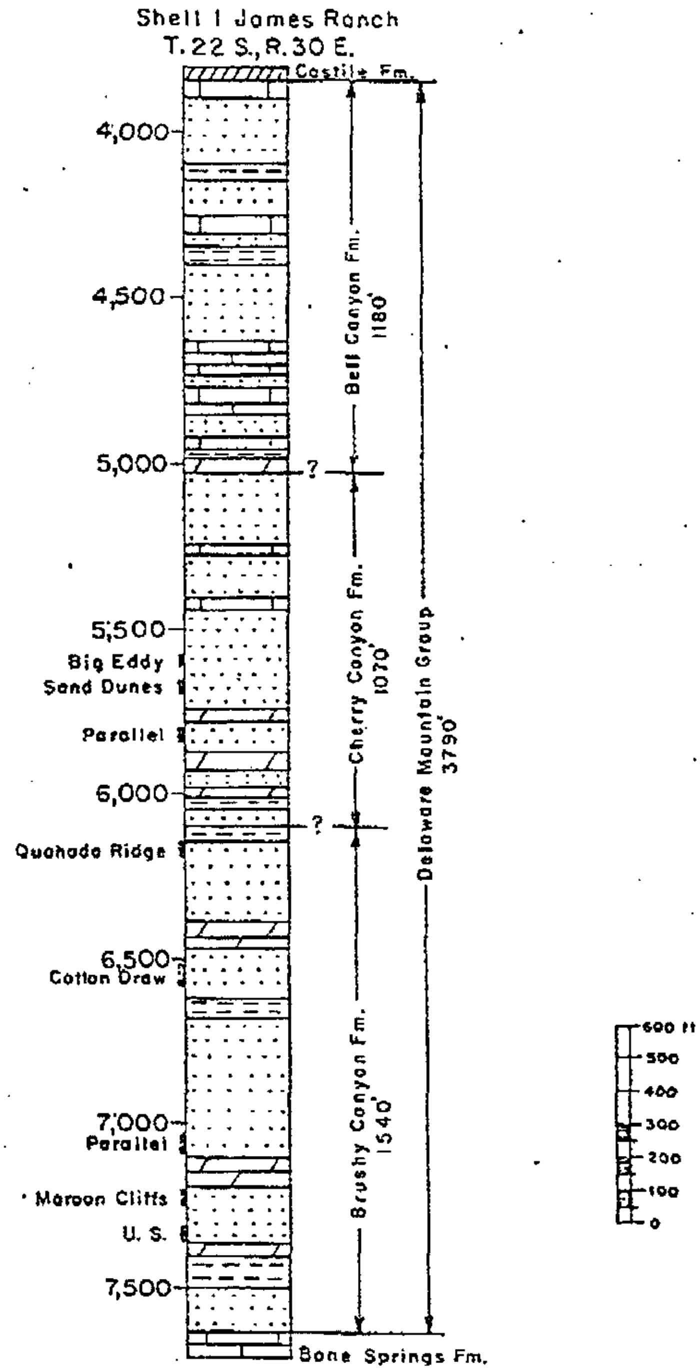


Fig. 18 Delaware Mountain Group reference section showing stratigraphic position of study area fields

Hale, W.E., Hughes, L.S., and Cox, E.R. 1954. Possible Improvement of Quality of Water of the Pecos River by Diversion of Brine at Malaga Bend, Eddy County, NM. Pecos River Commission New Mexico and Texas, in cooperation with United States Department of the Interior, Geological Survey, Water Resources Division, Carlsbad, NM.

ABSTRACT, p B-1;

" About 420 tons of dissolved minerals of which about 370 tons is common salt is added daily to the mineral load of the Pecos River through seeps and springs along a stretch of about 3 miles in the Malaga Bend of the river in T.24 S., R.29 E., which is 17 miles southeast of Carlsbad in southern Eddy County, N.Mex. In this reach, the river gains on the average approximately 2 1/2 cfs, a mixture of water of which about 2 cfs is return from irrigation water applied to nearby lands and about 0.4 cfs (200 gpm) is a concentrated brine. Elimination of the small inflow of concentrated brine would result in substantial improvement in the quality of the water reaching the Red Bluff reservoir, the water from which is used for irrigation in the valley farther downstream in Texas.

Brine, almost saturated with sodium chloride, occurs at shallow depth in the alluvium in the Grandson Spring area on the inside of the Malaga Bend and between Livingston's Ford and the Lower Wading station on the outside and lower end of the Malaga Bend. Elsewhere at shallow depth in the Malaga Bend area, the ground water present is a mixture of brine and water derived from application of water to nearby farm lands. The chloride content of the water in the alluvium increases with depth and, in the lower part of the alluvium, the water is saturated with common salt.

The source of the concentrated brine in the alluvium at Malaga Bend is a brine aquifer that underlies the area at a depth of about 200 feet. The aquifer is developed mostly in gypsum near the base of the Rustler formation and in places directly overlies the thick sequence of impermeable salt and anhydrite beds of the Salado formation. The brine is under sufficient head in the brine aquifer to percolate upward through thin and incompetent beds of gypsum and clay into the overlying beds of sand, clay, and silt and thence into the river. The Malaga Bend area is the only known discharge area for this concentrated brine.

The basal brine aquifer extends northward from the Malaga Bend area in a strip 3 to 5 miles wide into Nash Draw. The known length of the aquifer containing brine is about 25 miles. The principal area of recharge is inferred to be in the vicinity of Bear Grass Draw in T. 18 N., R. 30 E., several miles north of Nash Draw. In the recharge area truncated beds of the Rustler formation are exposed or immediately underlie the alluvium in the area. Some recharge to the brine aquifer occurs at times through sinkholes in the area about 2 miles west of the Malaga Bend. The source of the dissolved salt in the basal brine aquifer is undoubtedly the salt in the underlying Salado formation.

The transmissibility of the brine aquifer obtained from aquifer tests appears to be about 60,000 gallons a day per foot, and on the basis of the width of the aquifer of 5 miles and a gradient of 1.4 feet per mile the aquifer is estimated to be transmitting about 0.6 cfs toward the discharge area in the Malaga Bend. This value is of the same order of magnitude as the rate of discharge (0.4 cfs) calculated on the basis of the observed gain in salt load of the river in the Malaga Bend area. The latter method of determining the discharge from the aquifer is considered to be more precise.

The alluvium in the Malaga Bend area extends to a depth of 150 feet below the Pecos River in places. It is composed of silt, sand, clay, and some gravel. The transmissibility of the alluvium appears to be small, of the order of 10,000 gallons a day per foot. Pumping of shallow wells constructed in the alluvium and finished only a few feet into the saturated brine would have the most immediate effect in eliminating the brine inflow to the Pecos River. The number of wells required would be large and, unless careful regulation of the discharge were maintained, considerable overlying fresh water would be drawn into the wells, which would diminish the efficiency of the pumping system. Wells finished and open only in the basal part of the alluvium probably could be pumped at rates greater than the shallower wells, and the number of wells required to effectively lower the head of the brine below river level throughout the bend area would be less than that required for a shallow-well system. Again, however, careful observations would need to be maintained and the pumping rate from each well regulated to prevent drawing in of fresher water in the upper part of the alluvium.

Aquifer tests indicate that the basal brine aquifer has a high coefficient of transmissibility and low coefficient of storage. One or two properly located wells in the basal brine aquifer could be pumped at such a rate as to lower the head of the brine below river level over the entire discharge area. There is little likelihood that the fresh water in the overlying alluvium would be drawn into the wells. An initial pumping rate of 600 to 700 gallons a minute from the deeper wells would lower the head of the brine to about river level in a few days. The pumping rate could be lowered in time and eventually could be reduced to approximately 200 gallons a minute, the natural discharge rate from the aquifer. Some additional water may be induced into the basal brine aquifer in the recharge area as a result of lowering of the head on the brine aquifer, but the amount probably would be small. A high initial rate of withdrawal of brine from the basal brine aquifer would induce the brine to move from the alluvium into the basal brine aquifer, hastening the diminution of flow of brine to the river.

Hawley, J.W. 1993. "The Ogallala and Gatuña Formations in the Southeastern New Mexico Region, a Progress Report." In Carlsbad Region, New Mexico and West Texas, New Mexico Geological Society, Forty-Fourth Annual Field Conference, Carlsbad, NM, October 6-9, 1993. D.W. Love et al., eds., pp. 261-269. New Mexico Geological Society, Socorro, NM.

ABSTRACT, p 261;

" The Ogallala Formation in the Southern High Plains section (Great Plains province) of southeastern New Mexico includes alluvial, eolian and playa-lake deposits and pedogenic calcretes of late Miocene and early Pliocene age (about 4-12 Ma). Beneath the Llano Estacado, it forms an almost continuous cover on rocks of Mesozoic age, is locally more than 400 ft (120 m) thick and is a major aquifer. In the Pecos Valley section of the Great Plains and along the Portales Valley through the western Llano Estacado, fine- to coarse-grained clastics of the late Miocene to middle Pleistocene age locally form thick fills (> 1000 ft., 300 m) in large solution-subsidence depressions. These features are aligned along segments of the ancestral Pecos and Brazos Valleys and are underlain by evaporites of Late Permian age. Some of these deposits have always been included in the Ogallala Formation, but in the lower Pecos Valley area (Roswell, NM to Pecos, TX), correlative depression and valley fills have been mapped variously as 'older alluvium, quartzose conglomerate, valley-fill alluvial deposits,' and as the Gatuña Formation. Gatuña-Ogallala chronologic and nomenclature problems have not yet been resolved in that area; however, it is clear that an ancestral 'lower' Pecos fluvial system has existed since late Miocene time near the present valley position between the Roswell (artesian) and Delaware Basins. In the sediment source area west of the Great Plains, Ogallala and Gatuña correlatives are discontinuous, commonly thin and only locally aquifers. The oldest deposits include piedmont fan alluvium, pediment veneers and valley and basin fills. They record semiarid climatic conditions, prior epeirogenic uplift and volcanism and ongoing Basin-and-Range tectonism in a broad area extending southward from the Southern Rocky Mountains through the Sacramento section of the Basin and Range province. Significant uplift of mountain fault blocks occurred along the Rio Grande rift margin in the western part of the (sediment) source region. The facies-distribution patterns of both the Ogallala and Gatuña Formations are quite complex west of the Southern High Plains. The oldest units may form basal fills of structural basins, solution-subsidence depressions, or stream valleys, or they may be preserved as piedmont alluvium capping high divides and tablelands, with younger deposits occurring as inset valley fills. Rising western highlands not only contributed runoff and sediment to prominent zones of secondary-carbonate accumulation in paleosols of the High Plains eolian cover indicates increasingly dry and more continental conditions in late Cenozoic time. Episodic deflation of alluvial plains prograding eastward and southeastward from mountain and piedmont source areas also produced eolian sediments that are a significant component of the Ogallala Formation and overlying Plio-Pleistocene deposits of the Llano Estacado area."

CURRENT INTERPRETATIONS OF LATE NEOGENE HISTORY AND

STRATIGRAPHY, p. 264, Col. 2, Para 4;

" Differential uplift and subsidence of Basin-and-Range and Rocky Mountain-Front Range blocks had a major impact on the Ogallala sediment source area, particularly during the late Miocene (O'Neill, 1988; S. Kelley et al., 1992). Uplift and east tilting of crustal blocks that form the major ranges of the southeastern Sacramento Section (Sacramento, Guadalupe, Delaware) has continued through late Quaternary time. Late Quaternary faults are well documented in the Salt and Tularosa Basins west, respectively, of the Guadalupe-Delaware and Sacramento uplifts (V. Kelley, 1971; Goetz, 1980; Seager, 1980; Pray, 1988)."

Hayes, P.T., and Bachman, G.O. 1979. Examination and Reevaluation of Evidence for the Barrera Fault, Guadalupe Mountains, New Mexico. Open-File Report 79-1520. U.S. Geological Survey, Denver, CO.

ABSTRACT, p. 1;

" In southeastern New Mexico a prominent escarpment marks the southeastern boundary of the Guadalupe Mountains and the massive Capitan limestone of Permian age is well exposed along the mountain front. Vincent Kelley (1971, 1972) described faults that he named the Barrera and Carlsbad faults along the escarpment. As part of the earth-science investigations for the Waste Isolation Pilot Plant (WIPP) site, we examined the evidence for those faults in the field and conclude that the faults are nonexistent and that Kelley's conclusions were based on misinterpretation of exposures of fan gravel, jointing and shrub alinement."

Hills, J.M., 1984. Sedimentation, Tectonism, and Hydrocarbon Generation in Delaware Basin, West Texas and Southeastern New Mexico. *American Association of Petroleum* Geologists Bulletin, Vol. 68.

Introduction;

" The Delaware basin is the western major structural subdivision of the Permian basin of west Texas and southeastern New Mexico (Figure 1). It covers an area of more than 13,000 mi^2 (33,500 km^2) and is filled to a maximum depth of 24,00 ft (7,300 m) by Phanerozoic sedimentary rocks-a volume of about 40,000 mi^3 (170,000 km^3) Figure 2). Its history as a separate structural unit dates from the Early Carboniferous, but an ancestral basin, the Tobosa (Galley, 1958), was in existence from latest Precambrian to middle Paleozoic. The separation of the Tobosa basin into the Delaware basin, Central Basin uplift, and Midland basin was influenced by Proterozoic lines of weakness connected with the development of a north-northwest-trending trough, which may have been an aulacogen on the edge of the North American craton during the Grenvillian orogeny about 1 b.y.B.P. If this was an aulacogen, subsidence must have ceased before the Paleozoic began, inasmuch as Lower Cambrian rocks are not present and Ordovician strata are not overly thickened.

Movement along these zones of weakness was not renewed until the Mississippian and culminated in the formation of a deep Delaware basin in the Early Permian.

The most important aspect of the Phanerozoic history of the Delaware basin is the repeated accumulation of large amounts of organic materials in the deep, poorly ventilated marine basin and the subsequent conversion of these substances to kerogen. After conversion to hydrocarbons, the fluids not only migrated into traps within the basin, but also into reservoirs associated with broad shelves of carbonate rocks surrounding the basin.

The very mild tectonism and increasing sedimentary overburden in the basin contributed to several generations of oil and gas formation. The deposition of thick evaporite beds in the Late Permian helped to seal the traps and preserve the hydrocarbons. Adams (1965) gave an excellent summary of the development of the Delaware basin as known at the time. The present paper attempts to add to the history of this basin and to point our the influence of sedimentation and tectonism on oil and gas generation and accumulation."

Conclusion, p. 266, para 7;

" The Delaware basin originated in the Proterozoic along the edge of the North American craton, perhaps as a result of northward movement of a segment of oceanic crust from a spreading center between North and South American craton. The basin persisted throughout the Paleozoic, first as a portion of the Tobosa basin and then as a separate subbasin of the larger Permian basin underlain by thickened crust.

Throughout its history, the Delaware basin remained unusually stable, with the most notable tectonic activity being a slow eastward tilting along faulted zones on its east side. During the Carboniferous, compressional forces formed several large anticlines in the older Paleozoic rocks of the eastern part of the basin. In later times, the basin was remarkably free of intense tectonic activity.

The sedimentary filling of the basin shows that through much of the Paleozoic, marine circulation in the basin was slightly restricted. The result was deposition of numerous shales with high organic contents, which became the source beds for large amounts of hydrocarbons."

Hiss, W.L., 1975. "Stratigraphy and Ground-Water Hydrology of the Capitan Aquifer, Southeastern New Mexico and West Texas," PhD dissertation. University of Colorado, Department of Geological Sciences,.Boulder, CO.

Introduction p 1, para 1;

" This study was started during the summer of 1965 by the U.S. Geological Survey in cooperation with the New Mexico State Engineer. The primary objective was to determine the effects on the Capitan aquifer of the withdrawal of fluids from this aquifer and other aquifers in measurable hydraulic communication; and, to assess, qualitatively, the effect, if any, of continued withdrawal of fluid from this aquifer on the flow of the Pecos River at Carlsbad, N. Mex. Secondary objectives included definition of the Capitan and other associated aquifers; and determination of (1) the stratigraphic position and dimensions of the Capitan aquifer; (2) the determination of the hydraulic characteristics of the Capitan aquifer and associated formation of Permian Guadalupian age; (3) the quality of water contained in these aquifers; (4) the stratigraphic and hydrologic relationships between the Capitan aquifers and other formation; and (5) the total amount of fluids of various types produced from the Capitan aquifers and other reservoirs of Permian Guadalupian age.

The Capitan aquifer is defined elsewhere in this report but is comprised chiefly of the Capitan and Goat Seep Limestones and the Carlsbad facies of the Artesia Group. The Capitan aquifer and several stratigraphic units of equivalent age are important sources of ground water for the city of Carlsbad and for irrigation in the Pecos River basin in New Mexico and Texas. In addition to the fresh water produced for domestic, municipal, and agricultural use in New Mexico and the slightly to moderately saline water used of irrigation in Texas, large quantities of saline ground water are being withdrawn from the Capitan aquifer in Lea County, New Mexico, and Winkler and Ward Counties, Texas (Guyton and Associates, 1958; Brackbill and Gaines, 1964; and Table 1). This water, along with additional saline waste water produced with oil, is transported to other areas where it is injected into several formations to repressurize partly depleted reservoirs in a number of oil fields."

Location and extent of the area, p 8;

" The concentration of project activities was more intensive in New Mexico than in Texas. Emphasis was placed on an arcuate strip following the trend of the Capitan aquifer along the north and east margins of the Delaware basin between the Guadalupe Mountains southwest of Carlsbad and the Glass Mountains southwest of Fort Stockton, Tex. (figs. 2 and 3)."

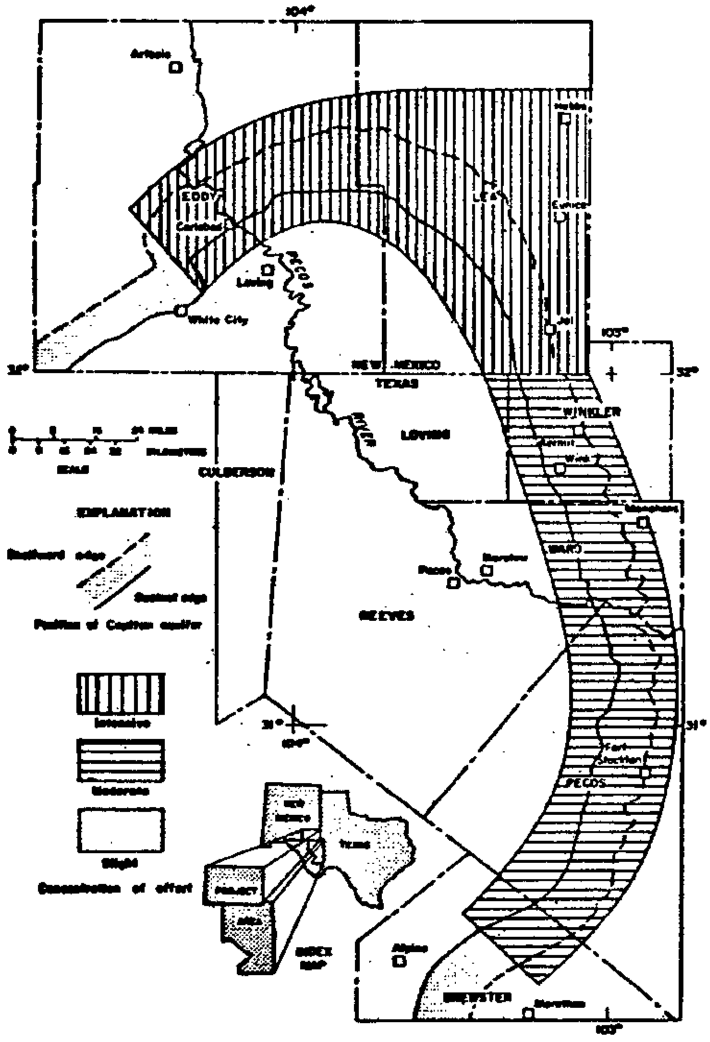


Figure 3.—Map showing concentration of effort within project area.

Structural configuration of the Guadalupian Series, p 114;
"   ... Rocks in the Delaware Mountain Group dip gently eastward from the Delaware and Guadalupe Mountains, northeast from the Apache Mountains, and northward from the Glass Mountains, toward the center of basin in eastern Reeves and northern Pecos Counties, Texas, at about the same rate."

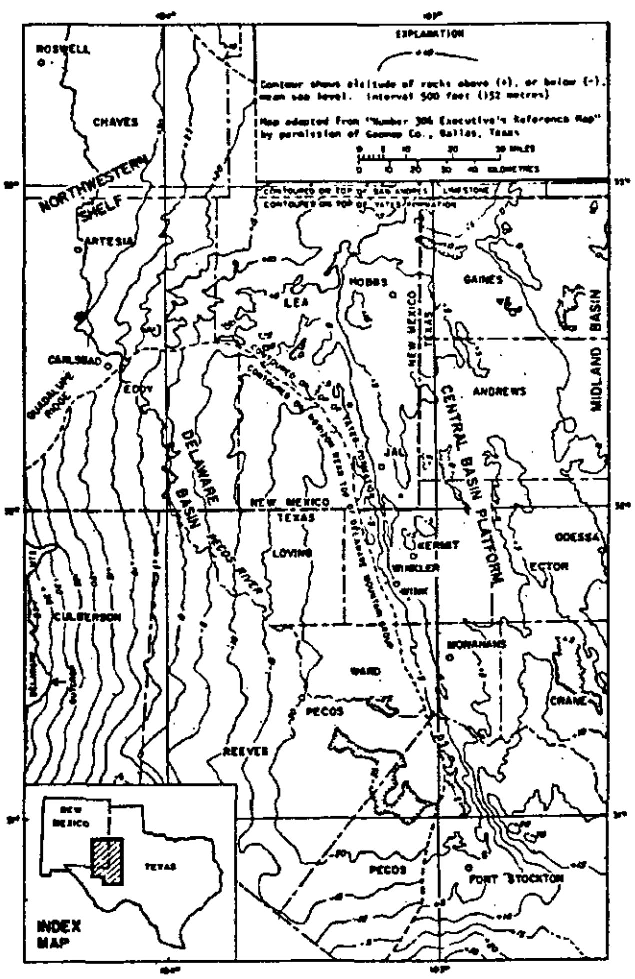


Figure 15.--Map showing structural configuration of the Delaware basin, Northwestern shelf, and Central Basin platform near the top of rocks of Permian *Guadalupian* age.

Regional hydraulic conductivity, p. 198;

" Meager data of often-questionable reliability, in conjunction with an interpretation of the geohydrological history of the region, suggest that the hydraulic conductivity of the Capitan aquifer along the western margin of the Central Basin platform in Texas and New Mexico ranges from 1 to 25 ft/day (.3 to 7.6 m/day) (table 7). The hydraulic conductivity of the Capitan aquifer probably averages 5.0 ft/day (1.5 m/day) in most of southern Lea County, New Mexico, but appears to increase progressively southward to an estimated 10.0 ft/day (3.0 m/day) near the Pecos-Brewster County boundary in Texas. The hydraulic conductivity of the Capitan aquifer in the Glass Mountains is probably very high because of the numerous small caverns developed in this area (D. J. Sibley, Jr., personal commun.).

An average hydraulic conductivity of 5.0 ft/day (1.5 m/day) also would seem to be reasonable for the Capitan aquifer over a span of approximately 15 miles (14 kilometers) immediately east of the Pecos River valley at Carlsbad. Values of hydraulic conductivity in the Capitan aquifer west of the Pecos River at Carlsbad are apparently larger by as much as several orders of magnitude (Hale, 1945a and 1945b).

Local variations in transmissivity

The transmissivity of the Capitan aquifer in a small area near the boundary between Eddy and Lea Counties, New Mexico, in the vicinity of the deeply incised Laguna submarine canyons appears to be the lowest encountered anywhere within the project area.

A representative transmissivity for this major restriction has not yet been determined. However, the general response to stresses placed on the aquifer by (1) withdrawal of water in the water fields to the east, (2) recharge by floods in the Pecos River valley, and (3) precipitation in the Guadalupe Mountains to the west, suggest that the transmissivity must be at least one and perhaps two orders of magnitude lower than the average transmissivity of the Capitan aquifer.

Values of transmissivity for the Capitan aquifer in the area extending east of the Pecos River at Carlsbad around the northern and eastern margin of the Delaware basin to the Pecos-Brewster County boundary in Texas are estimated to range from approximately 10,000 ft^2/day (900 m^2/day) in the thicker intercanyon nodes to less than 500 ft^2/day (450 m^2/day) in the vicinity of the more deeply incised submarine canyons."

"Conclusions

Permian Guadalupian age strata can be divided into three aquifers. The Capitan aquifer is lithosome that includes the Capitan and Goat Seep Limestones and most or all of the Carlsbad facies of Meissner (1972). Some of the shelf-margin carbonate banks or stratigraphic reefs in the upper of San Andres Limestone are included within the Capitan aquifer whenever they cannot be readily distinguished from the Goat Seep Limestone and Carlsbad facies. Saturated strata yielding significant quantities of water from the San Andres Limestone and the Bernal and Chalk Bluff facies of Meissner (1972) comprise the shelf aquifers. The contact between the Capitan and shelf aquifers is gradational and is difficult to discern with accuracy is some areas. Similarly, saturated strata yielding significant quantities of water from the Brushy Canyon, Cherry Canyon, and Bell Canyon Formations of the Delaware Mountain Group are referred to as the basin aquifers."

Hiss, W.L. 1976. Structure of the Permian Guadalupian Capitan Aquifer, Southeast New Mexico and West Texas. Resource Map. New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.

INTRODUCTION;

" The Capitan aquifer of Permian (Guadalupian) age is an important source of the ground water used for municipal, industrial, and agricultural purposes at and in the vicinity of Carlsbad, N. Mex. In addition, water pumped from this aquifer in southern Lea County, New Mexico and Winkler and Ward Counties, Texas, is injected into other subsurface reservoirs by oil companies to increase the recovery of petroleum from partly depleted oil fields (Hiss, 1971; White, 1971). A knowledge of the structural position of the Capitan aquifer in southeastern New Mexico and western Texas will be useful in programs designed either to explore for and develop additional ground-water supplies or to manage this important resource."

Structural position, para. 4;

" The contours showing the structural position of the top of the Capitan aquifer may falsely suggest a series of closed structural highs alternating with plunging synclines. However, when the configurations of the contours of the structural position and the thickness of the Capitan aquifer (Hiss, 1975b) are compared, there is a striking coincidence of features. Apparently, most of the features appearing as structural lows are depressions in the surface of the Capitan aquifer and are due to nondeposition and (or) erosion in surge channels and submarine canyons of Guadalupian age rather than to warping of the Capitan aquifer (Hiss, 1974; 1975a; 1975c)."

Holt, R.M., and Powers, D.W. 1984. Geotechnical Activities in the Waste Handling Shaft Waste Isolation Pilot Plant (WIPP) Project Southeastern New Mexico. WTSD-TME-038. U.S. Department of Energy, Carlsbad, NM.

ABSTRACT, p. v;

" The Waste handling shaft (waste shaft) at the Waste Isolation Pilot Plant (WIPP) site is an enlargement of the drilled, Site and Preliminary Design Validation (SPDV) ventilation shaft. Geotechnical activities in the waste shaft were designed to confirm the SPDV ventilation shaft mapping results and to provide additional information about identified zones of interest. The activities included identification of instrument locations, geologic inspections of the exposed shaft surface during sinking operations, reconnaissance geologic mapping of the waste shaft sump, and detailed geologic mapping in identified zones of interest. These activities were carried out concurrently with construction.

The results of the geologic inspections in the waste shaft and the reconnaissance geologic mapping in the waste shaft sump correlate well with previous characterizations. However, the detailed 360° geologic mapping performed in several zones of interest did not reveal post-depositional dissolution features, thought to occur at several stratigraphic horizons in the Rustler Formation at the WIPP site. At the waste shaft, zones previously identified as dissolution residues in nearby boreholes contained pronounced primary sedimentary features."

4.2.2.4 Culebra Dolomite Member, p. 4-6, para. 4;

" In the waste shaft, the Culebra occurs in the depth interval from 706.5 feet to 728.5 feet (Figure 9). The upper one-half to two feet of the Culebra is a medium brown, microlaminated to thinly laminated carbonate. This unit averages about 0.8 feet in thickness throughout the circumference of the shaft, but thickens up to two feet in the vicinity of mound-like dome structures. In general, the laminations within the carbonate unit are horizontal to subhorizontal. However, the laminae in the mound structures are often crenulated and dip slightly away from the center. It is likely that this unit is of algal origin. a 1/4 to 1-inch thick bed of cohesive, black claystone underlies the carbonate unit. The remainder of the Culebra primarily consists of brown, finely crystalline dolomite containing both empty and gypsum-filled vugs of varying size."

p. 4-9, para. 1;

" From a depth of about 781.0 feet to a depth of about 844.0 feet, the lower member consists of interbedded siltstone, sandstone, mudstone, and claystone with an abundance of primary sedimentary structures. These sedimentary structures include laminated sediments, cross-laminations, trough cross laminations, and channel lag (Plate 4) containing invertebrate fossil hash. The basal contact with the Salado is sharp, and the rock overlying the contact appears to be undisturbed by dissolution. The average depth to the Rustler/Salado contact in the shaft is about 844.0 feet."

Holt, R.M., and Powers, D.W. 1986. Geotechnical Activities in the Exhaust Shaft. DOE-WIPP-86-008. U.S. Department of Energy, Carlsbad, NM.

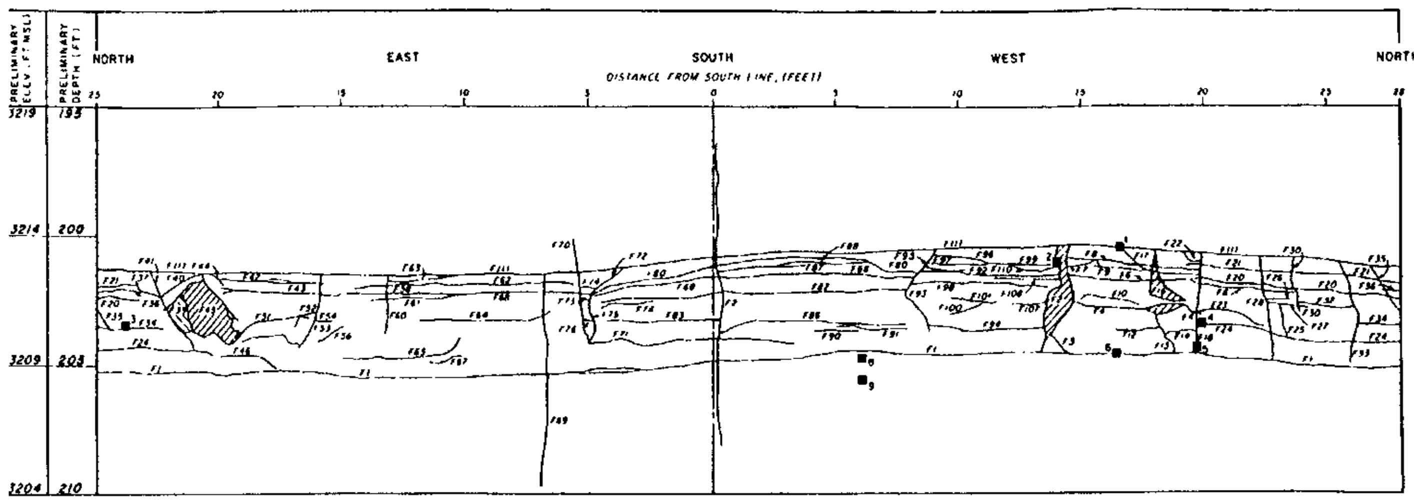
INTRODUCTION, p. 1-1;

" The Waste Isolation Pilot Plant (WIPP) project is a Department of Energy (DOE) research-and-development facility constructed to demonstrate the safe disposal of radioactive wastes derived from the defense activities of the United States. The WIPP project's mission consists of two parts. The first is to demonstrate the safe handling and disposal of transuranic (TRU) waste in bedded salt. The second is to create a research facility for in-situ examination of the technical issues related to the emplacement of defense-related radioactive waste in bedded salt.

The WIPP facility is located approximately 26 miles east of Carlsbad, New Mexico in an area known as Los Medanos (Figure 1). The underground portion of the facility is located at a depth of approximately 2,150 feet in the bedded salt deposits of the Salado Formation (Figure 2). An extensive program of site characterization and validation has been conducted for the past nine years (1976-1985). The results of these studies are summarized in the WIPP 'Geological Characterization Report' (Powers et al., 1978), the WIPP 'Safety Analysis Report' (DOE, 1980), the WIPP 'Preliminary Design Validation Report' (Bechtel, 1983), and the WIPP 'Results of Site Validation Experiments' (Black et al., 1983). Additional site investigations are being conducted as part of an ongoing program to further refine the understanding of the site-specific geology. The geotechnical activities conducted in the exhaust shaft are part of this program.

The exhaust shaft will provide a pathway for the release of exhaust air from the facility to the surface. The shaft is an enlargement of a six-foot diameter, upreamed shaft. The finished diameter is 14 feet in the lined portion of the shaft and 15 feet minimum in the unlined portion. Geotechnical activities consisting of reconnaissance geologic mapping, detailed geologic mapping in specific zones of interest, geologic confirmation of instrument locations, and field adjustment and modification of the key and aquifer seal design were performed concurrently with construction from July 16, 1984 to January 18, 1985. This report presents and discusses the findings from the geologic mapping efforts in the exhaust shaft. Also, the construction history of the exhaust shaft is summarized, and several engineering geology characteristics are discussed."

NOTE: The notes applicable to Figures 6, 7, & 8 (Figure 6 - Sh 2 of 11 through 11 of 11; Figure 7 - Sh 2 of 9 through 9 of 9; and Figure 8 - Sh 2 of 6 through 6 of 6) have not been included in this document to reduce document size.



NOTES

1) THIS INTERVAL WAS MAPPED ON 10-3-84.
2) THE LITHOLOGY OF THIS INTERVAL IS DESCRIBED IN FIGURE 4.
3) DEPTHS AND EVALUATIONS ARE RELATED TO THE REFERENCE ELEVATION OF 3409 FEET ABOVE MSL.
4) ONLY FRACTURES THAT WERE DEEMED "MAPABLE" AT A SCALE OF ONE INCH EQUALS FIVE FEET ARE INCLUDED ON THE MAP.
5) MAPPING EFFORTS WERE CONCENTRATED IN THE DEPTH INTERVAL FROM 195.0 FEET TO 200.0 FEET.

EXPLANATION

F20 MAPPED FRACTURE #20, SEE FRACTURE NOTES FOR DESCRIPTION
24 SAMPLE LOCATION, EXHAUST SHAFT DETAILED MAPPING SAMPLE #24
F29 MAPPED FRACTURE #29, FRACTURE SURFACE EXPOSED

FIGURE 6 - SHEET 1 OF 11

FRACTURE LOG IN
THE DEWEY LAKE REDBEDS
DEPTH 190.0 THROUGH 205.0 FEET
EXHAUST SHAFT

WASTE ISOLATION PILOT PLANT
CARLSBAD, NEW MEXICO

PREPARED FOR
WESTINGHOUSE ELECTRIC CORPORATION
CARLSBAD, NEW MEXICO

IT CORPORATION

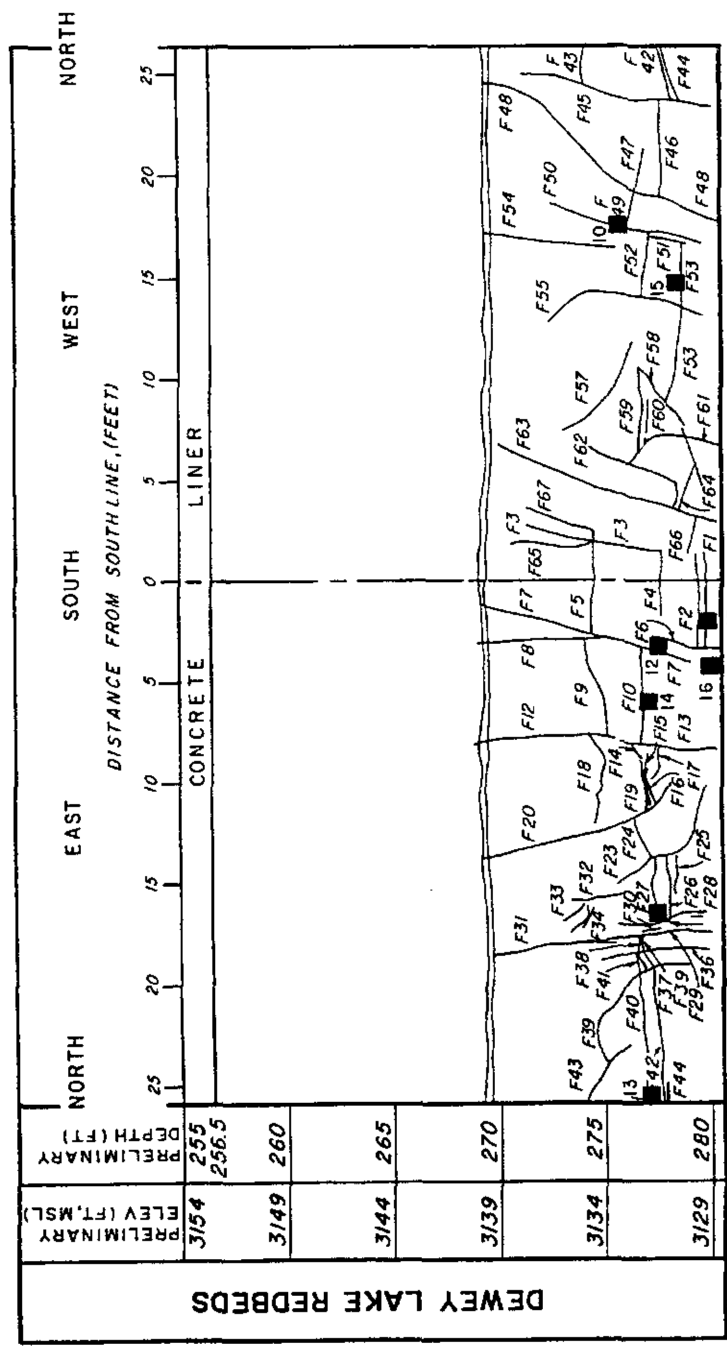


FIGURE 7 - SHEET 1 OF 9
FRACTURE LOG IN THE DEWEY LAKE REDBEDS
DEPTH 256.5 TO 280.5 FEET, EXHAUST SHAFT
WASTE ISOLATION PILOT PLANT
CARLSBAD, NEW MEXICO
PREPARED FOR
WESTINGHOUSE ELECTRIC CORPORATION
CARLSBAD, NEW MEXICO
IT CORPORATION

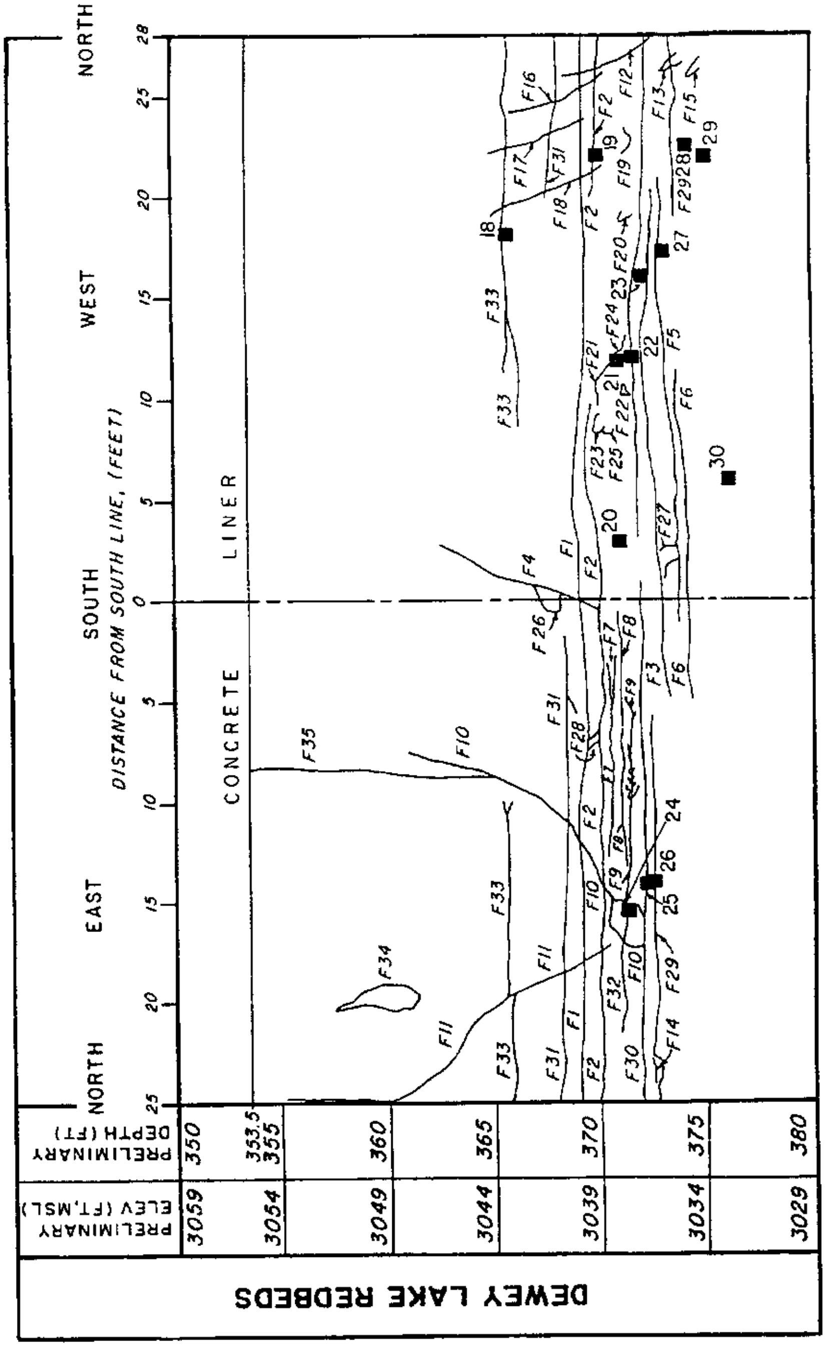


FIGURE 8 - SHEET 1 OF 6
FRACTURE LOG IN THE DEWEY LAKE REDBEDS
DEPTH 353.5 TO 380.0 FEET, EXHAUST SHAFT

WASTE ISOLATION PILOT PLANT
CARLSBAD, NEW MEXICO

PREPARED FOR
WESTINGHOUSE ELECTRIC CORPORATION
CARLSBAD, NEW MEXICO

IT CORPORATION

Holt, R.M., and Powers, D.W. 1990. Geologic Mapping of the Air Intake Shaft at the Waste Isolation Pilot Plant. DOE/WIPP 90-051. U.S. Department of Energy, Carlsbad, NM.

EXECUTIVE SUMMARY, p ES-1;

" The air intake shaft (AIS) at the Waste Isolation Pilot Plant (WIPP) site was constructed to provide a pathway for fresh air into the underground repository and maintain the desired pressure balances for proper underground ventilation. It was up-reamed to minimize construction-related damage to the rock wall. The upper portion of the shaft was lined with slip-formed concrete, while the lower part of the shaft, from approximately 903 ft below top of concrete at the surface, was unlined. As part of WIPP site characterization activities, the AIS was geologically mapped.

The AIS was geologically mapped during the period from March 11, 1988 to November 14, 1989. The objectives of the geologic mapping were to: 1)provide confirmation and documentation of strata overlying the WIPP facility horizon; 2)provide detailed information of the geologic conditions in strata critical to repository sealing and operations; 3) provide technical basis for field adjustments and modification of key and aquifer seal design, based upon the observed geology; 4) provide geological data for the selection of instrument borehole locations; 5) and characterize the geology at geomechanical instrument locations to assist in data interpretation. All mapping activities were performed from a two deck galloway (work platform) and synchronized with shaft construction activities. The AIS was mapped according to the procedures described in WP 07-503, 'Geologic Mapping of Shafts' (April 25, 1988) (Appendix B).

The entire shaft section including the Mescalero Caliche, Gatuña Formation, Santa Rosa Formation, Dewey Lake Redbeds, Rustler Formation, and Salado Formation to the WIPP facility horizon was geologically described. The shaft construction method, up-reaming, created a nearly ideal surface for geologic description. Small-scale textures usually best seen on slabbed core were easily distinguished on the shaft wall while larger-scale textures not revealed in core were well displayed. Previously undescribed textures were interpreted, and the AIS data were used to further refine depositional and post-depositional models of the units mapped.

The upper part of the Dewey Lake Redbeds displayed features consistent with Schiel's (1988) interpretation of the depositional environments. The geologic mapping data indicated deposition in a fine-grained, ephemeral fluvial system (Schiel, 1988). The lower part of the Dewey Lake, however, was depositionally a continuation of Rustler style sedimentation and accumulated in saline mud flat/mud flat environments. Most gypsum-filled fractures developed incrementally in response to unloading, while some Dewey Lake are syndepositional. Within the Dewey Lake, a cement change between carbonate and, possibly, anhydrite was observed at a depth of 164.5 feet. Perched water tables within the Dewey Lake may rest on this cement change. Above the cement change, the shaft surface was moist and displayed an efflorescent crust consisting of halite. The source of the halitic water is attributed to the muck-piles north and east of the AIS.

The features observed within the Rustler are consistent with those reported by Holt and Powers (1984, 1986, and 1988). Mudstones within the Rustler created a spalling hazard as several feet of mudstone had spalled out of the units and large slabs to desk-top size had to be scaled from the rib prior to mapping. Liner plate was installed over all Rustler mudstones. The surface of the lower part of the Rustler required extensive washing and scaling prior to mapping as Culebra and construction waters dissolved halite crystals and cements. Extensive vertical fluxing was observed.

The AIS data from the Salado allowed the authors to add considerably to the understanding of the depositional and diagenetic history of the Salado. Unprecendeted halite textural and fabric data was collected, characterized, and interpreted from the Salado. An idealized Salado halite sequence was constructed, and all Salado halite observed within the AIS fits partially or wholly into the idealized sequence. Complete Salado halite sequences consist of four lithofacies, in ascending order: 1) stratified mud-poor halite; 2) 'podular' muddy halite; 3) 'dilated' mud-rich halite; and 4) halitic mudstone. These lithofacies developed in four distinct depositional environments: 1) a mud-poor salt pan; 2) a 'hummocky' salt pan; 3) a mud-rich salt pan; and 4) a saline mud flat.

Salado sulfate interbeds (including Markerbeds) displayed abundant previously undescribed textures and fabrics. Textural data from the AIS provided the basis for further interpretation of these interbeds. Salado sulfate interbeds were deposited in shallow saline lagoon environments following eustatically- or meteorically-driven, basin-wide flooding and freshening events (Lowenstein, 1982, 1983, 1988). Different hydrologic conditions produced three distinct types of sulfate interbeds within the Salado. The sulfate interbeds bounding the repository horizon may be laterally variable due to facies changes within the depositional environment. Geologic evidence of naturally occurring late-stage fluid migration or alteration within the halite of the Salado was not found. Mineralized and fluid-filled fractures occur within some sulfate interbeds within the Salado."

p. 3-3, para. 1;

" At the AIS, the Gatuña is 13 feet thick and consists of very calcareous, very friable, soft sandstone (Figures 4 and 5). The Gatuña is light red and mottled with dark stains. Carbonate occurs as stringers and concretions in probable rhizolithic structures. Clay-sized materials locally appear translocated. Some pebble-sized clasts of sandstone are probably derived from the underlying Santa Rosa Formation. The Gatuña overlies a sharp erosional contact on the Santa Rosa Formation."

p. 3-4, para. 2;

" The Dewey Lake is characterized by its reddish-orange to reddish-brown color and varying sedimentary structure. At the WIPP site (as exposed in the AIS), the Dewey Lake is 476 feet thick and consists of interbedded reddish-brown fine sandstone, siltstone, mudstone and claystone (Figure 5). The Dewey Lake is distinguished from other redbed units by the presence of greenish-gray reduction spots, which are liberally sprinkled throughout the formation, and locally abundant fibrous gypsum-filled fractures. Its upper contact with the Santa Rosa Formation is sharp and erosional (Figure 6). The lower contact of the Dewey

Lake with the Rustler Formation is sharp, with a minor amount of erosional relief (Figure 7 and 8). This contact is locally disconformable, but there is evidence of a regional unconformity (Holt and Powers, 1988)."

3.4.3 Origin and Significance of Gypsum-Filled Fractures, p. 3-8;

" With the exception of the upper portion, the Dewey Lake is characterized by locally abundant gypsum-filled fractures. Most of the fractures are filled with fibrous gypsum, although granular gypsum fracture fillings do occur in the upper portion of the Dewey Lake. In the AIS, gypsum-filled fractures are abundant below 164.5 feet. The fracture filling gypsum is fibrous indicating incremental growth. The fracture pattern and filling morphology is governed by the grain-size of the fractured host material, as discussed below."

3.4.4 Origin of Perched Water Tables in the Dewey Lake, p. 3-10, para. 2;

" At the AIS, the Dewey Lake is cemented with carbonate above 164.5 feet. The coarse-grained units (sandstones and siltstones) are usually moderately hard, though a few are soft. The mudstones and claystones are soft and commonly fissile. Fractures are unfilled or filled with carbonate, and carbonate-filled fractures increase downward. The surface of the AIS wall in the Dewey Lake is moist down to 164.5 feet, and a halitic efflorescence is sometimes present on the shaft wall. ..."

p 3-11, para 2;

" At the WIPP site, meteoric water probably infiltrates through the surface materials (dune sand and construction fill material) to the Mescalero caliche, where it moves downgradient off of the site or evaporites. When the Mescalero caliche and the Pleistocene and Triassic rocks have been disturbed by construction activities, this water can infiltrate along these newly created pathways into the underlying Dewey Lake. The water will infiltrate to the cement change surface and either stop or move down gradient. The impact of this process should be assessed with respect to shaft plugs and seals."

p 3-26, para 3;

" The lower mud-poor section of the sequence is dominated texturally by an overall sense of horizontal to subhorizontal stratification and is named the 'stratified' mud-poor lithofacies (Figure 1, Appendix F). It is subdivided into three zones with small-scale textures. The first zone is dominated by bottom growth halite textures including halite chevron, cornet, and cumulates and clay or sulfate laminae. The second zone shows abundant passive pore-filling halite cements in small dissolution pits and pores. The uppermost zone contains exhibits mostly expansive halite cement textures (displacive halite) mixed with various syndepositional solution textures and fabrics. These textures are consistent with deposition in a mud-poor salt pan.

The 'podular' muddy halite lithofacies is characterized by lenses and pods of fine to medium crystalline halite (Figure 1, Appendix F). Generally, it is more argillaceous then the 'stratified' mud-poor lithofacies. The 'podular' muddy halite lithofacies is subdivided into two zones which laterally and vertically interfinger: 1) a zone dominated by expansive (displacive) halite cements and 2) a zone with few expansive cements. Few textures reflecting subaqueous deposition are preserved, and continuous strata are very rare. Dissolution pits, pipes, and pores are common. Textures within this lithofacies are similar to 'hummocky' salt pan halite in the Devil's Golf Course in Death Valley, California."

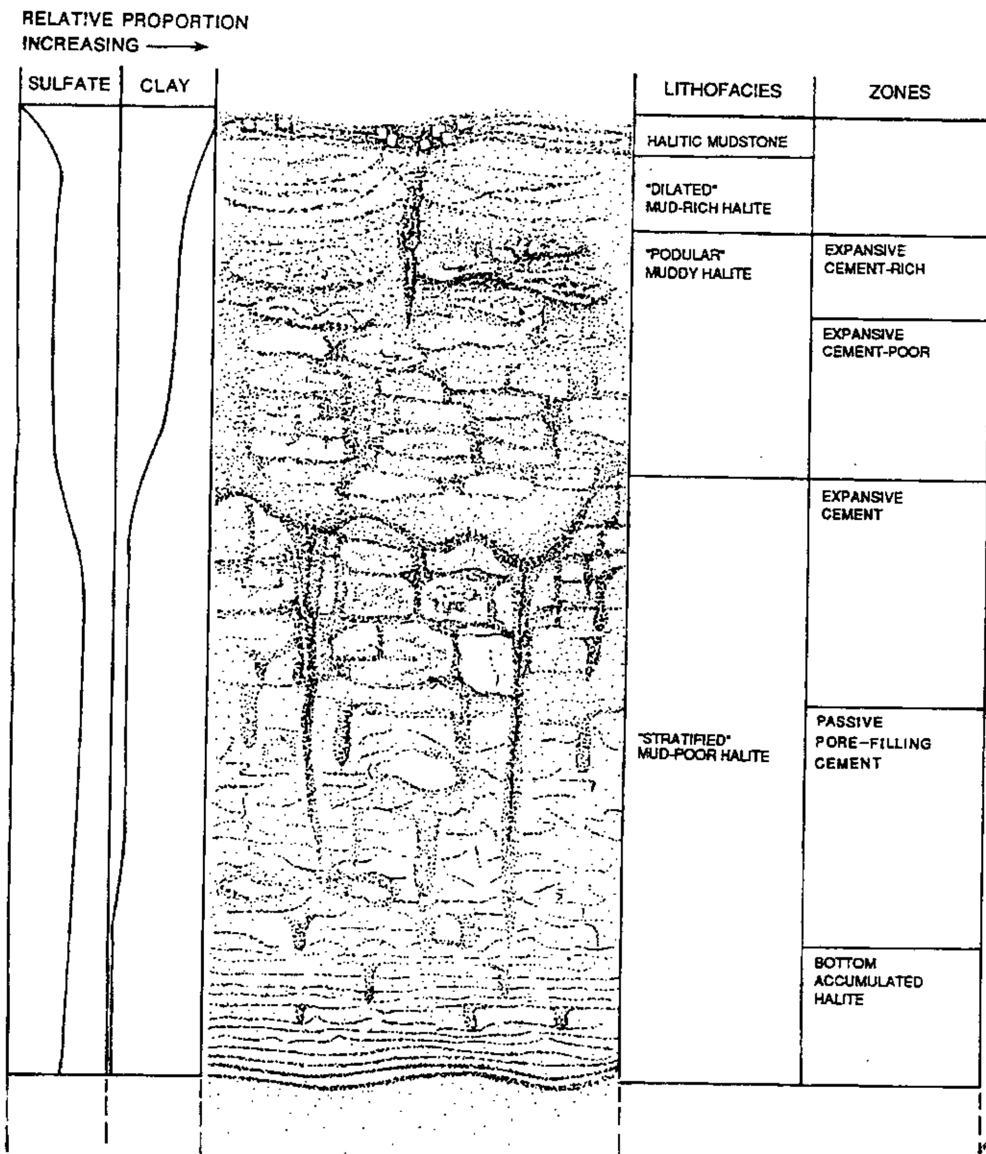
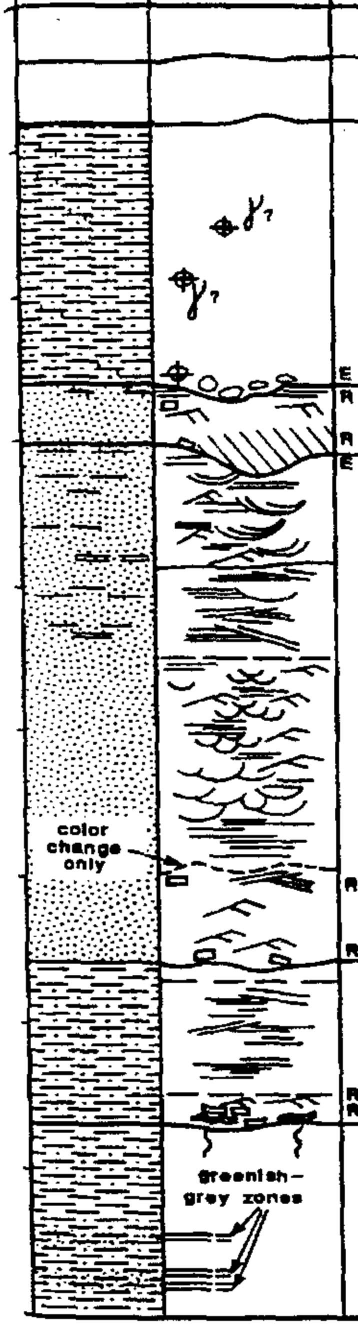


FIGURE 1 IDEALIZED SALADO HALITE SEQUENCE LITHOFACIES AND ZONES.

Appendix F - Figure 1

LITHOLOGY / FEATURES	REMARKS
	TOP OF SUBCOLLAR CONCRETE BASE OF SUBCOLLAR CONCRETE
	FILL MATERIAL, DARK REDDISH BROWN, MOTTLED; BECOMES LESS DISTURBED DOWNWARD.
	GATUNA FORMATION - UNDISTURBED. SANDSTONE, LIGHT RED, MOTTLED, VERY CALCAREOUS, SLIGHTLY ARGILLACEOUS. VERY FINE SAND TO SILT-SIZED GRAINS, SUBANGULAR TO ROUNDED, ESTIMATED 80 PERCENT QUARTZ, 5 PERCENT MAFIC GRAINS, 15 PERCENT OTHER. CARBONATE STRINGERS GENERALLY ORIENTED SUBHORIZONTALLY, CARBONATE CONCRETIONS ARE POSSIBLE ROOT CASTS. SOME CLAYS AND ARGILLACEOUS MATERIAL ARE POSSIBLY TRANS-LOCATED; POSSIBLE BIOTURBATION. UNIT LOCALLY CONTAINS CLASTS OF MORE CALCAREOUS, HARDER SANDSTONE (POSSIBLY REWORKED CALICHE CLASTS) AND GREENISH-GRAY CLASTS (POSSIBLY SANTA ROSA FM.). SURFACE OF UNIT IS LOCALLY MOIST AND EXHIBITS NaCl-RICH EFFLORESCENT CRUST; UNIT IS VERY FRIABLE, SOFT. BASAL CONTACT SHARP, EROSIONAL (2 FT RELIEF), OVERLAIN WITH COBBLE-SIZE RIPUPS OF UNDERLYING SANDSTONE AND GRANULE-SIZED RIPUPS OF DARK BROWN CLAYSTONE.
	SANTA ROSA FORMATION. SANDSTONE, CALCAREOUS, RED; SILT TO FINE SAND-SIZED GRAINS, 80 PERCENT QUARTZ, 5 PERCENT MAFIC, 15 PERCENT OTHER, GRAINS SUBANGULAR TO ROUNDED. TABULAR CROSS-CUTTING BEDS UP TO 2 FT THICK; UPPER SURFACE BOUNDED BY HARD, VERY CALCAREOUS, VERY THIN BEDS AND CLASTS OF SANDSTONE; DARKER BEDS MAY BE CROSS-LAMINATED; LIGHTER INTERBEDS CONTAIN THIN LAMINAE TO LAMINAE OF CALCAREOUS SANDSTONE PARALLEL TO CROSS-CUTTING SURFACES; CALCITE-RICH UNITS CONTAIN RIPUP CLASTS OF DARK RED SILTSTONE, LOCAL COBBLE-SIZE RIPUP CLASTS OF WELL-CEMENTED SANDSTONE. VERY RARE SUBVERTICAL FRACTURES ARE FILLED WITH CALCITE, LOCAL STRINGERS POSSIBLY DEVELOPED ALONG FRACTURES; UNIT IS SOFT TO MEDIUM HARD. BASAL CONTACT SHARP, EROSIONAL RELIEF OF 2 FT.
	SILTY SANDSTONE TO SILTSTONE, DARK REDDISH BROWN (10R3/6), WITH PALE OLIVE (10Y6/2) FROM 30 FT TO BASE; CALCAREOUS; FINE TO MEDIUM AT BASE TO FINE TO VERY FINE SAND GRAINS UPWARD; DOMINANTLY QUARTZ, 1-5 PERCENT MAFIC GRAINS; SOFT TO MODERATELY WELL INDURATED. THINLY LAMINATED TO CROSS-LAMINATED FROM 15-19 FT WITH LOCALLY ABUNDANT TROUGH CROSS-BEDS HAVING TANGENTIAL BOTTOMSETS, TROUGH .1-.3 FT DEEP AND 1 FT WIDE IN A CHANNEL BAR COMPLEX. PLANAR LAMINAE TO LOW ANGLE CROSS-LAMINAE (IN-CHANNEL BARS) FROM 19-22 FT IN SETS <.3 FT HIGH WITH LOCAL ARGILLACEOUS ZONES MARKING TOPS OF SETS. TROUGH CROSS-BEDS FROM 22-28 FT (CHANNEL DEPOSITS) IN SETS .4-.7 FT HIGH, DECREASING IN SIZE UPWARD TO .1-.3 FT SETS INTERBEDDED WITH THIN LAMINAE AND CROSS-LAMINAE. PARALLEL PLANAR, HORI-ZONTAL TO SUBHORIZONTAL, THIN BEDS TO LAMINAE FROM 28-30 FT, WITH SOME BROAD CROSS-CUTTING SETS (CHANNEL DEPOSITS); UNDULATORY, BUT SHARP, COLOR CHANGE AT ABOUT 30 FT CUTS ACROSS BEDDING; ZONE OF SMALL CLAYSTONE CLASTS (1/4" X 1") AT 30.3 FT; COARSENS DOWNWARD FROM FINE TO MEDIUM SANDSTONE FROM 30.5-33 FT, WITH MINOR SILT AND CLAY. SHARP, EROSIONAL BASE WITH ABOUT 6" RELIEF OVERLAIN BY A FEW REDDISH BROWN CLASTS.
	SILTSTONE, ARGILLACEOUS, SLIGHTLY SANDY, FINING UPWARD TO SILTY CLAYSTONE; PALE OLIVE (10Y6/2) IN BASAL 1.5 FT, INTERBEDDED WITH AND OVERLAIN BY DARK REDDISH BROWN (10R3/6) TO VERY DARK REDDISH BROWN (10R3/3) AT TOP, SMALL, GREENISH REDUCTION SPOTS NEAR GRADATION TO CLAYSTONE; VERY CALCAREOUS. BEDDING UNCLEAR NEAR BASE. INTERBEDDED REDDISH BROWN LAYERS IN GREEN ZONE CONSIST OF CLAYSTONE AND CLAYSTONE CLASTS, SMALL (<.1 FT) RIPPLES NEAR TOP OF GREEN ZONE. ABOVE GREEN ZONE, MAINLY HORIZONTAL TO SUBHORIZONTAL LAMINAE WITH LOW ANGLE CROSS-CUTTING BEDS; SUBUNITS ARE UP TO 1 FT THICK, FINE UPWARD INTERNALLY. CLAYSTONE IS WET AND PROBABLY COLLECTING WATER IN OVERLYING SANDSTONE; VARIABLE SALT EFFLORESCENCE ON SHAFT WALLS; MODERATELY WELL INDURATED IN GREEN ZONE, WELL INDURATED TO SOMEWHAT FISSILE NEAR TOP. SHARP BASAL CONTACT.
	DEWEY LAKE FORMATION. CLAYSTONE, SILTY AND SANDY, VERY DARK REDDISH BROWN (10R3/3), WITH GRAYISH GREEN (10GY5/2). SLIGHTLY MORE SANDY BEDS NEAR BASE AND GREEN REDUCTION SPOTS NEAR TOP. SLIGHTLY COARSER ZONES AND INTERBEDS ARE VERY CALCAREOUS, WELL INDURATED, AND USUALLY .1-.3 FT THICK AT .3 TO 1 FT INTERVALS. BASAL PART SHOWS FINING UPWARD CYCLES ABOUT .5-1 FT THICK AND INTERBEDDED SILTSTONE AND CLAYSTONE. VERTICAL TO SUBVERTICAL FRACTURES IN UPPER 1-2 FT ARE

AIR INTAKE SHAFT LITHOLOGIC LOG
SHEET 3 OF 22

FIGURE 5

NOTE: Figure 16 is a photograph and will not scan in properly, therefore it is not included here.

Howard, K.A., Aaron, J.M., Brabb, E.E., Brock, M.R., Gower, H.D., Hunt, S.J., Milton, D.J., Muehlberger, W.R., Nakata, J.K., Plafker, G., Prowell, D.C., Wallace, R.E., and Witkind, I.J. 1971 [reprinted 1991]. Preliminary Map of Young Faults in the United States as a Guide to Possible Fault Activity. Miscellaneous Field Studies Map MF-916, 1:5,000,000. 4 maps on 2 sheets. U.S. Geological Survey, Denver, CO.

RIO GRANDE BASIN AND RANGE, Sheet 2 of 2;
"Rio Grande.--Abundant high-angle normal faulting in the late Cenozoic has formed the Rio Grande trough and adjacent basins and ranges. Evidence for movements in the Quaternary is common. The Rio Grande fault systems blend northward with similar basin-and-range faults that are somewhat masked by the surrounding topography of high Colorado Rocky Mountains."

Hunter, R.L., 1985. A Regional Water Balance for the Waste Isolation Pilot Plant (WIPP) Site and Surrounding Area. SAND84-2233. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p. 3;

" The WIPP water-balance study area defined here comprises ~2000 mi^2 in Eddy and Lea Counties, southeastern New Mexico. Inflows to the study area are precipitation (roughly 1.47×10^6 ac-ft/yr), surface water (roughly 1.1×10^5 ac-ft/yr), water imported by municipalities and industries (roughly 3×10^4 ac-ft/yr), and ground water (volume not estimated). Outflows from the area are evapotranspiration (roughly 1.5×10^6 ac-ft/yr), surface water (roughly 1.2×10^5 ac-ft/yr), and possibly some ground water. The volume of surface and ground water in storage in Nash Draw has increased since the beginning of potash refining. Regional ground water flow in aquifers above the Salado Formation is from the northeast to the southwest, although this pattern is interrupted by Clayton Basin, Nash Draw, and San Simon Swale. The Pecos River is the only important perennial stream. Most of the area has no integrated surface-water drainage.

The available data suggest that ~1600 mi^2 of the study area are hydrologically separate from Nash Draw and the WIPP site. Ground water north of Highway 180 apparently discharges into Clayton Basin and evaporates. Water in San Simon Swale apparently percolates downward and flows to the southeast. Data are inadequate to create a water budget for the Nash Draw-WIPP site hydrologic system alone, although an attempt to do so can provide guidance for further study."

Table 10, p. 29;

"Minimum and Maximum Annual Ground-water Discharge to the Pecos River

Pairs of Stations	Gain in TDS (tons)	Minimum Discharge (ac-ft)	Maximum Discharge (ac-ft)
4040-4052	--	--	7400
4052-4065	168,300	397.6	6100
4065-4070	99,000	233.9	3100
4070-4075	330,000	779.7	7000

"

p 32, col. 1, para 4, line 18;

". . . If no ground water evaporates from the southern two-thirds (other than precipitation that falls locally and seeps into the lake through the ground.), and if 12 in. of rain is equivalent to 3 ft of evaporation from the lake (using Mr. Williamson's estimate), then 1.4 ft/acre of ground water evaporates from 660 acres of the lake. This rough calculation results in an estimate of 924 ac-ft/yr of natural ground-water discharge from Laguna Grande de la Sal. Surprise Spring is the largest of the springs discharging into the lake, and therefore its known discharge provides a check on the estimate of total ground-water discharge from the lake. In 1942, Surprise Spring discharged 120 gpm (194 ac-ft/yr) (National Resources Planning Board 1942, p 69). The estimate of 924 ac-ft/yr total ground-water discharge does not seem unreasonable. No correction for the volume of dissolved solids, which would further reduce the estimate of ground-water discharge, has been made in this report."

Izett, G.A., and Wilcox, R.E. 1982. Map Showing Localities and Inferred Distribution of the Huckleberry Ridge, Mesa Falls, and Lava Creek Ash Beds in the Western United States and Southern Canada. Misc. Investigations Map I-1325, scale 1:4,000,000. U.S. Geological Survey.

DISCUSSION;

" During the past 10 years there has been increasing interest among earth scientists for tephrochronological data useful for establishing volcanic ash beds as time-stratigraphic markers. When tephrochronological data are combined with other geological information such as stratigraphic position, faunal age, paleomagnetic direction, and isotopic age, the result is a multipronged analytical device with a combined resolving power far greater than that of any individual geologic technique. Correct identification of an isotopically dated volcanic ash bed can provide critical information to help resolve problems such as (1) the correlation (over long distances) of sedimentary deposits of diverse origins (marine, lacustrine, fluviatile, paludal, glacial, periglacial, and eolian); (2) the determination of the times and rates of fault movements and other types of crustal deformation; (3) the determination of the average rates of deposition of sediments; (4) the evaluation of geologic hazards such as volcanic eruptions and earthquakes; (5) the calibration of paleomagnetic stratigraphies and faunal chronologies; (6) the calibration of experimental dating methods such as uranium-trend dating; (7) the identification of tephra sources; and (8) the evolution of silicic magma bodies and related tephra ejection mechanics, transportation, and deposition. Several upper Cenozoic volcanic ash beds of the western United States have been studied in considerable detail including tephra of Holocene age from Mount St. Helens volcano in Washington (Fryxell, 1965; Mullineaux and others, 1975; Westgate, 1977) in Washington; the Mazama ash bed of Holocene age (Powers and Wilcox, 1964); the Glacier Peak ash bed of latest Pleistocene age (Powers and Wilcox, 1964; Westgate and Evans, 1978); and the Bishop ash bed of middle Pleistocene age (Izett and others, 1970; Borchardt and others, 1972; Merriam and Bischoff, 1975; Sama-Wojcicki and others, 1980). These volcanic ashes are found interbedded in various types of fluvial, colluvial, and lacustrine Holocene and Pleistocene sedimentary deposits scattered from the West Coast of the United States to as far east as central Nebraska. Another set of volcanic ashes, the Pearlette family ash beds, also has been extensively studied and used for long range correlations of the enclosing sediments and their contained fossil materials. These ash beds are the main subject of this report.

By the late 1950's, the Pearlette ash was widely used as an important stratigraphic marker in the Great Plains area, and was thought to be a single bed, marking an instant of time in the geologic record of the middle Pleistocene. Vertebrate and invertebrate paleontologists used it as a datum to stratigraphically relate their fossil collections and stratigraphers used it as a correlation tool to relate sedimentary deposits over large areas of the Great Plains. However, a few geologists and paleontologists questioned the prevalent idea that the Pearlette constituted a single bed. Smith (1940, p. 119), Hibbard (1944, p. 744), and Powers and others (1958) pointed out evidence that conflicted with the established concept of a single Pearlette ash, and Smith (1940), in particular, suggested that the Pearlette might represent several beds of distinctly different age. Although these and other geologists had suspected that the Pearlette might be a multiple set of ash beds, no one, however, had found stratigraphically superposed beds of Pearlette-like ash beds in the Great Plains. Recently, superposed beds of Pearlette ash of markedly different ages have been found in the type area of the Pearlette ash in central Meade County, Kans., by detailed geologic mapping and stratigraphic studies (G.A. Izett and J.G. Honey, unpublished mapping, 1980).

As a result of detailed mineralogical and chemical studies of the Pearlette ash using newly developed analytical tools (spindle stage study of microphenocrysts, atomic absorption photospectrometric analyses of glass shards, instrumental neutron activation analyses of glass shards, paleomagnetic studies, and electron microprobe analyses of glass shards and microphenocrysts) we determined in the late 1960's that the Pearlette comprised three different but closely related mineralogical-chemical ash varieties. We provisionally designated these ashes as types B, S, and O (Izett and others, 1970; Izett and others, 1971) and correlated them with three, voluminous rhyolite ash-flow tuffs in the Yellowstone National Park area then being mapped by R.L. Christiansen and H. R. Blank of the U.S. Geological Survey. These ash-flow tuffs were named the Huckleberry Ridge, the Mesa Falls, and the Lava Creek Tuffs by Christiansen and Blank (1972). Precise, potassium-argon age determinations of sanidine were made of the three ash-flow tuffs and their associated air-fall units (J.D. Obradovich, written commun., 1979). The K-Ar ages of these units, calculated using current decay constants and $^{40}K/^{39}K$ abundance (Steiger and Jäger, 1977), are as follows: Huckleberry Ridge Tuff 2.02 m.y.; Mesa Falls Tuff, 1.27 m.y.; and Lava Creek Tuff (members A and B), 0.62 m.y. By inference, the ages of the downwind ash beds (Huckleberry Ridge, Mesa Falls, and Lava Creek) equivalents of the K-Ar dated source-area tuffs are also firmly dated--provided that firm mineralogical and chemical correlations are made between the source-area pyroclastic units and their suspected downwind correlative ashes.

. . .

The ash localities shown on the map are numbered sequentially in each State and number keyed to table 1 that gives locality and other information. The localities are listed in alphabetical order, first by State and then by County. In addition to ash beds of the map being classified as either Huckleberry Ridge, Mesa Falls, Lava Creek A, or Lave Creek B ash, certain other ash beds are designated as Pearlette family ash or simply Pleistocene ash. Many of the ash beds on the map can only be designated as Pearlette family because insufficient tephrochronological work has been done to further identify them as belonging to the Huckleberry Ridge, Mesa Falls, or Lava Creek ashes. Many of the localities shown on the map as Pleistocene ash (especially in Oklahoma) may be Pearlette family ashes based on their inferred stratigraphic position, inferred Pleistocene ages, and geographic locations, but no chemical or petrographic information is available for them. Where we have identified an ash as being either Huckleberry Ridge, Mesa Falls, or Lava Creek we have sufficient analytical data available in our files to make the identification with a high probability."

Jarolimek, L., Timmer, M.J., and McKinney, R.F. 1983. Geotechnical Activities in the Exploratory Shaft -- Selection of the Facility Interval, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico. TME 3178. U.S. Department of Energy, Albuquerque, NM.

Section 1.0 ABSTRACT, p 1-1;

" This report on geotechnical activities in the exploratory shaft was prepared as part of the Site validation Field Program for the U. S. Department of Energy's Waste Isolation Pilot Plant near Carlsbad, New Mexico. The report (1) summarizes basic data on shaft drilling and construction, (2) presents the geologic mapping results which essentially correspond to the conditions predicted from previous investigations, and (3) discusses the optimization process based on the geologic conditions encountered and its results for the (a) adjustment and modification of the shaft key design, (b) selection of the facility interval, and (c) selection of the geotechnical instrument locations."

Section 4.3 STATION ZONE GEOLOGY, P4-6, PARA 4;

" Of particular interest during the mapping was the location and nature of MB 139 and the presence of any clay seams or partings. As shown in Figure 6 and Plates 8 and 10, MB 139 is approximately 2 to 3.4 feet thick and is principally composed of anhydrite with minor amounts of polyhalite that occur in stringers and thin beds, particularly in the upper portion of the bed. The upper contact of MB 139 is undulatory and occurs between the elevations of 1251.7 and 1253.9 feet MSL. This undulatory contact (with an amplitude of 1.6 feet around the shaft) is believed to be the result of syndepositional processes, such as differential compaction of soft sediments and/or growth of 'swallow-tail' gypsum crystals (Plate 10). The absence of displaced stratigraphic contacts implies a nontectonic origin to the undulatory top of MB 139. More detailed discussion on MB 139 is presented in TME 3179 (Jarolimek, et al., 1983)."

Section 6.3 CONFORMANCE OF SELECTED INTERVAL TO CRITERIA, p 6-5;

" Subsequent to the geologic mapping and ensuing discussions, the following observations were made and conclusions reached regarding conformance of the selected facility interval to the selection criteria, as listed in Section 6.1:

Criterion No. 1:

Faults and fractures were not observed in the facility interval and no features known to be due to dissolution were observed."

Jones, C.L., Bowles, C.G., and Bell, K.G. 1960. Experimental Drillhole Logging in Potash Deposits of the Carlsbad District, New Mexico. Open-File Report. U.S. Geological Survey, Denver, CO.

p 6, para 2;

" Polyhalite, which is one of the hydrous minerals, is the most abundant and widespread potassium mineral. It is not economically valuable, but is important in the stratigraphy of the Salado formation. The mineral forms discrete beds, and occurs with anhydrite in other beds. These polyhalite-anhydrite beds are widespread, laterally persistent layers that serve as stratigraphic marker beds. Some of them are recognized by names, such as the Union anhydrite of local usage, and others are recognized by number. Numbering of potassium-bearing beds was introduced by Smith (1938). A modification of his system currently is used by most of the potash companies in the Carlsbad district. The polyhalite-anhydrite marker beds are numbered, and salt beds containing potash deposits are given names, such as the First Ore Zone. The lithologic character and thickness of the polyhalite-anhydrite marker beds, the potassium-bearing ore zones, and the name or number by which each bed or group of beds is recognized are shown on the composite columnar section (fig. 1)."

Figure 1. Generalized columnar section and radioactivity log of potassium-bearing rocks, Carlsbad district, southeastern New Mexico is a drawing too large to include in this document.

Jones, C.L., Cooley, M.E., and Bachman, G.O. 1973. Salt Deposits of Los Medaños Area, Eddy and Lea Counties, New Mexico. Open File Report 4339-7.U.S. Geological Survey, Denver, CO.

ABSTRACT, p 1;

" The salt deposits of Los Medaños area, in Eddy and Lea Counties, southeastern New Mexico, are being considered for possible use as a receptacle for radioactive wastes in a pilot-plant repository.

The salt deposits of the area are in three evaporite formations: the Castile, Salado, and Rustler Formations, in ascending order. The three formations are dominantly anhydrite and rock salt; but some gypsum, potassium ores, carbonate rock, and fine-grained clastic rocks are present. They have combined thicknesses of slightly more than 4,000 feet, of which roughly one-half belongs to the Salado. Both the Castile and the Rustler are richer in anhydrite and poorer in rock salt than the Salado, and they provide this salt-rich formation with considerable protection from any fluids which might be present in underlying or overlying rocks.

The Salado Formation contains many thick seams of rock salt at moderate depths below the surface. The rock salt has a substantial cover of well-consolidated rocks, and it is very little deformed structurally.

Certain geological details essential for waste-storage purposes are unknown or poorly known, and additional study involving drilling is required to identify seams of rock salt suitable for storage purposes and to establish critical details of their chemistry, stratigraphy, and structure."

p. 8, Para. 2;

" The Castile Formation underlies Los Medaños area at depths ranging from 1,700 feet near the northwest corner of the area to 3,600 feet near the southeast corner. As developed in this area, the Castile is a very typical basinal evaporite showing great lateral continuity of individual rock units, a well-formed lamination in most units, and a marked paucity of terrigenous debris. In general, the formation is composed of as much as 1,830 feet of anhydrite and rock salt with subordinate limestone, but it is readily separable into three informal members by a salt-rich zone 200-400 feet above the base (fig. 4). The threefold division includes: a lower member composed chiefly of anhydrite, a middle member composed chiefly of rock salt, and an upper member composed chiefly of anhydrite. The three members are discrete, readily distinguished lithologic units throughout the southern and central parts of the area, but northward they merge into a single wedgelike mass of anhydrite that thins rapidly to a narrow tongue at the north edge of Los Medaños area (fig. 3).

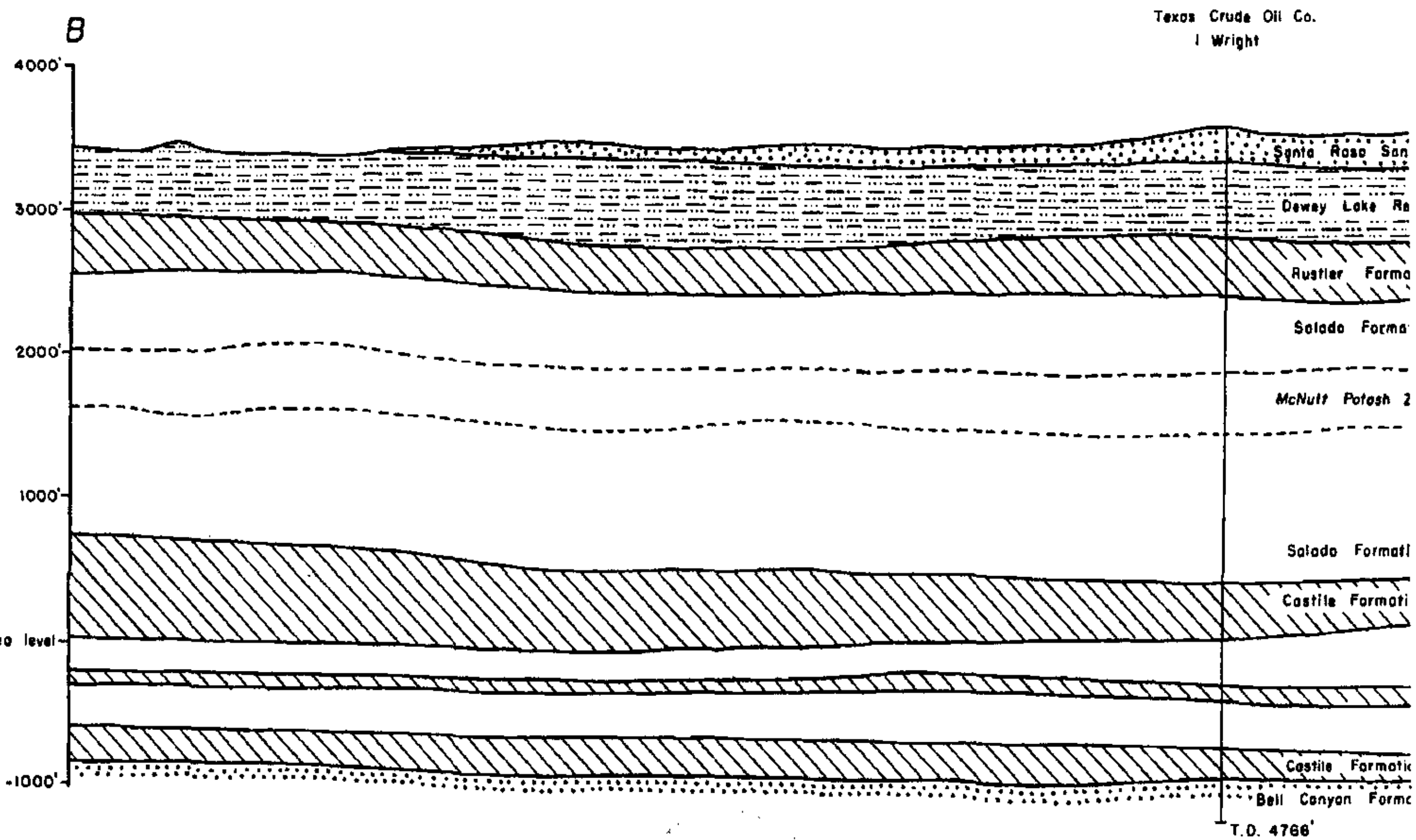
The lower member of the Castile Formation is a well-stratified evaporite consisting of laminae of gray anhydrite and brownish-gray limestone in regular, rhythmic alternation. Some beds of laminated dark-gray and brownish-gray limestones, a few inches to several feet thick, are present at wide intervals in the lower and middle parts of the member, and there are a few thicker beds of massive gray anhydrite at long intervals. The member is 200-240 feet thick along the southern border of Los Medaños area, but it thickens northward and reaches a thickness of at least 400 feet before merging with other members of the Castile to form a single unbroken mass of anhydrite in the northern part of the area (fig. 3).

The middle member of the Castile Formation is predominantly rock salt, but it includes some thin to thick beds of interlaminated anhydrite and limestone. The member ranges in thickness from about 560 feet near the southern margin of Los Medaños area to as much as 1,200 feet in deformationally thickened masses in the Culberson & Irwin 1 Murray well (figs. 3 and 4) and elsewhere in the central part of the area. The member terminates northward by grading laterally into, and intertonguing with, anhydrite.

The upper member of the Castile Formation is composed chiefly of anhydrite laminated by calcitic limestone and, to a lesser extent, of massive anhydrite, rock salt, and carbonate rock, including both magnesite and dolomite. The member includes a northwardly thinning tongue of anhydrite that overlaps the Capitan Limestone and Tansill Formation in the northern part of Los Medaños area (fig. 3). The main body of the member is 600-700 feet thick at the south end of the area. It thins rapidly northward and is as little as 170 feet thick in the central part of the area. The northward thinning is attributed to a transition involving a stratigraphic descent in the top of the member as beds of anhydrite give way laterally to rock salt of the Salado Formation (fig. 4). The transition is accomplished partly by direct gradation from anhydrite to rock salt, and partly in pinch out of anhydrite beds between tongues of rock salt.

The contact between the Castile Formation and the overlying Salado Formation is conformable and gradational, but, nevertheless, is generally rather sharply defined as the horizon at which dominant anhydrite below gives way to rock salt."

Figure 3 - Jones et al 1973 - B-B' is roughly North South



U.S. Geological Survey
OPEN FILE REPORT
This map is preliminary and has not been edited or reviewed for conformity with Geological Survey standards.

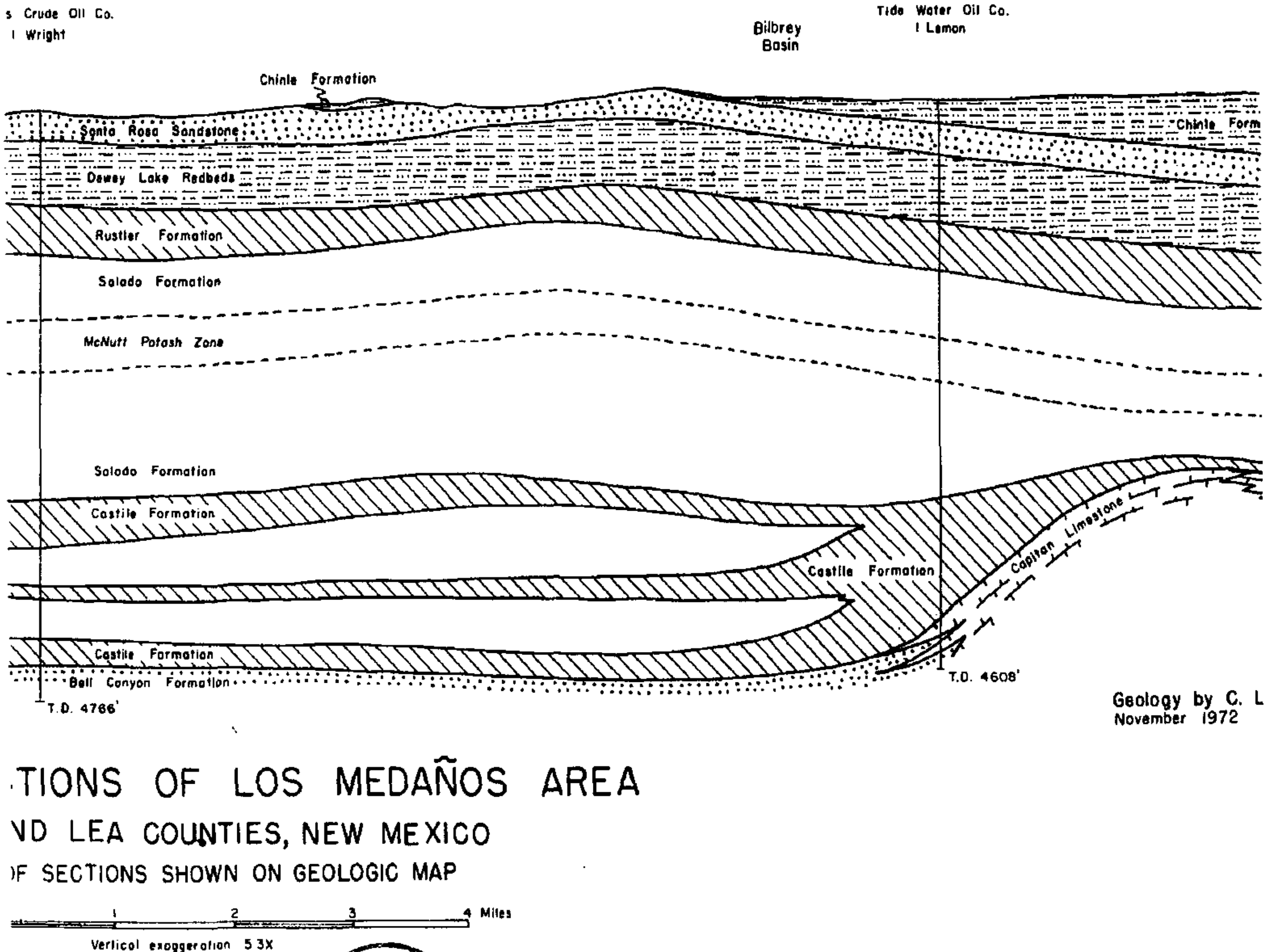
GEOLOGIC SECTIONS OF

EDDY AND LEA COU

TRACE OF SECTIONS SHO

Vertical exaggera

FIGURE

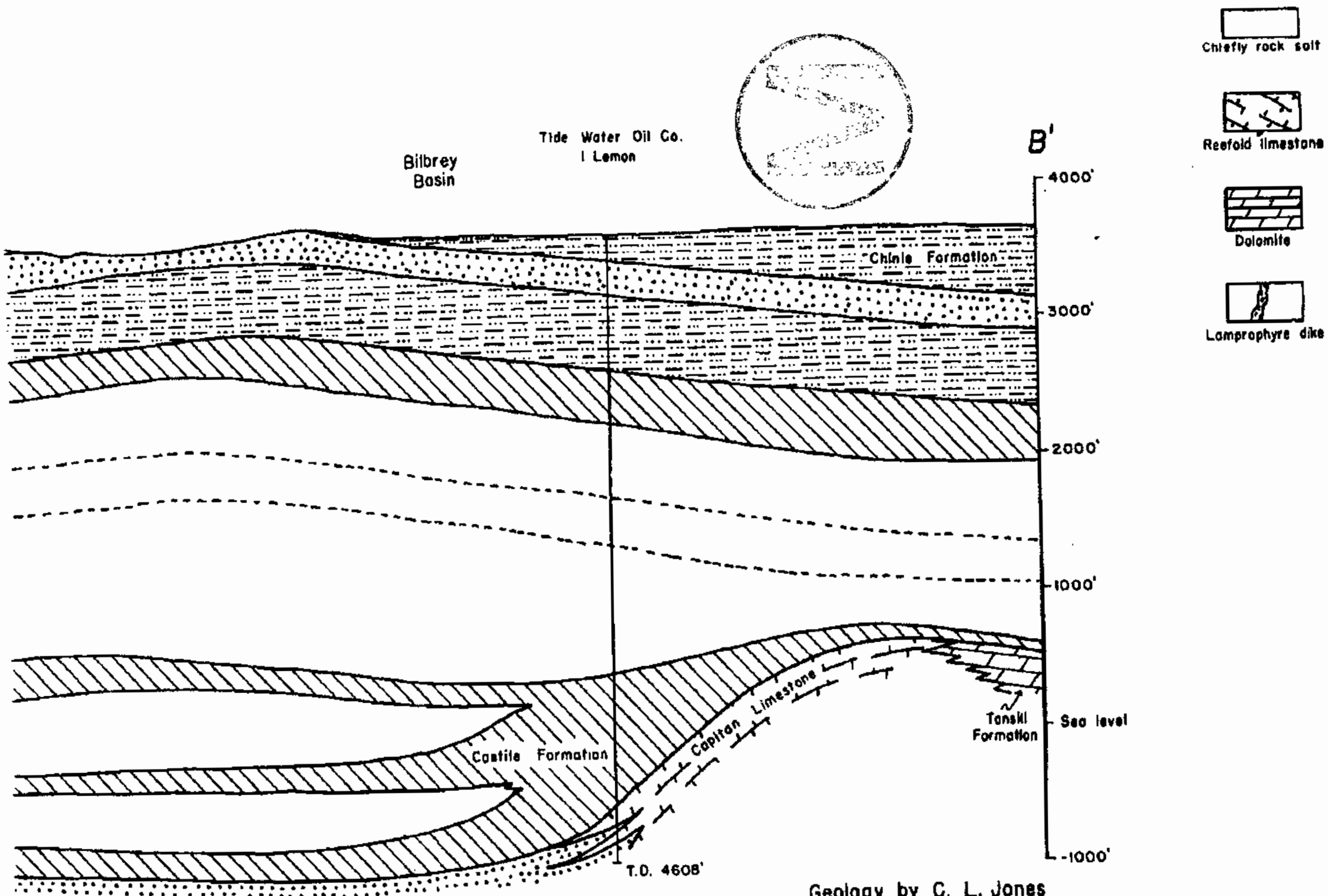


·TIONS OF LOS MEDAÑOS AREA

ND LEA COUNTIES, NEW MEXICO

OF SECTIONS SHOWN ON GEOLOGIC MAP

FIGURE 3



Geology by C. L. Jones
November 1972

DAÑOS AREA

MEXICO

C' MAP

4 Miles

Jones, C.L., 1978. Test Drilling for Potash Resources: Waste Isolation Pilot Plant Site, Eddy County, New Mexico. Open-File Report 78-592. Vols. 1 and 2. U.S. Geological Survey, Denver, CO.

ABSTRACT, p 1;

" Twenty-one borings to augment existing information on potash resources at the proposed site for a waste isolation pilot plant in eastern Eddy County, N. Mex., were drilled and logged in an 11-week period, mid-August to November 1976. The basic data developed from the borings are tabulated in the present report. The tabulation includes lithologic and geophysical logs of all the borings, as well as the results of chemical analyses, X-ray determinations, and calculations to establish a modal mineralogical composition of core samples from potash ore zones and mineralized salt beds."

Rustler Formation, p 9;

" Overlying the Salado Formation in all the resource-evaluation borings is the Rustler Formation, which was named by Richardson (1904) for exposures in the Rustler Hills in western Texas about 80 km (50 mi) southwest of the WIPP site. In the borings, the Rustler is 88-140 m (288-460 ft) of anhydrite (locally altered to gypsum), dolomite, and fine-grained clastic rocks. Rock salt is present locally but formerly was more widespread, as indicated by the presence of dissolution debris, convergence of beds, and structural evidence for subsidence. The clastic rocks range in composition from mudstone, through clayey siltstone, to very fine grained sandstone, and include structureless accumulations of unconsolidated clays and silts that are residual dissolution products of clayey and silty rock salt."

Table 9A--Abridged drill-hole history, p. 168;

" DRILLING RECORD: Commenced drilling on September 16, and completed on September 25, 1976, at 547 m (1,796 ft) below land surface.

Drilled with air foam to 225 m (738 ft) below land surface. Driller reported water at 67 m (220 ft) below land surface, making about 95 lpm (25 gpm)."

Jones, C.L. 1981. Geologic Data for Borehole ERDA-6, Eddy County, New Mexico. Open-File Report 81-468. U.S. Geological Survey, Denver, CO.

ABSTRACT, p. 1;

" ERDA-6 is an exploratory test hole drilled in eastern Eddy County, New Mexico, to evaluate a candidate site for a nuclear waste repository that was subsequently rejected on the basis of geologic data. The rocks penetrated include surficial deposits of Quaternary age; the Santa Rosa Sandstone of Triassic age; and the Dewey Lake Red Beds, the Rustler Formation, the Salado Formation, and part of the Castile Formation, all of Permian age. The pre-Quaternary rocks are sharply deformed into an anticline that has a faulted core of salt and anhydrite containing a reservoir of geopressurized brine carrying H_2S, CO_2, and CH_4 in solution. The structure of the rocks and the geopressurized brine are severe geologic impediments to the design, construction, and operation of a nuclear waste repository at the candidate site."

<u>Rock Deformation</u>, p. 18, Para. 2;

" Complex deformation of rock salt and anhydrite at ERDA-6 is documented by the irregular stratigraphic section caused by faulting, the schistosity and shear folds in rock salt, and the breccia and vein-filled fractures in banded anhydrite. These features also provide guides to the identification of the nature, magnitude, and timing of that deformation. Structurally all the rocks at ERDA-6 are higher in elevation than anticipated at the start of drilling, and their elevated position is attributed to the emplacement of Castile salt and anhydrite in the Salado Formation at a height of several hundred feet above their normal stratigraphic level. The emplacement has involved salt movement and accumulation in a swell or mound sufficiently thick at ERDA-6 to uplift in a pronounced arch or anticline at least 2,400 feet of strata ranging from Permian through Triassic in age. The stratigraphic relationship of the Castile and Salado to this anticline indicates episodic salt movement during Permian time, and it is inferred that the movement was due to updip sediment loading before dewatering of Castile salt was completed. Evidence to the upper limit of salt movement is lacking at ERDA-6. Elsewhere, on the ERDA-6 structure, however, the uplift and arching of Triassic rocks by salt movement was completed before deposition of the Ogallala Formation of Pliocene age. The Ogallala along the crest of the structure is flat-lying and undeformed but truncates uplifted and eroded Triassic rocks."

Jones, T.L., Kelley, V.A., Pickens, J.F., Upton, D.T., Beauheim, R.L., and Davies, P.B. 1992. Integration of Interpretation Results of Tracer Tests Performed in the Culebra Dolomite at the Waste Isolation Pilot Plant Site. SAND92-1579. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p i;

" Conservative tracer tests have been conducted within the Culebra Dolomite Member of the Rustler Formation at the H-2, H-3, H-4, H-6, and H-11 hydropads for transport scales ranging from approximately 20 to 40 m. Convergent-flow and two-well recirculating tracer tests provide data that is used to quantitatively characterize flow and transport processes. The observed long time period required for initial (detectable) tracer breakthrough (74 to 316 days) in the H-2 and H-4 tracer tests suggest the prevalence of single-porosity, matrix-only transport at these locations. Hydraulic-test responses at these two hydropads also indicate single-porosity, matrix-only conditions. The relatively poor quality of data defining the breakthrough curves from the H-2 and H-4 tracer tests precluded a detailed, quantitative analysis of transport parameter values from these tests. Interpretations of pumping tests and tracer tests at the H-3, H-6, and H-11 hydropads indicated that the Culebra dolomite behaves as a double-porosity (fracture-plus-matrix) medium at these locations. Both the H-3 and H-11 hydropads are located along the offsite transport pathways southeast of the Waste Isolation Pilot Plant waste-panel area. Significant fracture participation in transport is evidenced by rapid initial tracer breakthrough (1 to 21 hrs) on one travel path at each of these hydropads. The H-3, H-6 , and H-11 convergent-flow tracer tests were analyzed using the SWIFT II model with the Culebra fracture/matrix system idealized as three, orthogonal, intersecting fracture sets equally spaced in all three directions. Input values and ranges for the assigned transport parameters (effective thickness, well spacing, pumping rate, free-water diffusion coefficient, longitudinal dispersivity, and matrix porosity) were specified based on field measurements, laboratory measurements on Culebra core, and scientific judgement. Measurement and/or calculated uncertainties were also defined for the assigned parameters. Two approaches were used to model double-porosity transport. The first approach assumed that differences in tracer breakthrough behavior at a single hydropad were caused by differences (heterogeneity) in matrix-block length (fracture spacing) between different travel paths. The second approach assumed that differences in tracer breakthrough behavior were caused by horizontal anisotropy in the flow field. Interpretations based on the heterogeneous-analysis approach yielded matrix-block lengths ranging from 0.11 to 1.23 m and fracture porosities ranging from 5.0×10^{-4} to 1.0×10^{-3}. Interpretations based on the anisotropic-analysis approach yielded matrix-block lengths ranging from 0.15 to 0.48 m, fracture porosities ranging from 1.0×10^{-3} to 3.0×10^{-3}, and anisotropy ratios ranging from 3:1 to 7:1. Sensitivity analyses were conducted to provide insight into the relative impact of varying individual transport parameters and to provide estimates of fitted-parameter uncertainty. These analyses yielded minimum and maximum matrix-block lengths for all hydropads that ranged from 0.02 to 3.22 m. Sensitivity analyses also showed that neither single-porosity, fracture-only transport nor single-porosity, matrix-only transport can reproduce the observed transport behavior at the H-3, H-6, and H-11 hydropads."

Section 5.1.6 Matrix Porosity, p. 5-23, para. 2;

" Laboratory matrix-porosity determinations have been performed on 79 core samples from the Culebra at 15 borehole or hydropad locations at and surrounding the WIPP site (Table 5-3). Factors affecting core selection for laboratory porosity determinations included availability of core samples and competency of the core samples for analysis. Not all boreholes have core available. In addition, core recovery during drilling was very poor at some locations (e.g., approximately 10 and 40 percent at H-3b2 and H-3b3, respectively)."

Table 5-3 (cont'd). Summary of Porosities Determined Using Boyle's Law Technique on Culebra Core Samples (after Kelley and Saulnier, 1990), p. 5-26;

" . . .

Number of samples	= 79
Average porosity	= 0.153
Standard deviation	= 0.053
Range for all samples	= 0.028-0.303

Range for averaged hydropad or borehole porosities = 0.10-0.25"

Section 5.3 Identification of Independent Parameter Groups, p 5-46;

" The second matrix-parameter group is the characteristic matrix-diffusion time given by:

$$\tau' = \frac{L'^2}{\theta' D'} \qquad (5\text{-}13)$$

where:

τ' = characteristic matrix-diffusion time,

L$'$ = one half of the matrix-block length,

θ' = matrix tortuosity, and

D$'$ = free-water diffusion coefficient.

Physically, the characteristic matrix-diffusion time represents the time required for diffusion to penetrate from the fracture-matrix interface to the center of the matrix block, and for the concentration at that point to reach approximately 68 percent of its value at the fracture-matrix interface."

Keesey, J.J. 1976. Hydrocarbon Evaluation, Proposed Southeastern New Mexico Radioactive Material Storage Site, Eddy County, New Mexico. SAND71-7033. Vols. I and II. Sipes, Williamson, and Aycock, Midland, TX.

Introduction, Vol 1, p 1, para 2;

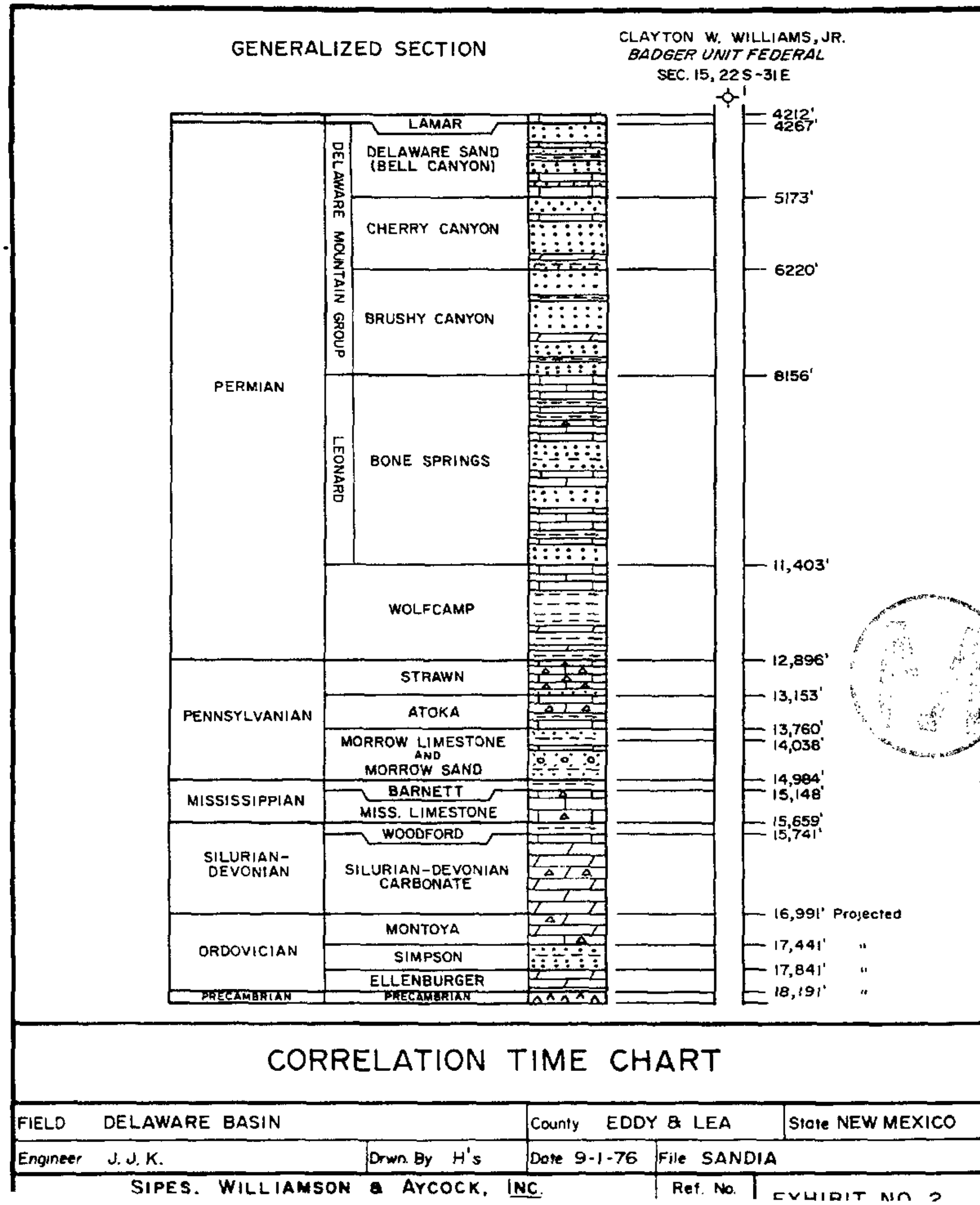
" The purpose of this evaluation was to determine the future remaining economically recoverable oil and gas reserves underlying the proposed radioactive waste material storage site, commonly known as the Los Medanos Site. This evaluation is to serve as a guideline to Sandia Laboratories in determining the acceptability of the "site area" and the potential value to the owners of the hydrocarbon rights. It is not, however, intended to be the basis for condemnation proceedings.

p. 4, Para. 1;

" Exhibit No. 2 is a geologic correlation time chart for this portion of the Delaware Basin. Hydrocarbon producing formations are first encountered in the Delaware formation at approximately 4,200 feet. Moving downward, hydrocarbon accumulations have been found in the Cherry Canyon, Brushy Canyon, Bone Springs, Wolfcamp, Strawn, Atoka, Morrow, Devonian and Ellenburger zones. This multi-zone pay development is typical of the Southeastern New Mexico-West Texas area. The shallower Delaware sand formations were developed during the late 1930's with deeper tests to the Morrow and Ellenburger zones generally beginning in the early to mid-1950's."

Summary

The proposed radioactive waste material storage site is located in the northern portion of the Delaware Basin. No hydrocarbon production exists within the current boundaries of the "site area", but oil and gas are being produced from 60 wells in a 38 square-mile area around the site. These wells produce from the Delaware, Bone Springs, Wolfcamp, Strawn, Atoka and Morrow zones at a total rate of about 22,682 MCF of gas and 429 barrels of oil per day. This area is considered to be potentially rich in hydrocarbon reserves and the lack of fuller development and exploration drilling is due primary to low gas prices, lack of sales outlets and/or pipelines and moratoriums on drilling in the potash areas. Proved producing and proved nonproducing reserves are present in two wells in the Los Medanos Field area immediately adjacent to the southwest corner of the "site area". In addition, proved undeveloped, probable and possible reserves exist at six potential drilling locations in the Los Medanos Field. Further, probable and possible reserves were assigned to fifteen other potential drilling locations in the northwest ans south-central portions of the "site area". Total future economically recoverable reserves projected for these wells are 62,253,244 MCF of gas and 409,628 barrels of oil. The future net undiscounted revenue to the oil operators was determined to be $48,410,821. The discounted future net revenue is $21,216,899, discounted at 10 percent per annum. The fair market value for these projected reserves is $12,730,139, assuming a fair market factor of 0.50."


GENERALIZED SECTION
CLAYTON W. WILLIAMS, JR.
BADGER UNIT FEDERAL
SEC. 15, 22S-31E
PERMIAN
DELAWARE MOUNTAIN GROUP
LEONARD
LAMAR
DELAWARE SAND (BELL CANYON)
CHERRY CANYON
BRUSHY CANYON
BONE SPRINGS
WOLFCAMP
PENNSYLVANIAN
STRAWN
ATOKA
MORROW LIMESTONE AND MORROW SAND
MISSISSIPPIAN
BARNETT
MISS. LIMESTONE
SILURIAN-DEVONIAN
WOODFORD
SILURIAN-DEVONIAN CARBONATE
ORDOVICIAN
MONTOYA
SIMPSON
ELLENBURGER
PRECAMBRIAN
PRECAMBRIAN
4212'
4267'
5173'
6220'
8156'
11,403'
12,896'
13,153'
13,760'
14,038'
14,984'
15,148'
15,659'
15,741'
16,991' Projected
17,441' "
17,841' "
18,191' "
CORRELATION TIME CHART
FIELD DELAWARE BASIN
County EDDY & LEA
State NEW MEXICO
Engineer J. J. K.
Drwn. By H's
Date 9-1-76
File SANDIA
SIPES. WILLIAMSON & AYCOCK, INC.
Ref. No.
EXHIBIT NO. 2

Kelley, V.A., 1971. Geology of the Pecos Country, Southeastern New Mexico. Memoir 24. New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.

ABSTRACT, p. 1, col. 2, para. 6;

" Two faults, Barrera and Carlsbad, are mapped at the base of the Capitan reef escarpment. Offsets at the surface suggest that the basin side is downthrown, although not of a magnitude equal to that of the escarpment. Most of the relief of the escarpment is due to erosion of the relatively weak basin evaporitic facies. Little or no confirmation of these faults is found in subsurface vertical separations. Strike slip is considered possible, but the nature and origin of the faults are unknown."

BARRERA FAULT, p. 48, col. 2, para. 5;

" The Barrera fault lies along the base of the Capitan reef escarpment and it is traceable in outcrop expression for 18 miles. It is projected as a possible buried feature beneath alluvial outwash 5 to 6 miles to the southwest along the base of the escarpment to about R. 22 E. It is extended also to the northeast for 7 to 8 miles, past the turn of the reef monocline into the Frontier Hills monocline, beneath alluvium and at the southern base of a small hill of Rustler. The fault is expressed at the surface by small scarps and a line of bushes. It is shown strikingly on air photos by a smooth well-defined line (fig. 23)."

CARSLBAD FAULT, p. 50, col. 2, para 1;

" The Carlsbad fault is expressed in outcrop about 2 miles north of the entrance to Dark Canyon for 5 miles northeasterly toward Carlsbad. Where well exposed in sec. 6, T. 23 S., R. 26 E., it strikes N. 56°E. and dips 60°S. Its expression on air photos is sharp and straight (fig. 23). At the surface red mudstone and gypsum of the Salado Formation is clearly dropped against Tansill dolomite which dips south toward the fault at 5 degrees."

Kelley, V.A., and Saulnier, Jr., G.J. 1990. Core Analyses for Selected Samples from the Culebra Dolomite at the Waste Isolation Pilot Plant Site. SAND90-7011. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p. i;

" Two groups of core samples from the Culebra Dolomite Member of the Rustler Formation at and near the Waste Isolation Pilot Plant were analyzed to provide estimates of hydrologic parameters for use in flow-and-transport modeling. Whole-core and core-plug samples were analyzed by helium porosimetry, resaturation porosimetry, mercury-intrusion porosimetry, electrical-resistivity techniques, and gas-permeability methods.

Seventy-nine (79) helium-porosity determinations indicated that the distribution of Culebra porosities was skewed toward lower porosity values with an arithmetic mean and standard deviation of 0.153 and 0.053, respectively.

The vertical heterogeneity of porosity was indicated by 21 pairs of helium-porosity determinations where each sample of the pair was separated by approximately 5 cm. The porosity differences between the samples in the pairs varied from 0.050 to 0.093.

Water-resaturation-porosimetry results showed a near 1-to-1 correlation with the results from helium-porosity determinations. In some cases, the resaturation porosities were slightly larger than the helium porosities, possibly due to mineral dissolution by the resaturation fluid (deionized water) or to the experimental reproducibility of the two measuring techniques.

Endpoint mercury pore-volume saturations for 25 samples ranged from 66.7% to 99.9%, with an average endpoint pore-volume saturation of 95.4%. The endpoint pressure was 207 MPa. The median pore-throat radius varied over an order of magnitude from 0.077 μm to 0.588 μm, with an arithmetic average value of 0.315 μm. Eighty-four percent of the pore-throat radii in the samples analyzed were between 0.1 μm and 0.5 μm. The average mercury-intrusion porosity was 0.148, as compared with the helium-porosity average of 0.154.

Seventy-three (73) grain-density measurements indicated a skewed distribution toward larger values of grain density with an arithmetic average of 2.82 g/cm^3 and a standard deviation of 0.19 g/cm^3. The most common value of grain density was 2.83 g/cm^3, which was also the median of the distribution.

Electrical-resistivity measurements of 15 saturated core plugs were used to calculate estimates of formation factor and tortuosity. Formation-factor values were log-normally distributed and values ranged from 12 to 407, with a geometric mean of 58.8. Tortuosity ranged from 0.04 to 0.33, with an arithmetic average of 0.14 and a median of 0.12. The results show a general trend of increasing tortuosity with increasing porosity. The diffusion porosities and diffusion tortuosities determined by Dykhuizen and Casey (1989) agree with the lower range of the values determined by this core-analysis study.

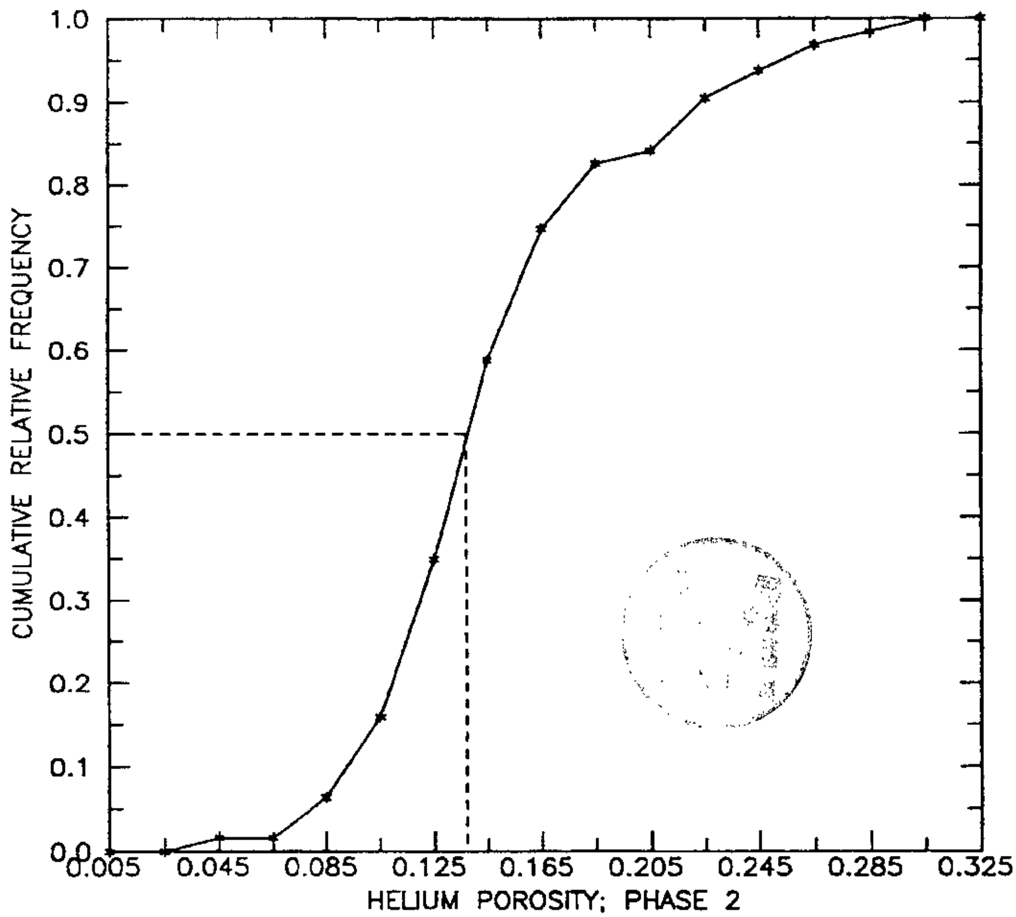
Sixty-six (66) horizontal-permeability measurements ranged from 7.9E-18 m^2 to 3.6E-13 m^2, and the distribution had an arithmetic average of 6.2E-15 m^2, a geometric mean of 4.5E-16 m^2, and a median of 2.7E-16 m^2. Twenty-six (26) vertical-permeability

measurements ranged from 8.4E-18 m^2 to 5.2E-14 m^2, with an arithmetic mean of 5.1E-15 m^2, a geometric mean of 9.0E-16 m^2, and a median of 3.5E-16 m^2. Plots of the $\log_{10}$ of permeability versus porosity indicated a weak correlation between the $\log_{10}$ of permeability and porosity. A plot of $\log_{10}$ of horizontal permeability versus the median pore-throat radii determined for the same samples indicated that the $\log_{10}$ horizontal permeability is directly related to median pore-throat radius."

p 4-10;

" There are several possible explanations for the endpoint mercury saturations being less than 100% for most samples. The most obvious explanation is that all non-saturated pore spaces have radii less than the radius accessible to mercury at 207 MPa. Another possible explanation lies in the sequence of laboratory procedures. K & A Laboratories determined helium porosity before conducting mercury-intrusion porosimetry and then used that porosity to define sample pore volume. Figure 4.4 shows that K & A Laboratories consistently determined a higher helium porosity than Terra Tek when testing the same core-plug samples. If Terra Tek's values were actually more representative of the true porosity, this fact could explain the less than 100% endpoint mercury saturations reported. Alternatively, if large pore spaces were only accessible by extremely small pore radii, it is conceivable that the larger pores could not be accessed by mercury intrusion.

Median pore-throat radii calculated from the cumulative-frequency plots of the results of mercury-intrusion porosimetry range from a low of 0,077 μm to a high of 0.588 μm. The arithmetic mean of the calculated mean pore-throat radii is 0.315 μm. Given the assumptions implicit to mercury-intrusion porosimetry, 50% of the pore-throat radii for the 25 samples are greater than 0.315 μm. The distributions of pore-throat radii for the samples analyzed by K & A Laboratories (Appendix D) indicate that the pore-throat radii are distributed differently between samples. However, most pore radii generally range between 0.05 and 0.6 μm and the median pore radii for all samples have a range of approximately one order of magnitude."



Sample Size = 63
Median = 0.134

Drawn by ABW	Date 12/6/89	Cumulative Relative-Frequency Curve for Phase 2 Helium Porosities
Checked by G.S.	Date 12/6/89	
Revisions	Date	
#105000R019	12/6/89	
INTERA Technologies		Figure 4.7

King, P.B. 1948. Geology of the Southern Guadalupe Mountains, Texas. Professional Paper 215. U.S. Geological Survey, Washington, D.C.

ABSTRACT, P 1;

" This report deals with an area of 425 square miles in the western part of Texas, immediately south of the New Mexico line. The area comprises the south end of the Guadalupe Mountains and the adjacent part of the Delaware Mountains; it includes the highest peaks in the State of Texas. The area is a segment of a large mountain mass that extends 50 miles or more northward and southward. The report describes the geology of the area, that is, the nature of its rocks, tectonics, and surface features, and the evidence that they give as to the evolution of the area through geologic time. Incidental reference is made to the geology of surrounding regions in order to place the area in its environment.

Stratigraphy of Permian Rocks-- . . ."

FEATURES OF EARLY CENOZOIC AGE, p 108, col 1, para 3;

" The Permian rocks now exposed in the Guadalupe Mountains had a broadly warped structure by Cretaceous time. Afterwards, as shown in figure 15, A, and plate 21, they were broken into tilted fault blocks. The close relation of the fault blocks to the present topography suggests that most of the post-Cretaceous disturbance took place in later Cenozoic time, which implies that the region was little deformed during early Cenozoic time."

HISTORY OF GUADALUPE AND DELAWARE MOUNTAINS UPLIFT, p 120, col 2;

" The early phases of the uplift of the Guadalupe and Delaware Mountains are imperfectly recorded in this region. The initial uplift, however, may have taken place at the same time as that farther northwest in the Sacramento section, where deposits, land forms, and tectonic features related to it are well exposed and have been studied by Kirk Bryan and his students.[85] According to Bryan, the initial uplift here took place before the deposition of the Santa Fe formation, and hence were probably of Miocene or early Pliocene age. They thus correspond approximately to the post-volcanic deformation in trans-Pecos Texas.

East and west of the Guadalupe Mountains, deposits of about the same age as the Santa Fe formation were formed as a result of erosion that followed the initial uplifts. To the east they form the cap of the Llano Estacado and are a part of the Ogallala formation. To the west, they probably form the main mass of the thick, unconsolidated deposits of the Salt Basin. The nature of the latter deposits is little known, however, because they are everywhere covered by Quaternary deposits.

In the mountains themselves, some indication of the nature of the initial uplift is given by the present stream patterns in the limestone uplands (fig. 19). Some of the streams seem to be unrelated, and hence antecedent, to the fault blocks that they cross; thus, the stream in McKittrick Canyon crosses from the downthrown to the upthrown side of the Lost Peak fault zone with little or no deflection (pl. 22). Other streams, such as those in the upper courses of Dog and West Dog Canyons, follow depressed fault blocks, and appear to belong to a later generation. In the parts of the mountains where no faulting has taken place, the two generations of streams cannot be differentiated. It seems plausible, however, that most of them were consequent on the surface of the original uplift, and that in the limestone areas their courses become relatively fixed by incision into the resistant rock.

As indicated by the stream pattern, the initial uplift was a broad arch, not broken by as many faults as at present. The crest of the arch was probably near the present summits of the southern Guadalupe Mountains,for the supposedly consequent streams radiate northeastward, northward, and northwestward from it (fig. 19). The slopes of the arch seem to have been more gentle than the present slopes of the mountains, and its crest may not have stood as high. The incised streams of the limestone areas have distinctive, meandering courses, and join one another at wide angles, forming an open, dendritic pattern, as though they originally flowed down a gentle slope. This pattern, shown in the stippled areas of figure 19, is unlike that shown in the southeast part of figure 19, where the rocks are less resistant, and where the streams could adjust their courses to the steeper gradients of later periods.

Part of the jointing of the rocks of the Guadalupe and Delaware Mountains probably took place during the initial uplift. Fracturing of the rocks near the surface is likely to take place, even under the application of stresses too gentle to produce faults. If the rocks were jointed during the early phases of the uplift, the faults that came into existence later followed the pre-existing fractures.

If it could be proved that the joints normal to tilted beds in the western part of the area were originally formed in a vertical position, and had been rotated along with the beds at the time of block faulting, the suggested conclusion that the joints were older than the faults would be confirmed. It is equally possible, however, that the joints originated in their present attitudes, after the beds had been tilted."

Later Phase, p. 121, col. 2, para. 4;

" Younger movements in the Guadalupe and Delaware Mountains are indicated by the faulting of deposits of probable older Pleistocene age. The movements took place after an extended period of quiescence, for some of the deposits that are now faulted were laid down on a pediment carved from the disturbed Permian rocks.

Movements appear to have taken place only along faults that were already in existence, and to have resulted in displacements in the same direction as during the main phase. The displacements, however, were only about a tenth as great as the older ones, amounting at most to several hundred feet (p. 113). Movement took place along the faults of the Border zone and those immediately west of it, or in a much narrower belt than during the main phase. Faults in the east and west were undisturbed.

No definite evidence is available as to whether or not the faulting of the later phase was accompanied by further uplift of the mountain area. An increase in the relief of the mountains with respect to the floor of the Salt Basin is indicated not only by the displacements on the faults themselves but also by the dissection of the older, probably early Pleistocene deposits, which was caused by the accelerated activity of streams resulting from a change in base level. This dissection, however, may have been caused by a subsidence of the basin, rather than an uplift of the mountains. The dissection of similar older deposits on the east flank of the mountains by streams draining into the Pecos River may have resulted in part from actual uplift of the mountains, although it is undoubtedly influenced by other factors.

The later phase of the uplift is younger than the deposits of probable early Pleistocene age and older than deposits of Recent and perhaps later Pleistocene age, which are undisturbed by it. It is, therefore, perhaps of later Pleistocene age. No evidence for any still younger movements has been found in the Guadalupe and Delaware Mountains."

EARLY PLEISTOCNE (?) TOPOGRAPHIC FEATURES AND DEPOSITS, p. 144, col. 1, para 3;

" In the Guadalupe Mountains, a period of movement later than the initial (Pliocene?) uplift is suggested by the second generation of consequent streams--those consequent on tilted fault blocks. During this second period of movement, faulting was apparently a dominant feature. The second period of movement was probably a major uplift, comparable to major uplifts farther northwest in the Sacramento section, which are assigned to a post-Santa Fe (late Pliocene or early Pleistocene) age."

Kloska, M.B., Saulnier, Jr., G.J., and Beauheim, R.L. 1995. Culebra Transport Program Test Plan: Hydraulic Characterization of the Culebra Dolomite Member of the Rustler Formation at the H-19 Hydropad on the WIPP Site. On file in the Sandia WIPP Central Files.

1.DESCRIPTION OF THE EXPERIMENT, p. 1;

" The hydraulic testing described in this Test Plan constitutes one component of a Sandia National Laboratories (SNL) program to understand solute transport through the Culebra Dolomite Member of the Rustler Formation at the Waste Isolation Pilot Plant (WIPP) site. The overall Culebra Transport Program is discussed below, followed by a summary of the specific activities described in this Test Plan and their objectives."

1.1, p. 1, para. 3;

" Evaluation of WIPP's compliance with 40 CFR 191B by the WIPP Performance Assessment Computational Support Department of SNL relies on a model of radionuclide transport through the Culebra. Modeling of transport through the Culebra requires, first, a conceptual model of the mechanisms and processes governing that transport and, second, quantitative estimates of the parameters required for numerical simulation of those processes. The Culebra Transport Program represents the combined efforts of the SNL Geohydrology (6115) and WIPP Chemical and Disposal Room Processes (6748) Departments to provide the conceptual understanding and data necessary to construct a numerical model for Culebra transport.

Field tracer tests are a major component of the Culebra Transport Program. Tracer tests provide data with which to evaluate different processes affecting transport and to estimate transport parameters. Interpretations of previous tracer tests conducted at the WIPP site (Jones et al., 1992) indicated that the Culebra behaves locally as a double-porosity medium in which advective flow occurs through fractures while diffusion of solutes from the fractures to the surrounding rock matrix acts to retard solute transport. Using a double-porosity transport model based on these tracer-test interpretations, the WIPP PA Department (1993) showed that physical retardation arising from matrix diffusion makes the Culebra an effective barrier to release of radionuclides to the accessible environment.

This Test Plan supports the Culebra Transport Program by providing for the hydraulic characterization of the Culebra at a future tracer-test-site, the H-19 hydropad, which has been established southeast of the WIPP surface facilities between the H-3 hydropad and observation well DOE-1 (Figure 1-2; Saulnier and Beauheim, 1995). Figure 1-3 shows the as-built pattern of the test wells at the H-19 hydropad. The activities described in this Test Plan are designed to provide information about the hydrologic connections between the wells at the H-19 hydropad. This information will be used in the design and interpretation of subsequent tracer tests. The activities will involve single- and cross-hole tests of the entire thickness of the Culebra and/or of individual layers within the Culebra. Figures 1-4 and 1-5 show the completions of the H-19 test wells. This Test Plan describes plans, procedures, and specifications for the hydraulic tests to be conducted at the H-19 hydropad. The tracer *testing to be performed at the H-19 hydropad after hydraulic characterization of the Culebra* is completed will be described in a separate Test Plan prepared specifically for that activity."

Lambert, S.J., 1983a. Dissolution of Evaporites in and Around the Delaware Basin, Southeastern New Mexico and West Texas. SAND82-0461. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p 3;

" Permian evaporites in the Ochoan Castile, Salado, and Rustler Formations in the Delaware Basin of southeastern New Mexico and west Texas have been subjected to various degrees of dissolution (notably of halite and gypsum) through geologic time. Eastward tilting of the Delaware Basin has resulted in the exhumation and erosion of Ochoan rocks in the western part of the basin. Waters in the Capitan, Rustler, Castile, and Bell Canyon Formations have previously been proposed as agents or consequences of evaporite dissolution according to four principle models; solution-and-fill, phreatic dissolution, brine density flow, and stratabound dissolution (along bedding planes). Several geomorphological features of positive and negative relief have previously been cited as indicators of evaporite dissolution. Brine density flow has been used to explain the selective dissolution of certain evaporite horizons during the late Cenozoic. A review of available geological data has revealed that

- Halite deposition was probably not so extensive as formerly believed
- Waters with potential to dissolve evaporites are in the Rustler and Capitan, but not in the Bell Canyon, Salado mine seeps, or the Castile brine reservoirs
- Brine density flow has not been active in removing most of the 'missing' halite, nor are 'point-source' dissolution features likely to have their roots at the Bell Canyon
- Major evaporite dissolution has not been confined to the late Cenozoic, but much of it took place during the Permian, Triassic, Jurassic, and Tertiary periods
- The Bell Canyon Formation has not been a sink for dissolution-derived brine

Stratabound dissolution is an efficient process for the removal of evaporites and is well exemplified in Nash Draw. This process entails downdip migration of meteoric water within beds of competent fractured rock, with upward and downward excursions of the water into adjacent halite-bearing beds. The chief weakness in the stratabound model for dissolution is the as-yet-unidentified sink for dissolution brine. If the stratabound model of dissolution is active in removal of lower Salado halite, the threat of dissolution to the WIPP in the next 250,000 yr is comparable to the threat to the same area posed by the growth of Nash Draw during the past 600,000 yr. The regional geological history showed the past threat to be negligible."

Lambert, S.J. 1983b. "Evaporite Dissolution Relevant to the WIPP Site, Northern Delaware Basin, Southeastern New Mexico," In Scientific Basis for Nuclear Waste Management VI, Materials Research Society Symposium Proceedings, Boston, MA, November 1-4, 1982, SAND82-1416C. D.G. Brookins, ed., pp. 291-298. Elsevier Science Publishing Company, New York, NY.

ABSTRACT, p 291;

" Evaluation of the threat of natural dissolution of host evaporites to the integrity of the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico has taken into consideration (1) the volume of 'missing' rock salt, (2) the occurrence (or not) of characteristic dissolution brines, (3) geomorphic features, some of which are unrelated to dissolution, and (4) the time intervals over which dissolution may have been active. Even under the assumption that all 'missing' halite was originally present and has been removed by dissolution, there is no evidence of active preferential removal of the lower Salado Formation halite by any geologically reasonable process. The geologic record contains evidence of dissolution in the Triassic and Jurassic; to constrain all removal of basinal halite to the late Cenozoic yields an unrealistically high rate of removal. Application to the lower Salado of a strata-bound mechanism known to be active in Nash Draw, a near-surface feature within the Basin, allows a minimum survival time of 2,500,000 years to be predicted for the subsurface facility for storage of radioactive waste at WIPP. This calculation is based on an analysis of all known dissolution features in the Delaware Basin and takes into account the wetter (pluvial) climate during the past 600,000 years."

ORIGINAL AND SURVIVING EVAPORITES, p 292;

" An issue central to the discussion of evaporite dissolution as a threat to WIPP has been the amount of halite which has been removed by dissolution since deposition. Recent descriptions of the Delaware Basin [2,3] have cited the variation in thickness of halite beds in the Castile and Salado Formations as evidence of dissolution. Anderson [2] proposed that the lower Salado Formation has been preferentially dissolved so as to undermine the evaporite section overlying marker bed 136. (Reference [4] describes the marker bed nomenclature.) This conclusion was drawn to account for 'missing' halite beds as inferred from acoustic logs of a number of boreholes. In actual fact, dissolution to account for regionally 'missing' halite is neither inescapable nor in some cases geologically reasonable.

As an example of some possible misinterpretation of 'missing' halite as evidence of dissolution, Figure 1 shows an overlay of Snider's [5] isopach map of Castile Anhydrite I (the lowermost evaporite unit in the Delaware Basin) on Anderson's [6] map of 'deep sinks' in the immediately overlying Halite I. At several locations the local thinnings in Halite I correspond to local thickenings in Anhydrite I. Anhydrite is not known to exhibit the same plastic behavior as halite under comparable overburden conditions, so the local thickenings of anhydrite cannot be attributed to flowage. The total thickness of Anhydrite I plus Halite I throughout the Delaware Basin remains nearly the same, indicating that subsurface variations in Halite I thickness are depositional, not dissolutional, in nature.

There are various hypotheses to account for regionally 'missing' halite in the evaporite section:

Nondeposition. There are several delaware Basin boreholes in which a thinning (or absence) of halite is compensated by an underlying thickening of anhydrite; the local anhydrite substrate stood above the depositional base level for halite, and so precluded halite deposition.

Lateral facies changes. The basin-margin equivalents of halite in the Castile Formation, for example, are anhydrites. These anhydrites preserve their laminations [7], are correlatable throughout the basin and are largely undeformed. IN basinal locations in the Salado and Castile, the relative proportions of halite and anhydrite show considerable variation, whereas the total thickness remains the same [8].

Uniform halite removal. a 1° eastward tilting of the Delaware Basin has resulted in the exposure of progressively older rocks to the west, until at the western margin no evaporites remain. Much of the western basin evaporites consist now only of exposures of gypsum, attesting to the increased access of meteoric waters to the western rocks for dissolving halite and gypsifying anhydrite.

Salt tectonics. Growth of a subsurface structure can result in flowage of salt away from the crest of an antiformal fold [9].

Widespread preferential dissolution of a bed. A preferential 'undermining' type of dissolution has been proposed to account for the truncation of individual halite beds."

THE THREAT OF DISSOLUTION TO WIPP, p. 296, para. 7;

" Any postulated process must leave identifiable dissolution products. If no evidence of active dissolution can be found, or if the proposed mechanisms are not supported by the geological observations, it must be concluded that dissolution is not active. Furthermore, it may not be possible to identify details of the process(es) which caused the dissolution. If so, application of the uniformitarian principle to predictive geology leads us to seek the processes presently active and extrapolate their consequences, based on their past observed effects.

Extensive research has been made for old and active dissolution features. Some 25 WIPP project boreholes, many of which provided core and all of which were geophysically logged, have explored the subsurface geology of breccia pipes, brine reservoirs, depressions, hills, and sites of geophysical anomalies. Except for the breccia pipes, all the holes have terminated in or penetrated stratified, nonchaotic sections of evaporites. The only basinal area found to contain dissolution brines, textures or residues was Nash Draw.

Nash Draw was formed by solution-and-fill [21] and by stratabound dissolution [8] in the last 600,000 years. The age is well established because the Gatuña Formation dissected in Nash Draw contains a remnant of the Pearlette type 'O' ash bed, whose age has been determined by fission-track dating [16]. Whereas solution-and-fill has been active in the removal of the near-surface Rustler gypsum units in Nash Draw, the stratabound model more effectively describes removal of halite in the lower Rustler and upper Salado Formations. The most active subsurface dissolution in Nash Draw is associated with marker bed 103, a 4- to 5-meter-thick anhydrite layer about 15 meters below the top of the Salado Formation."

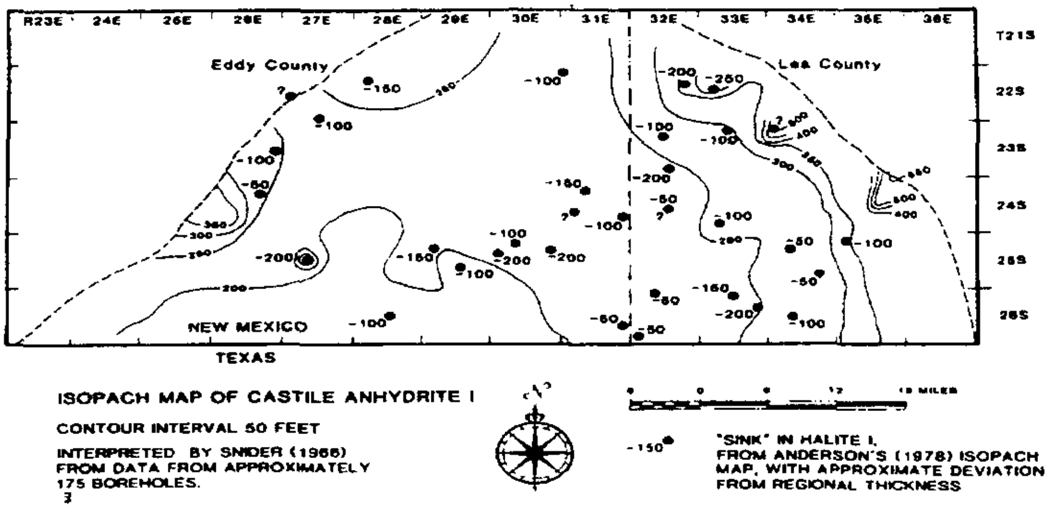


Fig. 1. Thickness distribution of Anhydrite I in the lower Castile Formation [5], superimposed on locations of "sinks" in overlying Halite I [6]. The dashed line marks the depositional edge of the Delaware Basin and the basinward extent of Capitan limestone.

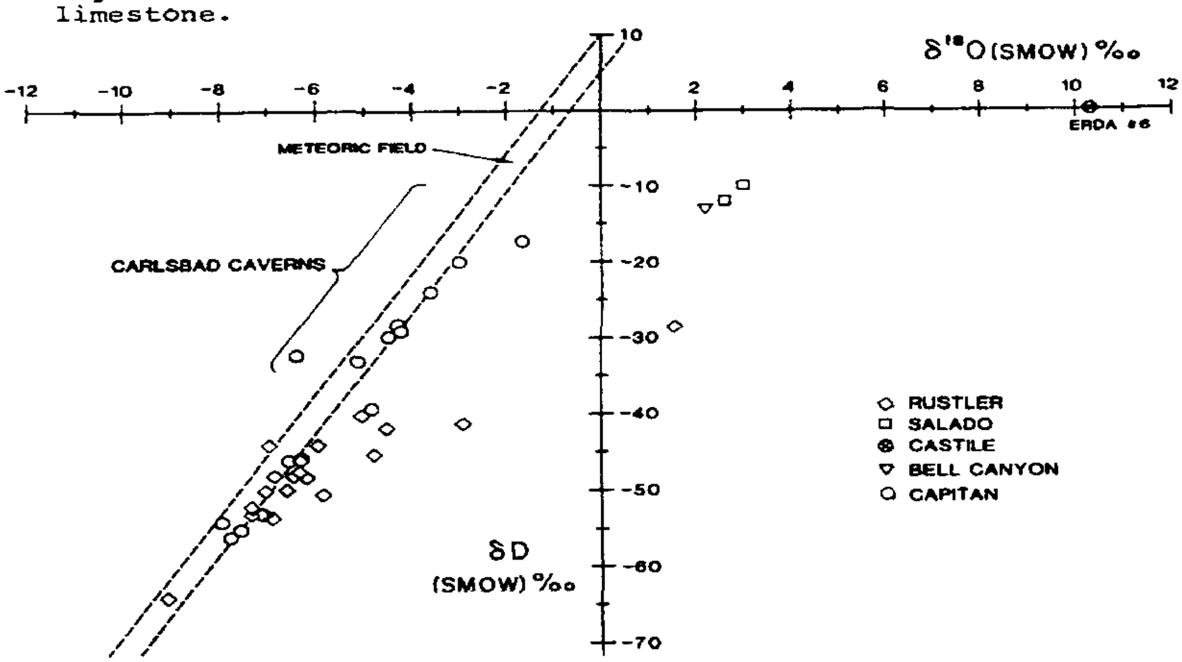


Fig. 2. Stable-isotope relationships for some Delaware Basin groundwaters, δD versus $\delta^{18}O$. "Meteoric field" is delineated after H. Craig, Science 133, 1702 (1961) and S. Epstein et al., Science 168, 1570 (1970).

Lambert, S.J. 1987. Feasibility Study: Applicability of Geochronologic Methods Involving Radiocarbon and other Nuclides to the Groundwater Hydrology of the Rustler Formation, Southeastern New Mexico. SAND86-1054. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p. i;

" Radiocarbon, tritium, and ^{36}Cl were measured in groundwaters from the dolomite aquifers of the Rustler Formation in the northern Delaware Basin of southeastern New Mexico to determine the feasibility of using these nuclides in dating the groundwater at and near the Waste Isolation Pilot Plant, a facility for geological disposal of radioactive waste. No measurable ^{36}Cl was found in any of these groundwaters, which derive their dissolved chloride from Permian evaporites. Demonstrably uncontaminated groundwaters contained no significant amounts of tritium (<0.2 TU). Percent modern carbon (PMC) correlates linearly and directly with bicarbonate concentration, indicating mixing of a high-PMC/high-bicarbonate reservoir with a low-PMC/low-bicarbonate reservoir. This relationship, together with the history of development of the wells sampling the groundwaters, indicates contamination by anthropogenic modern carbon rather than simple dilution by dissolving rock carbonate. $\delta^{13}C$ does not linearly correlate with bicarbonate, indicating no single source of contaminant radiocarbon. Values of PMC and $\delta^{13}C$ for groundwaters were used to calculate apparent radiocarbon ages according to an interpretive model that accounts for water/rock interactions in carbonate aquifers. All but six pairs of values gave significant negative ages (-1,000 to -7,000 years). This suggests that in contaminated samples the model over-adjusts (based on $\delta^{13}C$) for radiocarbon loss due to dilution and isotopic exchange with the rock. Four groundwater samples (3 from the Rustler and 1 from the overlying Dewey Lake Red Beds) gave apparent radiocarbon ages $>$ 10,000 a, and their carbon-isotope systematics suggest that their apparent ages are all the result of a single evolutionary trend of rock/water interaction involving carbon isotope exchange, with a probable recharge age of 13,000 a b. p. This time of isolation from the atmosphere, which is unrelated to travel time within the Rustler, is consistent with paleoclimatic evidence of wetter conditions more conducive to recharge in the Late Pleistocene than at present."

TABLE 5, p. 50;

" TABLE 5. RADIOCARBON AGES, MODEL OF EVANS ET AL.[1]

Well	$\delta^{13}C$(‰) All Replicates	PMC All Replicates	Apparent Age (radiocarbon years)
Pocket Dewey Lake	-3.8	3.67 (cyl)[2]	14,000
WIPP-25 Magenta	-6.8 -6.4	50.7 (bulk)[3] 49.27 (pptn)[4]	-3,250 -3,490
WIPP-27 Magenta	-7.0 -9.0	69.6 (bulk) 67.76 (pptn)	-5,650 -3,460
H-4B Culebra	-6.7	4.82 (bulk)	16,100
H-5C Culebra	-3.7	18.0 (bulk)	714
H-6C Culebra	-8.4	9.7 (pptn)	12,100
H-9B Culebra	-2.4	2.22 (cyl)	14,900
WIPP-25 Culebra	-7.6 -7.1	59.8 (bulk) 56.6 (pptn)	-3,760 -3,830
WIPP-26 Culebra	-5.9 -5.8	36.2 (bulk) 33.3 (pptn)	-1,560 -1,000
WIPP-27 Culebra	-4.3 -5.1	30.7 (bulk) 30.0 (bulk)	-2,560 -1,120
WIPP-29 Culebra	-5.1	49.76 (bulk)	-5,300
RF-10 Culebra	-5.4	39.7 (cyl)	-3,020
Engle Culebra	-2.8	11.5 (cyl)	2,410
WIPP-26 R/S	-7.1	90.7 (bulk)	-7,730
WIPP-28 R/S	-4.7	48.5 (bulk)	-5,710
WIPP-29 R/S	-4.8	53.4 (bulk)	-6,340

1. $\delta^{13}C_r$ = 5.7‰; ε_{13} = 5.2‰ for dolomite
2. cyl- Water samples collected in 500 mL steel cylinders, whose carbon-isotope compositions were analyzed by accelerator mass spectrometry.
3. bulk- Bulk water samples (in was-sealed polyethylene jerrycans) from which carbon dioxide was liberated by acidification and nitrogen-purging in the laboratory.
4. pptn- carbon dioxide samples obtained by acidification of the barium carbonate precipitate prepared in the field immediately following the collection of the water."

p. 66, para. 4;

" There is a conspicuous dichotomy in carbon-isotope systematics between waters containing less than 10 PMC (four sampling localities having apparent radiocarbon ages of 12,000 to 16,000 years) and those containing more than 10 PMC (12 sampling locations for which one could argue that contamination had taken place during well development). The wide geographic separation (Figure 1) of sampling localities yielding model ages > 10,000 a suggests that water of this apparent age was originally widespread throughout the area near the WIPP site. The mathematical relationships among the data from the contaminated wells suggest that the mechanism generating the observed PMC values has involved nonsystematic modern mixing of three carbon-reservoir endmembers: (1) ancient organic material dissolved in the water at the time of recharge, (2) carbonaceous species dissolved from the host carbonate rock, and (3) modern organic material introduced during water-well development. The last two dominate the more contaminated samples, but such samples probably contain some component of original dissolved carbon dioxide. Consequently it is concluded that the contaminated waters were derived from the original widespread Pleistocene-age waters."

Lambert, S.J., and Carter, J.A. 1987. Uranium-Isotope Systematics in Groundwaters of the Rustler Formation, Northern Delaware Basin, Southeastern New Mexico, I. Principles and Preliminary Results. SAND87-0388. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p i;

" Values for uranium concentration ([U]) and $^{234}U/^{238}U$ activity ratio (A.R.), have been determined for groundwaters and host rocks from the Rustler Formation near the Waste Isolation Pilot Plant (WIPP) site in the northern Delaware Basin of southeastern New Mexico. [U] varies from about 0.02 to 40 x 10^{-9} g/g, increasing westward across the WIPP site to Nash Draw, a dissolution valley underlain by outcrops of Rustler Formation evaporites. Large deviations from secular equilibrium (A.R. $\approx$ 1) in the groundwaters increase eastward from about 2 to 3 in Nash Draw to almost 12 in the eastern part of the WIPP site. [U] and A.R. variations cannot be completely explained by simple mixing due to congruent dissolution of uranium from rock (without isotopic fractionation). A.R. values typically increase along the flow path in a reducing environment, and the observed eastward increase in A.R. suggests a relict flow system whose dominant flow direction (eastward) was at high angles to that now observed. A westward decrease in A.R., coupled with a steady increase in [U] indicates not only that there was a change in flow direction since recharge, but that Rustler groundwater is now draining from areas of high potentiometric level and low permeability near the WIPP site, without appreciable recharge. The maximum time required for this westward drainage is about 200,000 a. The minimum time required to achieve the highest observed A.R.s during the earlier episode of eastward flow from recharge in the west is 10,000 to 30,000 a. Radiocarbon and stable-isotope studies of the Rustler Formation near the WIPP indicate that the modern Rustler flow system is not at steady state, recharge being dominated by wetter climatic conditions in the Pleistocene. Uranium-isotope studies are consistent with these results, and further suggest that present flow directions are qualitatively different from those existing at the time of recharge."

Lambert, S.J., and Harvey, D.M. 1987. Stable-Isotope Geochemistry of Groundwaters In the Delaware Basin of Southeastern New Mexico. SAND87-0138. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p i;

" $^{18}O/^{16}O$ and D/H ratio measurements have been made on groundwaters sampled from the Rustler Formation (Ochoan, Permian) and related rocks in the northern Delaware Basin of southeastern New Mexico. Most confined Rustler waters at the Waste Isolation Pilot Plant (WIPP) site and to the west in Nash Draw and confined waters from the Capitan limestone constitute one population in $\delta D/\delta^{18}O$ space, while unconfined groundwaters inferred to originate as modern surface recharge to alluvium, sandstones in the Ogallala Formation, the near-surface Rustler in southwestern Nash Draw, and the Capitan vadose zone in the Guadalupe Mountains (Carlsbad caverns) constitute a distinctly different population; the two do not overlap. A likely explanation for this distinction is that meteoric recharge to most of the Rustler and Capitan took place in the geologic past under climatic conditions significantly different from the present. Available tritium and radiocarbon data are consistent with this hypothesis, and the apparent age of confined groundwaters is in excess of 12,000 radiocarbon years, suggesting that recharge took place under wetter conditions in the late Pleistocene. Processes governing recharge in the Delaware basin are significantly different from those in the nearby Roswell Artesian Basin, but may be similar to those previously described for the Albuquerque (New Mexico) and Murray (South Australia) Basins. Rustler water from the WIPP site and east-central Nash Draw is not discharging from springs in southwestern Nash Draw; the discharge there is part of a local shallow groundwater system associated with surficial gypsum karst and discharge from nearby potash refining. Water at the Rustler/Salado contact at the WIPP site is of meteoric origin, but has experienced isotope shift that increases with decreasing permeability, and is part of the same isotopic trend as the ERDA 6 brine occurrence and fluid inclusions from Salado Formation halite core. Radiometric ages of secondary Salado minerals are not consistent with vertical mixing between deep brines and meteoric waters to form the fluid inclusions. Mine seeps and WIPP fluid inclusions have similar isotopic compositions, perhaps related to syndepositional mixing of evaporite brines and rainwaters. Rustler dolomites have not recrystallized in isotopic equilibrium with Rustler water, but much of the gypsum in the Ochoan section has done so. The absence of modern meteoric recharge to the Rustler at and near the WIPP site indicates that the hydrologic system there is not at steady state. Instead, the system is responding to the cessation of local recharge, this cessation occurring some 10,000 to 30,000 years ago."

4.5.3 The Age of Rustler Groundwaters, p 100, para 1;

" Four groundwater (three Rustler and one Dewey Lake) gave significant positive ages, all of which were found to be statistically indistinguishable (in radiocarbon years): H4, 16,100 a; H9, 14,900 a; H6, 12,100 a (all Culebra); Pocket (Dewey Lake), 14,000 a. Given that these groundwaters could contain traces of contaminant ^{14}C, these were regarded as <u>minimum</u> times of isolation from the atmosphere. If the flow path to the vicinity of the

WIPP site is long, these results represent travel times from the recharge area. If recharge was originally local, these results more likely represent a discrete recharge event of end of a discrete recharge-time interval, probably indicative of wetter climate in the Pleistocene. Other evidence of a wetter Pleistocene climate in southeastern New Mexico has been presented by Van Devender (1980), who determined from packrat middens in Rocky Arroyo east of Carlsbad (Figure 1) that a juniper-oak plant community existed there 10,500 to 10,000 years ago, at an elevation of about 3700 feet, where now desert scrub communities have been stable for the last 4,000 years. Thus, a limited number of the groundwaters interpreted here to be distinct from modern meteoric precipitation, in fact have radiocarbon ages indicative of late Pleistocene recharge."

4.5.4 Summary: Meteoric Recharge of Rustler Groundwaters, p 103, para 4;
"　The absence of significant (e.g., >5-10 TU) tritium in groundwaters of the Rustler Formation is another compelling bit of evidence that argues against direct (rapid) recharge to the Rustler. If recharge is taking place, its rate is very slow, in that no tritium has shown up in the 36 years of atmospheric testing of nuclear weapons, or the amount of recharge is miniscule, being diluted by mixing with older groundwater to concentrations indistinguishable from zero. Not even background levels of tritium have been found (10 TU is estimated as the local upper concentration limit for precipitation containing tritium generated by cosmic rays; Gross et al., 1976). If the Rustler receives its water by direct infiltration, either the expected tritium spike has not yet reached the Rustler, or the amount of tritium in this recharge is diluted by mixing with older groundwater to concentrations not significantly different from zero. If the dilution factor is indeed large, one should question whether this minute amount of recharge is to be considered significant."

Lang, W.B. 1939. Salado Formation of the Permian Basin. American Association of Petroleum Geologists Bulletin, Vol. 23, pp. 1569-1572.

"

SALADO FORMATION OF THE PERMIAN BASIN[1]

WALTER B. LANG[2]
Washington, D.C.

The Delaware basin is a structural depression in western Texas and southeastern New Mexico. This depression was filled and overlain by chemical deposits of late Permian age which are now either partially eroded away west of the Pecos River, or, east of it, masked from view by a covering of younger deposits. Most of the detailed information now at hand concerning these deposits has been obtained from the study of well cuttings and has disclosed that these sediments are divisible into two formations:[3] The lower, or Castile formation, is composed of typically banded anhydrite and calcite and in the northeast half of the basin includes thick beds of clean white halite. The upper, or Salado formation, occupies not only the eastern portion of the Delaware basin but spreads northward and eastward above and beyond the basin rim, which is formed by the Capitan reef. This upper formation, which is absent in most of the western half of the basin, is apparently exposed nowhere at the surface. It is composed essentially of halite with relatively thin beds of anhydrite, polyhalite, reddish sandy shale, and locally other potash-bearing salts. However, in southern Reeves and northwestern Pecos counties, Texas, the halite grades into massive anhydrite. Therefore, a complete section of the Castile and Salado deposits can be found only in the subsurface in the northeastern portion of the Delaware basin. Even here a section may not display all phases and aspects of the deposits. The Castile and Salado formations have also been referred to as the 'Lower Castile' and 'Upper Castile,' respectively.[4]

In 1921, the Pinal Dome Corporation's Means well was drilled in the SE. corner, Sec. 23, Blk. C-26, P.S.L., slightly east of the center of Loving County, Texas, to a depth of 5,208 feet, and approximately in the middle of the northeastern half of the Delaware basin where a complete section of both formations is present. It was, and still is, one of the best sampled and analyzed standard cable-tool wells in the basin. Cuttings were taken every 5-10 feet and potash analyses were made of the salt section to 3,600 feet or through 2,700 feet of salt. In this and other wells drilled about the same time it was observed that showings of polyhalite extended downward in the thick salt sections only part way, but in the shorter sections outside the Delaware basin, underlain by the Carlsbad limestone and correlative deposits, polyhalite was found almost to the base of the salt. In the Means well evident showings of polyhalite are last observed at 2,340 feet. When the writer originally defined the Salado, he arbitrarily selected the figure of 2,350 feet as the base. At this time, only a few widely spaced wells had been drilled and correlation of the various anhydrite beds could not be made with certainty. In the light of additional evidence it is now desirable to redefine the base of the Salado.

This may be accomplished in several ways, four of which are worthy of consideration.

I. One method would be to place the lower boundary of the Salado at the 'base of the salt,' where it overlies the reef limestones and is separated from them by 50-100 feet or more of solid anhydrite; but, if this contact be extended into the basin, it lies at different horizons due to the interfingering of anhydrite with halite. Were it not for the interfingering this method would have merit, in that it is simple and easily applied. The chief point against it is that it is a temporary expedient and would soon fall into disfavor as the minute details of correlation continue to accumulate. In the Means well this contact may be selected at 2,965 feet.

2. The presence of potash in the form of polyhalite is an outstanding feature of the Salado. If the last showings of polyhalite in well cuttings are plotted they form a fairly regular horizon in the reef and back-reef areas but are far less consistent in the basin. For this reason, though the evidence is important, it is not in itself sufficiently reliable for the purpose of selecting boundaries. This lack of consistency is demonstrated in the Means well, for at 2,325-2,340 feet are two analyses showing respectively the presence of 3.10 and 3.31 per cent of K_2O in soluble salts and thus corroborating the visual evidence of polyhalite. These are followed to a depth of 3,600 feet by a succession of analyses, all showing results of less than 1.0 percent of K_2O in soluble salts, though 500 feet or more of the section below 2,340 feet must be equivallent to salts that yield evidence of polyhalite at or near the area of the reef.

3. In like manner the first indication of banded anhydrite or of calcite reveals the presence of the Castile, though these features may not appear at the same horizon in different places because prominent banding or calcite may be lacking in the deposits, or because the observer may be unable to recognize them. In general, the top of the observed banded anhydrites forms a fairly uniform horizon, though in places the actual position of this banding may be far below its hypothetical position. Thus it is not well to place too much reliance on the observed position of the top of the banded anhydrites. The beds of typical, banded anhydrite do not extend beyond the basin but lap against the marginal reef deposits. In the Means well the banded anhydrites appear at about 3,400 feet.

4. If one surface is postulated to pass through the deepest indications of polyhalite and another to include the highest showings of banded anhydrite, a gap of 500-700 feet or more lies between them. Within this gap may be found a third surface that represents the stratigraphic position of the base of the beds that lie disconformably on the top of the reef. The top of the reef is a definite, recognizable, and continuous horizon, marking the top of the Capitan and Carlsbad limestones and the correlative beds of the back-reef. Immediately overlying the limestone is a dense non-banded anhydrite, 50-100 feet thick. The top of this anhydrite is the so-called 'base of the salt' in the reef and back-reef areas. The writer included this anhydrite in the top of the Castile in 1937.[5] Whether the top or bottom of this anhydrite member is chosen to separate the Salado ('Upper Castile' of some authors) from the Castile ('Lower Castile' of some authors) the boundary between the two units would be at a definite, fundamental stratigraphic position. The sedimentary characteristics that are typical of each formation would thus be placed in their proper province.

In redefining the Salado formation, the writer prefers to include the anhydrite as its basal member, for this anhydrite does not show any of the characteristics of the typical anhydrite beds in the Castile. It is in places magnesitic, dense, non-banded, and contains no calcite. If placed in the Salado it confines the Castile to the Delaware basin and eliminates the awkward situation of having to carry a thin strip of Castile across the reef and back-reef areas for no apparent good reason. Within the Delaware basin the horizon of the top of the anhydrite member is found in most well samples with no greater facility than the base. The base of the Salado formation in the Means well as redefined in this note is placed at a depth of approximately 3,300 feet or at a position equivalent to the base of the anhydrite member on the crest of the capitan reef on the northeastern rim of the Delaware basin.

[1] Printed by permission of the director of the Geological Survey, United States Department of the Interior, Manuscript received, August 31, 1939.

[2] Geologist, United States Geological Survey

[3] W. B. Lang, "Upper Permian Formations of Delaware Basin of Texas and New Mexico," *Bull. Amer. Assoc. Petrol. Geol.*, Vol 19 (1935), pp. 262-70.

[4] L. D. Cartwright, "Transverse Section of Permian Basin, West Texas and Southeast New Mexico,' *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14 (1930), pp. 979-80.

[5].W. B. Lang, "Permian Formations of the Pecos Valley of New Mexico and Texas,"*Bull. Amer. Assoc. Petrol. Geol.*, Vol. 21 (1937), pp. 833-98."

Lang, W.B. 1942. Basal Beds of Salado Formation in Fletcher Potash Core Test near Carlsbad, New Mexico. American Association of Petroleum Geologists Bulletin, Vol. 26.

ABSTRACT, p 63;

" The Fletcher potash core test, drilled east of Carlsbad, New Mexico, penetrated a section of the salt-bearing Salado formation of Permian age, from which no other consecutive cores are available either from potash core tests or the numerous wells drilled for oil. These cores have been studied in detail for the sedimentary and stratigraphic evidence they disclose; a detailed log has been compiled of the section; and some of the minerals of the core have been determined by means of chemical analysis and X-rays. The sequence here described extends from above the Cowden anhydrite member of the Salado formation into the underlying Carlsbad limestone. Two members of the Salado formation, the La Huerta and Fletcher anhydrite members, are here defined. Also evidence for an erosional unconformity between the Fletcher anhydrite member and the Carlsbad limestone as disclosed by the core is presented."

p. 63, Para. 3;

" Although churn-drill samples are not available, it is possible from the driller's log and the core material to classify the rocks into the following formations.

Age	Formation	Internal (Feet)	Thickness (Feet)
Quaternary.......	Surface sand and caliche......	0- 10	10
Triassic.........	Santa Rosa(?)sandstone........	10- 65	55
Triassic.........	Pierce Canyon redbeds.........	65- 570	505
Permian..........	Rustler formation(upper part).	570- 660	90
Permian..........	Rustler formation(lower part).	660- 890	230
Permian..........	Salado formation.............	890- 1,380	490
Permian..........	Carlsbad limestone...........	1,380-1,381½	1½

"

FLETCHER ANHYDRITE MEMBER OF THE SALADO, p 75;

" The lowest halite bed of the Salado grades within a foot or two into an uncommonly massive bed of anhydrite, which may range from 50 to 100 feet or more in thickness. In this core test it is 69 feet thick. Because of its stratigraphic importance this unit is here called the Fletcher anhydrite member of the Salado formation, the name being taken from the well in which this core test was made."

LaVenue, A.M., Haug, A., and Kelley, V.A. 1988. Numerical Simulation of Ground-water Flow in the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) Site; Second Interim Report. SAND88-7002. Sandia National Laboratories, Albuquerque, NM. WPO 28588.

EXECUTIVE SUMMARY, p ii;

" This hydrologic modeling study has been performed as part of the regional hydrologic characterization of the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico. The study resulted in an estimation of the transmissivity distribution, hydraulic potentials, flow field, and fluid densities in the Culebra Dolomite Member of the Permian Rustler Formation at the WIPP site.

The three-dimensional finite-difference code SWIFT-II . . ."

Section 6.0 CONCLUSIONS, p 6-1, para 2;

" (1) The calibrated transmissivity distribution contains the same general trend over the model area as the observed transmissivities with predominantly lower transmissivities ($<1 \times 10^{-7}$ m^2/s) east of the WIPP-site boundary, intermediate transmissivities in the central part of the model area (1×10^{-6} to 1×10^{-4} m^2/s) and high transmissivities ($>1 \times 10^{-3}$ m^2/s) in the western part of the model area representing Nash Draw. local differences to the general trend are present west of WIPP-30 and WIPP-26 and between H-17 and P-17. The transmissivities in these areas were increased to reduce the differences between the calculated and observed heads below the uncertainties of the observed heads. The high-transmissivity feature between H-17 and P-17 is less transmissive than a similar feature proposed in Haug et al. (1987).

ELEVATION DATA BASE - UPDATED 12-29-87

WELL	GROUND-SURFACE ELEV FT AMSL	GROUND-SURFACE ELEV SOURCE	CULEBRA DEPTH FT BGS T	C	B	CULEBRA ELEVATION M AMSL T	C	B	CUL THICK M
H-1	3397.9	MERCER 83	676	688	699	829.6	826.1	822.6	7.0
H-2A	3377.8	RLB	623	634	645	839.7	836.3	833.0	6.7
H-2B1	3377.6	RLB	624	633	642	839.3	836.6	833.8	5.5
H-2B2	3377.6	REDDY	623	634	645	839.6	836.2	832.9	6.7
H-2C	3377.7	RLB	624	633	642	839.3	836.6	833.8	5.5
H-3B1	3389.4	RLB	670	682	694	828.9	825.2	821.6	7.3
H-3B2	3388.3	S 86-7109	676	688	700	826.7	823.1	819.4	7.3
H-3B3	3387.1	S 86-7109	673	685	696	827.3	823.8	820.3	7.0
H-4A	3332.8	RLB	496	508	520	864.7	861.0	857.3	7.3
H-4B	3332.7	RLB	490	503	516	866.4	862.5	858.5	7.9
H-4C	3332.5	RLB	490	503	516	866.4	862.4	858.5	7.9
H-5A	3505.6	RLB	897	909	920	795.1	791.6	788.1	7.0
H-5B	3505.4	RLB	897	909	920	795.0	791.5	788.0	7.0
H-5C	3505.8	RLB	899	912	924	794.5	790.7	786.9	7.6
H-6A	3347.3	MERCER 83	604	616	627	836.1	832.6	829.1	7.0
H-6B	3347.6	MERCER 83	604	616	627	836.2	832.7	829.2	7.0
H-6C	3347.9	MERCER 83	604	616	627	836.3	832.8	829.3	7.0
H-7B1	3163.6	RLB	237	256	274	892.0	886.4	880.8	11.3
H-7B2	3164.0	CALCULATED	237	256	274	892.1	886.5	880.9	11.3
H-7C	3163.4	RLB	237	256	274	892.0	886.3	880.7	11.3
H-8B	3433.8	S 87-0039	588	601	614	867.4	863.4	859.5	7.9
H-8C	3433.0	MERCER 83	588	601	614	867.2	863.2	859.2	7.9
H-9A	3405.4	RLB	647	662	677	840.8	836.2	831.6	9.1
H-9B	3405.6	MERCER 83	647	662	677	840.8	836.2	831.7	9.1
H-9C	3405.9	MERCER 83	647	662	677	840.9	836.3	831.8	9.1
H-10B	3687.0	MERCER 83	1360	1376	1391	709.3	704.5	699.8	9.4
H-10C	3686.9	MERCER 83	1360	1376	1391	709.2	704.5	699.8	9.4
H-11B1	3412.1	REDDY	730	743	756	817.5	813.5	809.6	7.9
H-11B2	3412.1	REDDY	733	745	757	816.6	812.9	809.3	7.3
H-11B3	3412.1	REDDY	734	747	759	816.3	812.5	808.7	7.6
H-12	3426.0	REDDY	823	837	850	793.4	789.3	785.2	8.2
H-14	3345.6	RLB	545	559	572	853.6	849.5	845.4	8.2
H-15	3480.2	RLB	861	872	883	798.3	795.0	791.6	6.7
H-16	3409.6	REDDY	700	712	724	826.0	822.2	818.4	7.6
H-17	3384.0	REDDY	706	719	731	816.3	812.4	808.5	7.8

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INTERA Technologies

Ground-Surface and Culebra Dolomite Elevations for WIPP-Area Boreholes

Table B.1

ELEVATION DATA BASE - UPDATED 12-29-87

WELL	GROUND-SURFACE ELEV FT AMSL	GROUND-SURFACE ELEV SOURCE	CULEBRA DEPTH FT BGS T	C	B	CULEBRA ELEVATION M AMSL T	C	B	CUL THICK M
DOE-1	3465.1	REDDY	820	832	843	806.2	802.7	799.2	7.0
DOE-2	3418.4	RLB	824	835	846	790.8	787.4	784.1	6.7
P-1	3345.1	MERCER 83	538	552	565	855.6	851.5	847.4	8.2
P-2	3479.4	MERCER 83	857	870	883	799.3	795.3	791.4	7.9
P-3	3382.7	MERCER 83	642	654	665	835.4	831.9	828.4	7.0
P-4	3443.8	MERCER 83	775	789	802	813.5	809.3	805.2	8.2
P-5	3470.9	MERCER 83	804	816	827	812.9	809.4	805.9	7.0
P-6	3354.1	MERCER 83	537	549	560	858.7	855.1	851.6	7.0
P-7	3332.0	MERCER 83	496	509	522	864.4	860.5	856.5	7.9
P-8	3338.6	MERCER 83	563	576	588	846.0	842.2	838.4	7.6
P-9	3411.5	MERCER 83	734	746	757	816.1	812.6	809.1	7.0
P-10	3509.3	MERCER 83	931	944	957	785.9	781.9	777.9	7.9
P-11	3503.9	MERCER 83	912	925	938	790.0	786.0	782.1	7.9
P-12	3373.6	MERCER 83	633	645	656	835.3	831.8	828.3	7.0
P-13	3345.2	MERCER 83	604	616	627	835.5	832.0	828.5	7.0
P-14	3359.8	REDDY	573	584	595	849.4	846.1	842.7	6.7
P-15	3309.8	RLB	413	424	435	882.9	879.6	876.2	6.7
P-16	3317.9	MERCER 83	500	512	523	858.9	855.4	851.9	7.0
P-17	3335.8	REDDY	558	571	583	846.7	842.9	839.1	7.6
P-18	3477.3	REDDY	912	926	940	781.9	777.6	773.4	8.5
P-19-	3545.1	MERCER 83	967	982	997	785.8	781.2	776.7	9.1
P-20	3552.7	MERCER 83	953	966	979	792.4	788.4	784.5	7.9
P-21	3509.0	MERCER 83	899	912	924	795.5	791.7	787.9	7.6
WIPP-11	3426.1	MERCER 83	844	856	867	787.0	783.5	780.0	7.0
WIPP-12	3471.3	REDDY	810	823	835	811.2	807.4	803.5	7.6
WIPP-13	3405.4	RLB	701	713	724	824.3	820.8	817.3	7.0

Drawn by	Date
Checked by	Date
Revisions	Date
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INTERA Technologies

Ground-Surface and Culebra Dolomite Elevations for WIPP-Area Boreholes

Table B.1 (cont.)

ELEVATION DATA BASE - UPDATED 12-29-87

WELL	GROUND-SURFACE ELEV FT AMSL	GROUND-SURFACE ELEV SOURCE	CULEBRA DEPTH FT BGS			CULEBRA ELEVATION M AMSL			CUL THICK M
			T	C	B	T	C	B	
WIPP-18	3456.4	RLB	787	798	808	813.6	810.4	807.2	6.4
WIPP-19	3433.1	S 87-0039	756	768	779	816.0	812.5	809.0	7.0
WIPP-21	3417.1	REDDY	729	741	753	819.3	815.7	812.0	7.3
WIPP-22	3425.8	S 87-0039	742	753	764	818.0	814.7	811.3	6.7
WIPP-25	3212.5	RLB	447	460	472	842.9	839.1	835.3	7.6
WIPP-26	3151.7	RLB	186	198	209	904.0	900.4	896.9	7.0
WIPP-27	3177.2	RLB	292	305	318	879.4	875.4	871.5	7.9
WIPP-28	3346.6	RLB	420	433	446	892.0	888.1	884.1	7.9
WIPP-29	2977.0	RLB	12	27	42	903.7	899.1	894.6	9.1
WIPP-30	3427.5	RLB	631	642	653	852.4	849.0	845.7	6.7
ERDA-6	3540.2	MERCER 83	710	723	735	862.6	858.8	855.0	7.6
ERDA-9	3408.8	RLB	704	716	727	824.4	820.9	817.4	7.0
ERDA-10	3371.2	MERCER 83	476	490	504	882.5	878.2	873.9	8.5
CB-1	3327.3	RLB	503	516	529	860.8	856.9	852.9	7.9
ENGLE T	3419.0	S 87-0039	659	670	681	841.2	837.9	834.5	6.7
AEC-7	3654.0	MERCER 83	870	883	896	848.6	844.6	840.6	7.9
AEC-8	3531.5	MERCER 83	833	846	859	822.5	818.5	814.6	7.9
FFG242 *							726.2		

AVG THICKNESS = 7.7 m

REFERENCES

* - FFG242 DEPTH TO BASE OF CULEBRA VALUE FROM DAVIES (1988)
A THICKNESS OF EIGHT M IS ASSUMED FOR MIDPOINT-VALUE CALCULATION

Drawn by	Date	Ground-Surface and Culebra Dolomite Elevations for WIPP-Area Boreholes
Checked by	Date	
Revisions	Date	
H09700R554		
INTERA Technologies		Table B.1 (cont.)

Lord, K.J., and Reynolds, W.E., eds. 1985. Archaeological Investigations of Three Sites within the WIPP Core Area. Prepared for the U.S. Army Corps of Engineers (COE), Albuquerque District in NM. Eddy County, NM, Chambers Consultants and Planner, Albuquerque, NM.

ABSTRACT, p i;

" Archaeological investigations of ENM 10222, ENM 10230, and ENM 10418 have produced significant information on one portion of the seasonal round of prehistoric groups which inhabited southeast New Mexico between 1000 B.C. and A.D 1400. The results of intensive surface collections and subsurface testing suggest that a hunter-gatherer subsistence system was in effect for the entire occupational history of the sites. This system developed out of an indigenous Late Archaic population and continued well into the Neoarchaic. During the Neoarchaic period an overlay of Jornada Mogollon traits entered the area, i.e., ceramics and arrow points. The evidence suggests that these additions did not effect the basic adaptive strategy.

ENM 10222 and ENM 10230 represent plant collection and processing localities and probably were satellite sites to more complex limited base camps. ENM 10418 represents one of these limited base camps. Both functional categories represent one subset in a seasonal round of activities. The three sites investigated represent the summer portion of a seasonal round with acorn and mesquite being the primary subsistence focus."

B. Bradley in Lord, K.J., and Reynolds, W.E., eds. 1985. *Archaeological Investigations of Three Sites within the WIPP Core Area.* Prepared for the U.S. Army Corps of Engineers (COE), Albuquerque District in NM. Eddy County, NM, Chambers Consultants and Planner, Albuquerque, NM.

ABSTRACT;

" A cultural resource inventory of a 100 foot wide by 18 mile long corridor (218 acres) for a water pipeline for the Waste Isolation Pilot Plant (WIPP) was completed in June, 1982. This project was undertaken for the U. S. Army Corps of Engineers, Albuquerque District by Complete Archaeological Service Associates of Cortez, Colorado. One small prehistoric site was located adjacent to the proposed right-of-way, but will not be affected by the pipeline installation. An additional four isolated artifact occurrences were recorded within the right-of-way, two of which were collected. Archaeological clearance is recommended for construction of the pipeline."

Lowenstein, T.K. 1987 Post Burial Alteration of the Permian Rustler Formation Evaporites, WIPP Site, New Mexico: Textural, Stratigraphic and Chemical Evidence. EEG-36. New Mexico Health and Environment Department, Santa Fe, New Mexico.

PREFACE, p vii;

" A repository for permanent isolation of defense transuranic wastes is being excavated in southeastern New Mexico, about 40 km 925 miles) east of Carlsbad. The Waste Isolation Pilot Plant (WIPP) repository has been designed for the disposal of waste in the lower part of the Salado (salt) Formation at a depth of 655 meters (2150 ft). The water-bearing zones of the Rustler Formation, which overlies the Salado, are considered to be the main pathway for the transport of radionuclides to the biosphere, if the repository is breached.

The Rustler Formation is 150 meters (490 feet) thick, 6.4 Km (4 miles) east of the center of the WIPP site. The thickness reduces drastically to the west so that it is only 91 meters (300 ft) thick in the western part of the WIPP site. At its thickest location, the Rustler consists of siltstone and anhydrite with two dolomite beds and both clear and clayey halite. Halite is progressively missing from deeper layers from east to west in the Rustler cross-section across the WIPP site. These observations were interpreted by Powers et al (1978), Mercer (1983), Lambert (1983), Chaturvedi and Rehfeldt (1984), Bachman (1984), Snyder (1985), Chaturvedi and Channell (1985) and others as indicating post-burial dissolution of halite and increased gypsification of anhydrite further west. Increased permeability of the water-bearing dolomites from east to west also was thought to result from the increased fracturing as a result of dissolution.

In 1984, Powers and Holt (1984) and Holt and Powers (1984) expressed doubts about the concept of post-burial dissolution of Rustler evaporites, on the basis of detailed mapping in the WIPP Waste Handling Shaft, and stated the following:

> 'Post-depositional dissolution features were not observed in any stratigraphic horizons in the Waste Shaft. In fact, several zones previously identified as dissolution residues in nearby boreholes (e.g. ERDA-9) contain pronounced primary sedimentary features. This is of great significance since dissolution has, historically, been considered as an important process that has greatly modified the Rustler Formation in this area.'
> (Holt and Powers, 1984)

This statement was based on the first detailed sedimentological study of the Rustler stratigraphy, but only at one location, albeit in situ, in a shaft. It clearly signaled the need for further work on the lateral variations in the stratigraphy of the Rustler Formation across the WIPP site. Since the interpretation by Powers and Holt was based on sedimentary features, the need was for a sedimentological study of the Rustler Formation.

To resolve this issue, the Environmental Evaluation Group (EEG) asked Dr. Tim K. Lowenstein to perform a sedimentological study of the available cores of the Rustler Formation. Dr. Lowenstein is a sedimentologist with special interest in the study of evaporites and has studied the Ochoan evaporites of the delaware Basin (Lowenstein, 1982, 1985). For this study, he performed a detailed sedimentological analysis of the Rustler cores from four wells, viz. DOE-2, W-19, H-11 and H-12. This included visual examination of the cores, preparation and petrographic analyses of 52 thin sections from selected locations of the cores, and x-ray diffraction analyses of 40 samples from selected locations of the cores. In addition, descriptive data on the rock cuttings and geophysical logs of borehole P-18 were used for correlation purposes. This report is a result of these analyses and correlation of sedimentary features between the drill-holes.

This study was confined to a miniscule area (only about 0.05%) of the total extent of the Rustler Formation and therefore cannot be considered to be a study of post-burial alteration of the Rustler Formation as a whole. Within the confines of this area, however, detailed stratigraphic correlations by Dr. Lowenstein based on sedimentary structures and textures indicate overall uniformity of depositional setting. Further, the physical and chemical alteration features, based on crosscutting relations, represent the last processes which have operated on these rocks. Four distinct dissolution zones in the Rustler Formation have been interpreted by Dr. Lowenstein. Although the strata above and below the inferred dissolution zones are chemically and physically altered, they contain abundant sedimentary structures and internal stratigraphy that can easily be matched from well to well. Dr. Lowenstein does not see a contradiction between post depositional dissolution and the survival of sedimentary structures. His interpretation is that the dissolved species produced by solution are removed from the site of reaction and the zones in which the effects of dissolution are now seen were at the periphery of main dissolution activity and therefore may exhibit some alteration as well as primary sedimentary structures."

CULEBRA DOLOMITE MEMBER, p. 19;

" The Culebra Dolomite Member is a tan to gray colored dolostone with minor quartz silt (Fig. 5 and Photos 10 and 11). The rock is predominantly structureless, although vague layering, on a scale of 1-5 cm, is seen in places. Well preserved mm-scale lamination is present at the base of the unit. The top of the Culebra Member, about 30 cm in thickness, is finely laminated and the unit is capped by a brown to black laminate with sub-mm scale, black organic-rich and tan carbonate-rich layers. One common feature of the Culebra Dolomite is the large number of nodular masses and open vugs from a mm to greater than 10 cm in diameter. They are roughly spherical to ellipsoidal in shape and are in sharp contrast with the surrounding dolostone. In core H-12, the vugs are open or filled with (1) a core of anhydrite laths and a rim of gypsum (Photo 10) or (2) gypsum. In the other 3 cores, most of the vugs are open but some are entirely filled with coarse gypsum crystals (Fig. 5)."

CRITERIA FOR RECOGNIZING LATE STAGE ALTERATION, p. 29;

" Features interpreted to have been produced by late-stage alteration have been observed in all four cores of the Rustler Formation in the study area. This alteration has occurred to varying degrees in the top of the Lower Member (A-1 anhydrite and Mudstone I), the Culebra Dolomite Member, the Tamarisk Member (A-2 anhydrite, Mudstone II and A-3 anhydrite), the Magenta Dolomite Member, and the Forty Niner Member (A-4 anhydrite, Mudstone III and A-5 anhydrite)(see Figs. 4, 5 and 6). The alteration has involved physical processes such as brecciation, slumping, fracturing and faulting and chemical processes such as rehydration of anhydrite to gypsum, gypsum precipitation and dissolution of halite, anhydrite and gypsum.

Two assumptions that have led to the above interpretations are first addressed. . . ."

p. 30, para. 2;

" The second assumption is that sometime after deposition, most, if not all, of the $CaSO_4$ in the Rustler Formation was anhydrite. The abundant pseudomorphs of gypsum, now composed of anhydrite, indicate that an originally gypsum-rich sediment has since been converted to anhydrite. This assumption is backed by evidence from many other ancient evaporites where primary gypsum has been wholly converted to anhydrite upon burial. therefore, the gypsum now present in the Rustler is interpreted to have formed as a rehydration replacement of anhydrite or as a void filling cement, or fracture filling, the three of which are commonly associated. There is abundant evidence indicating that the formation of gypsum as one of the above textures has been the last process that has operated in the Rustler Formation. This evidence includes (1) gypsum-filled fractures that crosscut all other sedimentary features, (2) gypsum crystals with remnants of anhydrite in the cores of nodules and clasts, and gypsum rims around anhydrite nodules (Culebra Dolomite), and (3) gypsum-cemented breccias. Thus, where the gypsum of the Rustler Formation forms anything other than a void-filling, it is interpreted to have undergone the transformation sequence of dehydration of gypsum to anhydrite (upon burial) and rehydration of anhydrite to gypsum (upon exhumation). Such changes should result in the loss of primary sedimentary structures compared to rocks still composed of anhydrite and in general this is true. In such 'gypsified' rocks, the gypsum crystals may crosscut the original gypsum pseudomorph boundaries, which confirms that the gypsum is a later alteration product.

The presence of gypsum in the Rustler Formation therefore serves as a general indicator of late stage alteration (see Figs. 4, 5 and 6). In all zones identified as altered in the study area, gypsum is present. Waters capable of directly precipitating gypsum and rehydrating anhydrite to gypsum on a large scale are not likely to be connate evaporite formation waters, but were probably introduced into the rock at some later time. In the Rustler Formation, the most likely candidate for an introduced 'alien' water is groundwater. The present-day Rustler Formation waters (in the Culebra and Magenta Dolomites) are for the most part 'dilute' and probably meteoric in origin. These waters have not migrated from the evaporite within or below the Rustler Formation. The chemistry of present-day Rustler Formation waters will be further discussed below.

Evidence for late-stage chemical alteration.

The textural features in the Rustler Formation interpreted to have formed during late stage chemical alteration by the introduction of alien waters include (1) precipitation of gypsum as void-filling cement, breccia cement and fracture filling (Figs. 4, 5 and 6 and Photos 8, 9, 11, 15, 19), (2) replacement of anhydrite by gypsum by rehydration (Figs 4, 5 and 6 and Photos 8, 10, 22, 23, 24), (3) precipitation of euhedral gypsum crystals and gypsum crystal rosettes (Figs. 4, 5 and 6 and Photo 13), (4) dissolution of gypsum and anhydrite (open vugs in Culebra and Magenta Dolomite Members, Photos 10 and 11) and (5) precipitation of calcite (Figs. 4, 5 and 6)."

Lowenstein, T.K. 1988. "Origin of Depositional Cycles in a Permian Saline Giant: the Salado (McNutt Zone) Evaporites of New Mexico and Texas." Geological Society of America Bulletin, Vol. 100, No. 4, pp. 20-21, 592-608.

ABSTRACT, p 592, col 1;

" Two types of metre-scale depositional cycles have been recognized within the McNutt Potash Zone of the Permian Salado evaporites. The cycles record progressive drawdown and concentration of brine in a shallow, marginal marine basin. 'Type I' cycles, made of basal carbonate-siliciclastic mudstone, then anhydrite-polyhalite pseudomorphous after primary gypsum, overlain by halite and capped by muddy halite, are interpreted as marine sea water dominated. They formed by massive spillover of sea water through a connection with the Permian Ocean at high relative sea-level stands (lagoonal mudstone and anhydrite-polyhalite after subaqueous gypsum), followed by relative lowering of sea level and gradual basin restriction (shallow saline-lake and salt-pan halite) and ending with a desiccated basin, isolated from the Permian Ocean (salt-pan halite and saline mudflat muddy halite cycle cap). 'Type II' cycles occur between the Type I cycles and contain halite overlain transitionally by muddy halite. They record a temporal evolution of environments from a shallow saline lake to an ephemeral salt-pan-saline mudflat complex and are interpreted as continental-dominated sequences sourced by meteoric inflow from surrounding land areas that mixed with variable amounts of sea water, either residual or introduced into the Salado basin by seepage.

The vertical stacking of Type I cycles is best explained by periodic invasions of sea water into the Salado basin coincident with eustatic sea-level rises. The continental-dominated Type II cycles formed during intervening periods of eustatic sea-level fall and low stands. The *maximum* time interval between major marine incursions is an average of 10^5 yr."

INTRODUCTION, p 592, col 3, para 2, line 3;

" The Salado Formation is a 'giant' evaporite deposit (150,000 km^2) with potash-bearing intervals."

Lucas, S.G., and Anderson, O.J. 1993a. "Triassic Stratigraphy in Southeastern New Mexico and Southwestern Texas." In Carlsbad Region, New Mexico and West Texas, New Mexico Geological Society, Forty-Fourth Annual Field Conference, Carlsbad, NM, October 6-9, 1993. D.W. Love et al., eds., pp. 231-235. New Mexico Geological Society, Socorro, NM.

ABSTRACT, p 231;

" Upper Triassic strata exposed in southeastern New Mexico and southwestern Texas are assigned to the Santa Rosa, San Pedro Arroyo and Dockum Formations of the Chinle Group. In southeastern New Mexico (Chaves, Eddy and Lea Counties) the Santa Rosa Formation is as much as 25 m thick and is mostly trough-crossbedded extraformational conglomerate and sandstone with minor beds of mudstone or siltstone. It disconformably overlies Upper Permian (Artesia Group or Quartermaster Formation) strata. The San Pedro Arroyo Formation conformably (?) overlies the Santa Rosa Formation and is at least 50 m of variegated smectitic mudstone and minor sandstone/conglomerate. Regional geologic maps have greatly overstated the extent of Upper Triassic exposures in southeastern New Mexico. In southwestern Texas (area from Pecos to Mitchell Counties) the Dockum Formation consists of the basal Camp Spring Member and overlying strata here assigned to a new stratigraphic unit, the Iatan Member. The Camp Springs Member is at least 15 m thick and is dominantly extraformational, siliceous conglomerate. It disconformably overlies the Upper Permian Quartermaster (=Dewey Lake) Formation and is conformably (?) overlain by the Iatan Member, which is 80-100 m thick and characterized by intercalcated, persistent intervals of red smectitic mudstone and trough-crossbedded micaceous sandstone. Fossil vertebrates indicate the Camp Springs and Iatan Members are of late Carnian (Tuvalian) age. Physical stratigraphy and lithology suggest correlation of the Santa Rosa Formation with the Camp Springs Member and the San Pedro Arroyo Formation with the Iatan Member."

Santa Rosa Formation, p 232, col 1;

" We assign the basal sandstones and conglomerates of the Upper Triassic section in southeastern New Mexico to the Santa Rosa Formation, as did Lang (1935) and subsequent workers. The Santa Rosa is as much as 25 m thick and is mostly trough-crossbedded extraformational conglomerate and sandstone with minor beds of mudstone or siltstone. Typical colors are grayish red (10 R 4/2) and pale reddish brown (10 R 5/4) for the sandstones, siltstones and mudstones, whereas conglomerate beds are mostly yellowish gray (5 Y 8/1) to light greenish gray (5G Y 8/1). Sandstones are micaceous subarkoses or litharenites. Conglomerate clasts typically are rip-ups of underlying Permian red beds (Artesia Group or Quartermaster Formation) at the base of the Santa Rosa Formation. Some quartzite clasts (usually in the very coarse to pebbly size range) also are present in basal Santa Rosa conglomerates. Conglomerates higher in the unit contain reworked Triassic siltstone and sandstone clasts.

The base of the Santa Rosa Formation is a disconformity above Permian red beds. Permian strata are finer grained, more texturally and mineralogically mature, gypsiferous, more evenly bedded and a different color (mostly moderate reddish brown) than the Santa Rosa Formation. Despite these differences, in southeastern New Mexico both Miller (1955) and Vine (1963) incorrectly included uppermost sandstones of the Quartermaster Formation in the Santa Rosa Formation (Schiel, 1988; Lucas and Anderson, this volume).

The top of the Santa Rosa Formation in southeastern New Mexico is visible only at Maroon Cliffs. Here, variegated moderate reddish brown (10 R 4/6) and grayish red purple (5 RP 4/2) mudstone of the San Pedro Arroyo Formation rests directly (conformably ?) on the uppermost conglomerate bed of the Santa Rosa Formation (Fig. 2).

Other than undefinable fragments of petrified wood, bone and coprolites, no fossils have been collected in the Santa Rosa Formation in southeastern New Mexico. Nevertheless, regional correlation suggests this unit is of Late Triassic (late Carnian) age (see below)."

Lucas, S.G., and Anderson, O.J. 1993b. "Stratigraphy of the Permian-Triassic Boundary in Southeastern New Mexico and West Texas." In Geology of the Carlsbad Region, New Mexico and West Texas, D.W. Love et al., eds., Forty-Fourth Annual Field Conference Guidebook. New Mexico Geological Society, Socorro, NM.

TRIASSIC STRATA, p. 222;

" Triassic strata in southeastern New Mexico and west Texas pertain to the Chinle Group of Lucas (1993). In southeastern New Mexico, the basal unit of the Chinle Group is the Santa Rosa Formation, whereas in west Texas it is the Camp Springs Member of the Dockum Formation (Lucas and Anderson, 1992, 1993 and this volume).

In east-central New Mexico, the Santa Rosa Formation consists of, is ascending order, the Tecolitito, Los Esteros and Tres Lagunas Members. The medial, mudstone-dominated Los Esteros Member contains fossil plants and vertebrates that indicate a late Carnian age (Ash, 1988; Hunt and Lucas, 1988). In west Texas (Randall, Scurry and Crosby Counties) the Camp Springs Member of the Dockum Formation produced the phytosaur *Paleorhinus*, indicative of a late Carnian age (Hunt and Lucas, 1991). These fossils thus establish the age of the oldest Triassic strata in southeastern New Mexico and west Texas as Late Triassic (late Carnian). On the Harland et al. (1989) numerical time scale this is about 225 Ma."

Machette, M.N. 1985. "Calcic Soils of the Southwestern United States." In Soils and Quaternary Geology of the Southwestern United States. D.L. Weide and M.L. Faber, eds., Special Paper Vol. 203, pp. 1-21. Geological Society of America, Denver, CO.

ABSTRACT, p 1;

" Calcic soils are commonly developed in Quaternary sediments throughout the arid and semiarid parts of the southwestern United States. In alluvial chronosequences, these soils have regional variations in their content of secondary calcium carbonate ($CaCO_3$) because of (1) the combined effects of the age of the soil, (2) the amount, seasonal distribution, and concentration of Ca^{++} in rainfall, and (3) the $CaCO_3$ content and net influx of airborne dust, silt, and sand. This study shows that the morphology and amount of secondary $CaCO_3$ (cS) are valuable correlation tools that can also be used to date calcic soils.

The structures in calcic soils are clues to their age and . . ."

NOTE: The tables and text on the following pages are taken from p. 5 of the reference.

Calcic soils of the southwestern United States

TABLE 1. STAGES OF CALCIUM CARBONATE MORPHOLOGY OBSERVED IN CALCIC SOILS AND PEDOGENIC CALCRETES DEVELOPED IN NONCALCAREOUS PARENT MATERIALS UNDER ARID AND SEMIARID CLIMATES OF THE AMERICAN SOUTHWEST
[Modified from Gile and others (1966, p. 348, Table 1) and Bachman and Machette (1977, p. 40, Tables 2 and 3)]

Stage	Gravel content[1]	Diagnostic morphologic characteristics	$CaCO_3$ distribution	Maximum $CaCO_3$ content[2]
		CALCIC SOILS		
I	High-----	Thin, discontinuous coatings on pebbles, usually on undersides.	Coatings sparse to common	Tr-2
	Low------	A few filaments in soil or faint coatings on ped faces.	Filaments sparse to common	Tr-4
II	High-----	Continuous, thin to thick coatings on tops and undersides of pebbles.	Coatings common, some carbonate in matrix, but matrix still loose.	2-10
	Low------	Nodules, soft, 0.5 cm to 4 cm in diameter	Nodules common, matrix generally noncalcareous to slightly calcareous.	4-20
III	High-----	Massive accumulations between clasts, becomes cemented in advanced form.	Essentially continuous dispersion in matrix (K fabric).	10-25
	Low------	Many coalesced nodules, matrix is firmly to moderately cemented.	------------------do----------------	20-60
		PEDOGENIC CALCRETES (INDURATED CALCIC SOILS)		
IV	Any------	Thin (<0.2 cm) to moderately thick (1 cm) laminae in upper part of Km horizon. Thin laminae may drape over fractured surfaces	Cemented platy to weak tabular structure and indurated laminae. Km horizon is 0.5-1 m thick.	>25 in high gravel content >50 in low gravel content
V	Any------	Thick laminae (>1 cm) and thin to thick pisolites. Vertical faces and fractures are coated with laminated carbonate (case-hardened surface)	Indurated dense, strong platy to tabular structure. Km horizon is 1-2 m thick.	>50 in high gravel content >75 in low gravel content
VI	Any------	Multiple generations of laminae, breccia, and pisolites; recemented. Many case-hardened surfaces.	Indurated and dense, thick strong tabular structure. Km horizon is commonly >2 m thick.	>75 in all gravel contents

[1]High is more than 50 percent gravel; low is less than 20 percent gravel.
[2]Percent $CaCO_3$ in the <2-mm-fraction of the soil. Tr, trace of carbonate.

"Stage V and VI calcic soils are particularly well preserevd at numerous locations in the Southwest. The most spectacular of these soils are associated with the constructional geomorphic surfaces of the following geologic

$CaCO_3$ stage	Geomorphic surface and probable age	Geologic unit and probable age	Location
V	Upper La Mesa, early Pleistocene	Camp Rice Formation of Strain (1966), middle Pleistocene to Pliocene	Las Cruces, New Mexico
V	Mescalero middle Pleistocene	Gatuna Formation, middle Pleistocene	Southeastern New Mexico
VI	Mormon Mesa, early(?) Pliocene	Muddy Creek Formation, Miocene	Overton, Nevada
VI	Ogallala, late(?) Miocene	Ogallala Formation, Miocene	Eastern New Mexico and western Texas

units:

Madsen, B.M., and Raup, O.B. 1988. Characteristics of the Boundary between the Castile and Salado Formations near the Western Edge of the Delaware Basin, Southeastern New Mexico. New Mexico Geology, Vol. 10, No. 1.

ABSTRACT, p 1, col. 1;

" The contact between the Upper Permian Castile and Salado Formations throughout the Delaware Basin, southeast New Mexico and west Texas, has been difficult to define because of facies changes from the basin center to the western edge. Petrographic studies of core from a Phillips Petroleum Company well, drilled in the western Delaware Basin, indicate that there are major mineralogical and textural differences between the Castile and Salado Formations. The Castile is primarily laminated anhydrite with calcite and dolomite. The Salado Formation is also primarily anhydrite at the location of this core hole, but with abundant layers of magnesite. This magnesite indicates an increase in magnesium enrichment in the basin brines, which later resulted in the deposition of magnesium-rich potash deposits within the Salado Formation elsewhere in the basin. A breccia zone at the top of the Castile Formation shows evidence of massive recrystallization, which indicates a break in sedimentation and possible subaerial erosion. This breccia zone probably represents an unconformity along the western edge of the basin between the Castile and Salado Formations, which has been recognized by other workers."

Summary and conclusions, p 4, col 3, para 4;

" The Castile and Salado Formations in the Delaware Basin represent sediments that were deposited in an evaporite environment of steadily increasing salinity. The boundary between the two formations, in general, represents a change from sulfate, carbonate, and some chloride deposition in the Castile, to deposition of chlorides and magnesium-rich potash minerals in the Salado Formation.

Adams (1944) recognized an unconformity between the Castile and Salado Formations in the northern part of the Delaware Basin. Correlations of acoustical logs and facies studies by Anderson (1978, 1981) support Adams' interpretation. Anderson (1978, p. 17) said that 'there was an episode of non-deposition, angular unconformity, and even salt dissolution in the northern part of the basin following the deposition of the Halite III unit (upper halite) of the Castile Formation.'

The Phillips core hole, on which this study is based, was drilled at the western edge of the Delaware Basin where both the Castile and Salado Formations are now primarily anhydrite with some layers of carbonate. The major difference between the Castile Formation in this core, as compared to core from farther into the basin, is the absence of halite that has been removed by dissolution. The Salado Formation in the core can be distinguished from the underlying Castile Formation on the basis of anhydrite characterized by major inclusions of magnesite. The magnesite in this basin-edge facies indicates an enrichment of magnesium in the basin brines that later resulted in the deposition of magnesium-rich potash deposits within the Salado Formation elsewhere in the basin.

The top of the breccia zone in the Phillips core probably represents the unconformity, and perhaps the period of subaerial erosion at the top of the Castile that was described by Adams (1944) and Anderson (1978, 1981). This breccia zone in the core represents dissolution of halite that resulted in brecciation and massive recrystallization of the anhydrite at the top of the Castile before deposition of the overlying magnesitic anhydrite of the Salado Formation along the western edge of the basin. Contortion of the magnesite layers, as described from this core hole, probably resulted from slumping and differential compaction of soft sediments that were deposited over the irregular breccia surface at the top of the Castile Formation."

McGowen, J.H., and Groat, C.G. 1971. Van Horn Sandstone, West Texas: An Alluvial Fan Model for Mineral Exploration. Report of Investigations No. 72. Bureau of Economic Geology, Austin, TX.

ABSTRACT;

" The Van Horn Sandstone is an ancient alluvial-fan system with a northern highland source area of rhyolite, granite, metamorphic and sedimentary rocks. Sediment ranging in size from silt to boulders was transported southward through canyons by high-gradient mountain streams. South of the mouths of the canyons, sediment was transported by less confined braided streams.

The fan was deposited on a surface of faulted, folded, and highly dissected Precambrian sedimentary, metamorphic, and intrusive basic igneous rocks. Topography of the subjacent erosional surface was rugged and characterized by deep canyons that controlled the distribution of gravel downfan beyond the termination of high-gradient mountain feeder systems.

Three principle facies of the Van Horn area are, from north to south, (1) proximal, chiefly gravel; (2) mid-fan, alternating gravel and sand; and (3) distal, dominantly coarse and very coarse sand. The proximal facies is 300 to 600 feet thick in the northern outcrop area and consists of lower thick, massive cobble and boulder beds and upper thin to thick, horizontally bedded pebble, cobble, and boulder gravels. It grades southward and vertically into alternating gravel and sand of the mid-fan.

Mid-fan deposits are up to 300 feet thick in the northern outcrop area and about 30 feet thick in the central area where the facies plunge southward into the subsurface. Mid-fan gravels occur as lenses of parallel-bedded depositional units with flat bases and convex upper surfaces and as channel-fill deposits. Sands associated with the mid-fan occur either as broad channel-fill deposits or as lenses deposited in low areas flanking gravel lenses (or bars). Two stratification types, foreset and trough crossbeds, dominate these sands.

The distal facies consists chiefly of coarse and very coarse sand; the mid-fan facies grades southward downfan into distal facies, which also overlies mid-fan deposits throughout the fan. Maximum outcrop thickness of distal facies is about 700 feet. Three distal fan subfacies (main braided stream, braided distributary, and braided interlobe) have been differentiated. Main braided stream deposits occur as foreset and trough crossbeds; relative abundance of each crossbed type is variable. Scale of foresets and trough crossbeds decreases upward in the section and to the south. Braided distributary deposits are characterized by a relatively high content of muddy sand units, well-preserved channel-fill deposits, some ripple cross-laminated sand units, foreset- and trough-crossbedded sands (locally the facies may be dominated by small trough crossbeds), and units displaying soft sediment deformation and injection structures. Braided interlobe deposits consist of thick sand sequences composed almost exclusively of trough crossbeds. Muddy sand is uncommon and trough laminae are accentuated by heavy mineral placers. This subfacies contains the greatest heavy mineral concentration within the Van Horn Sandstone.

Facies relationships, textural trends, succession of sedimentary structures, and dip

direction of crossbeds indicate a southerly sediment transport direction. Depth of flow, slope of the fan surface, stream velocity, and competence decreased southward. Proximal facies developed under confined, rapid flow conditions; surges were common events within the feeder system and within the canyons. Mid-fan deposits were laid down by braided streams; both rapid and tranquil flow conditions are indicated by longitudinal gravel bars and by flanking transverse bars with dunes, respectively. The distal fan was the area of lowest physical energy. Tranquil flow conditions dominated, slope of the surface was extremely low, and sediment remained saturated for relatively lengthy periods following a depositional event.

The Bliss Sandstone (Ordovician) is the oldest sedimentary rock sequence that overlies the Van Horn. In places the contact between Bliss and Van Horn is discordant, but in others the contact is conformable.

Although placer gold has been reported in the Van Horn Sandstone, laboratory analysis of 71 samples revealed no significant amounts. Despite the absence of gold, the concentration of other heavy minerals in the braided interlobe subfacies of the distal-fan facies and the detailed descriptions of the facies relationships should contribute to a prospecting model that will be applicable to similar but ore-bearing alluvial fan systems."

McGuire, R.K. 1976. FORTRAN Computer Program for Seismic Risk Analysis. Open-File Report No. 76-67, pp. 1-68. U.S. Geological Survey.

ABSTRACT, p 1;
" A program for seismic risk analysis is described which combines generality of application, efficiency and accuracy of operation, and the advantage of small storage requirements. The theoretical basis for the program is first reviewed, and the computational algorithms used to apply this theory are described. The information required for running the program is listed. Published attenuation functions describing the variation with earthquake magnitude and distance of expected values for various ground motion parameters are summarized for reference by the program user. Finally, suggestions for use of the program are made, an example problem is described (along with example problem input and output) and the program is listed."

Mercer, J.W., Beauheim, R.L., Snyder, R.P. and Fairer, G.M. 1987. Basic Data Report For Drilling and Hydrologic Testing of Drillhole DOE-2 at the Waste Isolation Pilot Plant (WIPP) Site. SAND86-0611. Sandia National Laboratories, Albuquerque, NM. WPO 27646.

ABSTRACT;

" Drillhole DOE-2 was drilled to investigate a structural depression marked by the downward displacement of stratigraphic markers in the Salado formation ~2 mi north of the center of the WIPP site. This depression was named informally after the shallow borehole FC-92 in which the structure was described. The presence of the depression was confirmed by drilling. Contrary to several hypotheses, halite layers were thicker in the lower part of the Salado, not thinner as a result of any removal of halite. The upper Castile anhydrite in Drillhole DOE-2 is anomalously thick and is strongly deformed relative to the anhydrite in adjacent drillholes. In contrast, the halite was <8 ft thick and significantly thinner than usually encountered. The lower Castile anhydrite appears to be normal. The depression within the correlated marker beds in the Salado Formation in Drillhole DOE-2 is interpreted as a result of gravity-driven deformation of the underlying Castile Formation.

Several stratigraphic units were hydrologically tested in Drillhole DOE-2. Testing of the unsaturated lower portion of the Dewey Lake Red Beds was unsuccessful because of exceptionally small rates of fluid intake. Drill-stem tests were conducted in five intervals in the Rustler Formation, over the Marker Bed 138-139 interval in the Salado Formation, and over three sandstone members of the Bell Canyon Formation. A pumping test was conducted in the Culebra Dolomite Member of the Rustler Formation. Pressure-pulse tests were conducted over the entire Salado Formation. Fluid samples were collected from the Culebra Dolomite Member and from the Hays Member of the Bell Canyon Formation."

p. 23, Table 3-2. Stratigraphic Summary of Drillhole DOE-2, (condensed from text);

Rock Unit	Depth Interval (feet)
Quaternary	
Holocene	
Dune Sand	0 - 8
Pleistocene	
Mescalero Caliche	8 - 13
Triassic	
Santa Rosa Sandstone	13 - 133.3
Permian	
Dewey Lake Red Beds	133.3 - 639.1
Rustler Formation	639.1 - 960.9
Salado Formation	960.9 - 3082.8
Castile Formation	3082.8 - 4071.4
Delaware Mountain Group	4071.4 - 4248+

p 28, col 2, para 3;

" DOE-2 penetrated the upper part of the Bell Canyon Formation of the Delaware Mountain Group. From the top downward, units penetrated are the Lamar Limestone, the Ramsey sand, the Ford shale, the Olds sand, and the Hays sand. The Lamar Limestone was first described by Lang (1935); the other units are informal units of local usage."

p 312, para 4;

" Lithologic description	Depth interval Feet
Anhydrite, medium-dark-gray (N4), microcrystalline; nodular structure breaks and disrupts most dusky-yellow-brown (10YR-2/2) laminations; few 3-mm-thick laminae, wavy; basal contact sharp, slightly irregular, and horizontal	4045.3 - 4069.7
Dolomite and anhydrite, dusky-yellow-brown (10YR-2/2) and dark-gray (N3), horizontal laminae; oil bleeding from vertical nearly-healed fracture; basal contact sharp	

and horizontal 4069.7 - 4071.4

Shale, grayish-black (N2) to dark-gray (N3), calcareous, basal contact sharp 4071.4 - 4073.8

Limestone, grayish-black (N2), bedded with dark-gray (N3); pelecypod shells as long as 6 mm and corals(?); basal 5.5 ft alternating ..."

Miller, D.N. 1955. Petrology of the Pierce Canyon Formation, Delaware Basin, Texas and New Mexico [Ph.D. Dissertation]. University of Texas, Austin.

ABSTRACT, p. iii;

" The Pierce Canyon formation of the Delaware Basin is a red siltstone sequence about 350 feet thick that overlies the Permian Rustler evaporites and underlies the Upper Triassic Santa Rosa sandstone. It consists of crosslaminated, gypsiferous, slightly sandy and slightly clayey siltstone and ranks as submature to mature arkose or sub-arkose containing 20 to 30 per cent feldspar. Petrographic and textural analyses show that there is little variation in composition or texture either vertically or horizontally. These redbeds typically contain hollow sanidine grains which may prove useful as a stratigraphic marker. Authigenic biotite was detected in a few of the reduction spots.

The Pierce Canyon redbeds were probably derived predominantly from a granitic source in northern Coahuila, Mexico, under the influence of an arid climate, transported by the wind, and deposited in a shallow saline sea in west Texas and southeastern New Mexico.

Comparison with other redbeds shows that the Dewey Lake formation of the Midland Basin, and the Quartermaster formation of the Texas panhandle, have compositions that are essentially identical with that of the Pierce Canyon redbeds.

The Pierce Canyon differs mineralogically from the Yates, Rustler, Tecovas, Santa Rosa, Chinle, and Gatuna formations. If the Pierce Canyon is assigned to the Permian system, then there are eight mineralogic differences to distinguish Permian from Triassic redbeds."

Miller, D.N. 1966. Petrology of Pierce Canyon Redbeds, Delaware Basin, Texas and New Mexico. American Association of Petroleum Geologists Bulletin, Vol. 80.

ABSTRACT, p 283;

" The Pierce Canyon Formation of the Delaware basin is a brick-red siltstone about 150 feet thick that conformably overlies the Permian Rustler Formation and unconformably underlies the Upper Triassic Santa Rosa Sandstone. Field and laboratory data suggest that the Pierce Canyon is a first-cycle sediment derived from a granite source in northern Mexico under the influence of an arid climate, transported by the wind, and deposited in a shallow saline lagoon that covered western Texas and southeastern New Mexico at the close of the Permian.

In addition, surface and subsurface data from the encompassing strata substantiate the opinion that the Dewey Lake Formation of the southern Permian basin and the Quartermaster Formation of the Texas Panhandle and northwestern Oklahoma have essentially identical mineral assemblages and occupy the same stratigraphic position as the Pierce Canyon. Eight distinct mineralogic differences make it possible to distinguish these formations from the redbeds in the overlying Triassic Dockum Group. The name Pierce Canyon probably could be discontinued in favor of the name Dewey Lake."

Muehlberger, W.R., Belcher, R.C., and Goetz, L.K. 1978. Quaternary Faulting in Trans-Pecos Texas. Geology, Vol. 6, No. 6, pp. 337-340.

ABSTRACT, p 337;

" Faults that displace Quaternary units can be observed in scarps in Trans-Pecos Texas and are restricted to two north-trending zones in contrast to late Tertiary faults that cover the region and strike north, northwest, and west. The western zone of Quaternary faults, near El Paso, is usually included as the southern part of the Rio Grande rift. The eastern zone of Quaternary faults extends for 300 km from southern New Mexico along the Salt Basin graben through Van Horn, Texas; its probable extensions and subparallel associates extend southward to Presidio, Texas. This belt of faults is parallel to the Rio Grande rift zone and should be considered a southeast extension of that zone.

These fault zones die out southward into the edge of the Chihuahua tectonic belt, a region underlain by a thick Mesozoic carbonate and clastic section that in turn rests on a thick layer of evaporites. The evaporite zone may mask Cenozoic normal faulting and thus may define a zone of no data rather than a southern limit of basin-and-range or Rio Grande graben tectonics.

All Quaternary and most Tertiary faults trend parallel to pre-existing structures. The map pattern of Quaternary scarps suggest a maximum extension oriented about S80°W; however, first-motion studies of the 1931 Valentine, Texas earthquake show a maximum elongation direction of S50° to 55°W. This difference may be unique to this one earthquake or may be due to the pre-existing lines of weakness that control the location of presently active faults."

DESCRIPTION OF SCARPS IN SALT BASIN GRABEN, p 338, col 2;

" Only two fault scarps in Quaternary alluvium were found in the New Mexico portion of Salt Basin graben, and these are located along the eastern margin of the graben. The northernmost scarp, 50 km above the Texas border, was mapped northwest of the Brokeoff Mountains by Kelley (1971). A second scarp, 10 km south, was mapped in Crow Flat during our study. A cluster of faults, in the vicinity of Bitterwell Mountain, part of which was mapped by P. B. King (1948, 1965), constitutes the main area of scarps on the east side of the graben. Only two other fault scarps on the east side of the graben definitely can be shown to cut the youngest basin fill; one is at the western base of the southernmost Delaware Mountains, the other is located south of the Apache Mountains."

Nicholson, Jr., A., and Clebsch, Jr., A. 1961. Geology and Ground-Water Conditions in Southern Lea County, New Mexico. Ground-Water Report 6. New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.

ABSTRACT, p 1;

" Southern Lea County is at the southeastern corner of New Mexico. Most of the area is in the Pecos Valley section of the Great Plains physiographic province; it also includes the southern margin of the Llano Estacado. There are no perennial streams and no throughgoing surface drainage.

Rocks of Quaternary, Tertiary, and Triassic age are exposed and contain the principle aquifers. The most important aquifer is the Ogallala formation, which underlies the Llano Estacado and forms outliers south of it. In large parts of southern Lea County, however, the Ogallala has been removed by erosion and in the low-lying areas Quaternary alluvium, derived principally from the Ogallala formation, has been deposited and is the main aquifer. The two aquifers are continuous in the eastern part of the area. Below the Cenozoic rocks are sandstones and shales of the Dockum group of Late Triassic age, from which small quantities of water are obtained. No usable ground water is obtained from rocks older than the Triassic, but highly saline water is produced along with oil from Paleozoic rocks.

In 1954 about 6,000 acre-feet of ground water were used. Most of this quantity was needed for irrigation and for gasoline plants, in about equal amounts. Economic growth from a rapidly developing petroleum industry has brought about a demand for water for industrial and public supplies that is expected to continue. Development of adequate supplies is hindered by restricted occurrence and low transmissibility of the sediments. Because of the low recharge rate, most of the water pumped is being removed from storage.

The chemical quality of the ground water from the principal aquifers is generally fair to good. Production of large quantities of oil-field brine (3,700 acre-feet in 1955) has created a waste-disposal problem of major importance. Most of the brine has been discharged into surface pits. Leakage from the pits has caused contamination of the shallow water in some areas and unless other disposal methods are used, the problem will spread."

p 14, line 9;

" The lowest point within the swale is the San Simon Sink, in sec. 18, T. 23 S., R. 35 E., just west of the eastern escarpment of the swale. The sink is about 100 feet deep from its rim to the bottom and approximately half a square mile in area. Within the sink there is a secondary collapse about 25 to 30 feet deep (see fig. 6). The fill in the sink is mostly calcareous silt and fine sand. Active subsidence is reported to have taken place as recently as 25 to 30 years ago, when large annular fissures developed at the edge of the sink (see fig. 6, 7 and 8). These fissures are still evident and are still as deep as 5 feet in some places. The area immediately adjacent to the sink on the north, south, and west is a grassy plain underlain by sand and silt. Another sink, no longer active, is in sec. 33, T. 21 S., R. 33 E.

The San Simon Swale probably originated as the result of deep-seated collapse. The area may have subsided as a unit. More probably, however, the depression is the result of the removal of material by deflation and by fluvial erosion into large sinks of which the San Simon Sink may be the only one exposed, the others having been completely filled and hidden by the cover of dune sand."

NMBMMR (New Mexico Bureau of Mines and Mineral Resources). 1995. Final Report Evaluation of Mineral Resources at the Waste Isolation Pilot Plant (WIPP) Site. Vols. 1 to 4.

EXECUTIVE SUMMARY, p E-1;

" The Waste Isolation Pilot Plant (WIPP) land withdrawal area occupies 16 mi^2, on the southeastern edge of the Known Potash Leasing Area (administered by BLM), about 30 miles southeast of Carlsbad, Eddy County, New Mexico. It is four miles on a side and is located in secs. 15 to 22 and 27 to 34 of T22S R31E. This study includes an additional study area about one mile wide surrounding and containing an additional 20 mi^2. The combined study area comprises about 36 mi^2.

The amount and value of natural resources under the WIPP land withdrawal area have not been calculated for more than ten years. This report performs this calculation using current and projected prices, production, geologic data, and conditions. The need for recalculating the volume and value of mineral resources within the boundaries of the WIPP land withdrawal area stems from the discovery of oil and associated natural gas in adjacent lease tracts during the late 1980s and 1990s, and the approach of potash mining.

During the late 1980s and early 1990s oil was discovered in the lower parts of the Delaware Mountain Group (Permian: Cherry Canyon and Brushy Canyon Formations) along the eastern, southern, and western boundaries of the land withdrawal area. In the Delaware Basin as a whole, these formations were not generally recognized as exploratory and development targets until the late 1980s. Prior to that time, they were usually bypassed during drilling with little or no thought that they might contain economically recoverable oil resources. Although these two formations had been penetrated by thousands of wells throughout the Delaware Basin, few attempts were made to adequately test them.

The main reason for bypassing these formations during drilling was a lack of understanding of their production characteristics. Water saturations calculated from analysis of electric logs were often high and did not differentiate oil-productive sandstones from sandstones that would yield mostly water upon completion. However, recent developments in log analysis (Asquith and Thomerson, 1994) have made it possible to differentiate Delaware sandstones with a high percentage of movable hydrocarbons from those with a low percentage of movable hydrocarbons. This type of analysis, in conjunction with the discovery of several commercial oil pools in the Brushy Canyon Formations, set off an oil drilling boom throughout the Delaware Basin that continues to the present. The Delaware play is currently the primary exploration and development play in the Permian Basin and is one of the most active oil plays in the United States. Of special note in the vicinity of WIPP was the discovery and development of commercial oil accumulations in the Brushy Canyon Formation at Cabin Lake; Livingston Ridge, Lost Tank, and Los Medaños pools.

During the last decade or so, potash mining has continued and the mining front is now much closer to the WIPP boundary. Mining by IMC has reached the edge of the additional study area on the southwest side of the WIPP. Future mining may occur mainly there or on the north.

The value of potash (sylvite and langbeinite) and petroleum (oil and gas) were calculated using iterative economic models commencing in 1996 and lasting until 2031 (potash), 2026 (petroleum), and 2038 (natural gas plus associated oil). The potash and petroleum resources produced over this time frame were calculated from estimates based on drill hole data and projections of data and geology as needed. The value calculation used these resource data and projections of historical cost, price, and other economic data.

Potash Reserves

The results of the potash resources and reserve calculation are:

Resources and reserves of the 4th langbeinite ore zone (short tons in millions).

Area, Type of Lease, and Scenario	Tons	Avg % K_2O
Entire study area		
In-place resource (>4% K_2O & actual thickness)	168.7	8.02
BLM Lease Grade reserve (>4% K_2O & 4 ft mining height)	166.5	7.22
Minable reserve (>6.25% K^2O & 6 ft mining height	72.4	7.95
Inside WIPP boundary		
In-place resource (>4% K_2O & actual thickness)	47.0	7.21
BLM Lease Grade reserve (>4% K_2O & 4 ft mining height)	40.5	6.99
Minable reserve (>6.25% K^2O & 6 ft mining height	18.0	7.59
Outside of the WIPP boundary (about one mile)		
In-place resource (>4% K_2O & actual thickness)	121.7	8.33
BLM Lease Grade reserve (>4% K_2O & 4 ft mining height)	126.0	7.30
Minable reserve (>6.25% K^2O & 6 ft mining height	54.4	8.07

Resources and reserves of the 10th sylvite ore zone (short tons in millions).

Area, Type of Lease, and Scenario	Tons	Avg % K_2O
Combined Area		
In-place resource (>10% K_2O & actual thickness)	168.2	14.61
BLM Lease Grade reserve (>10% K_2O & 4 ft mining height)	157.3	14.64
Minable reserve (>12.25% K^2O & 4.5 ft mining height	107.8	15.33
WIPP Area		
In-place resource (>10% K_2O & actual thickness)	53.7	14.26
BLM Lease Grade reserve (>10% K_2O & 4 ft mining height)	52.3	13.99
Minable reserve (>12.25% K^2O & 4.5 ft mining height	30.6	15.00
Additional Area (~1 mile around WIPP)		
In-place resource (>10% K_2O & actual thickness)	114.5	14.77
BLM Lease Grade reserve (>10% K_2O & 4 ft mining height)	105.0	14.96
Minable reserve (>12.25% K^2O & 4.5 ft mining height	77.2	15.46

p. E-4;
"Petroleum Reserves

The Results of the calculation of probable petroleum resources are:

Oil and gas resources (probable)

	Combined Area	WIPP Area	Additional Area
Primary Oil (million bbls)	35.2	12.3	22.9
Secondary Oil (million bbls)	20.2	6.4	13.8
Oil Subtotals (million bbls)	55.4	18.7	36.7
Gas Subtotals (MCF)	354	186	168

NOTE: In addition, there is an unknown but significant amount of possible oil and gas resources beneath the WIPP land withdrawal area and surrounding one-mile-wide additional area."

p. VII-1, METHOD OF POTASH RESERVE EVALUATION;

" Evaluation of potash reserves was based solely on subsurface information from 40 core holes previously drilled within and around the WIPP Site. The nearest underground mine operations are currently no closer than one mile from the outer boundary of WIPP. All 40 holes were drilled using brine (containing potassium as well as sodium chloride) to inhibit dissolution of potassium minerals. The results of chemical analyses of the ore-bearing intervals were adjusted to calculate the percentage equivalent as individual natural mineral species. Only the K_2O percentages as either sylvite or langbeinite were used to compute ore reserves."

p. XI-1, OIL AND GAS RESOURCE ESTIMATES
Ronald F. Broadhead, Fang Luo, and Stephen W. Speer
SUMMARY OF OIL AND GAS RESOURCES;

" Rigorous, quantitative estimates were made of oil, natural gas, and natural gas condensate resources that exist beneath the 16 mi² area of the WIPP land withdrawal area and an additional one-mile wide study area around the WIPP site. Calculations were made for resources that are extensions of known, currently producible oil and gas resources thought to extend underneath the WIPP land withdrawal area with reasonable certainty (*probable resources*). Qualitative estimates were also made of oil and gas that may be present in undiscovered pools and fields beneath the WIPP land withdrawal area (*possible resources*). Possible resources were not quantified."

p. XI-2, INTRODUCTION;

" Oil and gas resources are typically divided into several categories (Potential Gas Committee, 1993; Energy Information Administration, 1994; **Figs. 1a, 1b**). For purposes of this report, five categories of resources are referred to: 1)cumulative production; 2) proved reserves; 3) probable resources (extensions of known pools); 4) undiscovered recoverable resources; and 5) unrecoverable resources. *Cumulative production* is the total volume of crude oil, natural gas condensate, and natural gas that have been withdrawn (produced) from a pool or well. *Proved reserves* are an estimated quantity of crude oil, natural gas condensate, or natural gas that analyses of geologic and engineering data demonstrate with reasonable certainty to be recoverable in the future from discovered oil and gas pools. Pools are considered proved that have demonstrated the ability to produce by either actual production or by conclusive formation tests (Potential Gas Committee, 1993), that is by drilling. This report restricts the definition of proved reserves to those producible resources identified as producible by existing wells (whether currently producing or abandoned). *Ultimate recovery* is the sum of cumulative production and proved reserves or probable resources for a pool or individual well.

The remainder of the resource base consists of *potential resources*. These can be summarized as hydrocarbons that can be inferred to exist, but have not yet been proven by drilling to exist. These can be grouped into: 1)*probable resources (extensions of known pools*; 2) *probable resources (new pools)*; 3) *possible resources*; and 4) *speculative resources*. These subdivisions of potential resources are differentiated on the basis of available geologic, geophysical, and engineering data and studies. *Probable resources (extensions)* consist of oil and gas in pools that have been discovered but have not yet been developed by drilling; their presence and distribution can generally be surmised with a high degree of confidence. *Probable resources (new pools)* consist of oil and gas that are surmised to exist in undiscovered pools within existing fields. *Possible resources* are less assured; they are postulated to exist outside of known fields but within productive stratigraphic units in a productive basin or geologic province. *Speculative resources* are expected to be found in stratigraphic units, basins, or geologic provinces that have not yet been proved productive; estimates of speculative resources are the least assured of all resource estimates. *Unrecoverable resources* are dispersed in such minute accumulations or under such conditions that they can not be extracted with existing or foreseeable technology."

p. XI-11, DELAWARE MOUNTAIN GROUP;

" The Delaware Mountain Group (Guadalupian) is the major oil producing unit near the WIPP site (Fig. 14). It is subdivided into three formations (descending): Bell Canyon, Cherry Canyon, and Brushy Canyon. It was deposited basinward of the Getaway, Goat Seep, and Capitan shelf-margin and reef complexes (Fig. 15). The Delaware Mountain Group consists of sandstone, siltstone, shale, and minor (<5%) limestone, dolostone, and conglomerate (Harms and Williamson, 1988). IN areas adjacent to the WIPP site, production is obtained from the Cherry Canyon and Brushy Canyon Formations with most production coming from the Brushy Canyon.

The Bell Canyon Formation, at a depth of approximately 4500 ft, has been penetrated by most wells in the study area (Fig. 2). Most oil and gas exploratory wells drilled in the WIPP area prior to 1965 reached total depth in the upper or middle part of the Bell Canyon. Objectives were upper Bell Canyon sandstones. . . ."

p. XI-28, para 1;

" . . . stratigraphic traps and stratigraphic trends have not been fully defined and the Bone Spring remains inadequately explored and developed in the area. It is highly likely that numerous significant commercial accumulations of oil and associated gas (possible resources) remain to be found, especially in stratigraphic traps in off-structure areas. The Potash Area, in particular, has been poorly explored because of restrictions on drilling (see Ramey, this report, for a discussion of drilling restrictions in the potash area)."

p. XI-32, ATOKA GROUP;

" The Atoka Group is found within the WIPP site area at depths of 12,700 to more than 13,700 ft. The Atoka is composed of interbedded limestone, sandstone, and shale and generally mimics the Strawn Group in structural configuration. It ranges from 210 ft to more than 270 ft in thickness.

Although prolific production has been established within the nine-township study area from this unit in both limestone and sandstone reservoirs, all of the productive wells found within or adjacent to the WIPP land withdrawal area produce primarily from one narrow and thin (5 to 15+ ft) lenticular sandstone channel deposit. . . . Estimated ultimate recoveries push the per well average to over 8 BCF and 70 KBC. . . ."

p. XI-33, para 2;

" Based on subsurface mapping of this particular reservoir, it appears that there is excellent potential for similar Atoka production within the confines of the WIPP land withdrawal area. . . ."

NRC (U.S. Nuclear Regulatory Commission). 1973. Design Spectra for Seismic Design of Nuclear Power Plants, Revision 1. Regulatory Guide 1.60, December 1973.

INTRODUCTION, p 1.60-1;

" Criterion 2, 'Design Bases for Protection Against Natural Phenomena,' of Appendix A, 'General Design Criteria for Nuclear Power Plants,' to 10 CFR Part 50, 'Licensing of Production and Utilization Facilities,' requires, in part, that nuclear power plant structures , systems, and components important to safety be designed to withstand the effects of earthquakes. Proposed Appendix A, 'Seismic and Geologic Siting Criteria,' to 10 CFR Part 100, 'Reactor Site Criteria,' would require, in part, that the Safe Shutdown Earthquake (SSE) be defined by response spectra corresponding to the expected maximum ground accelerations. This guide describes a procedure acceptable to the AEC Regulatory staff for defining response spectra for the seismic design of nuclear power plants. The Advisory Committee on Reactor Safeguards has been consulted concerning this guide and has concurred in the regulatory position."

p. 1.60-2, col. 1, para. 3;

" The horizontal and vertical component Design Response Spectra in Figures 1 and 2, respectively, of this guide correspond to a maximum horizontal ground acceleration of 1.0 g. For sites with different acceleration values specified for the design earthquake, the Design Response Spectra should be linearly scaled from Figures 1 and 2 in proportion to the specified maximum horizontal ground acceleration."

Nuttli, O.W. 1973. Design Earthquakes for the Central United States. Miscellaneous Paper S-73-1, pp. 1-45. U.S. Army Waterways Experiment Station, Vicksburg, MS.

SUMMARY, p. ix;

" The earthquake risk problem in the Central United States, taken to be approximately the area east of the Rocky Mountains and west of the Appalachians, is discussed. The seismic history of the area is reviewed and is used to divide the area into various seismic regions.

A design earthquake, defined as the largest earthquake that can be expected to occur within an area, is specified for each of the three seismic regions. Specification of the design earthquake is accomplished by giving ground displacement, particle velocity, and acceleration values in hard rock as a function of distance from the earthquake, for three particular wave frequencies. The results are presented i graphical and tabular form.

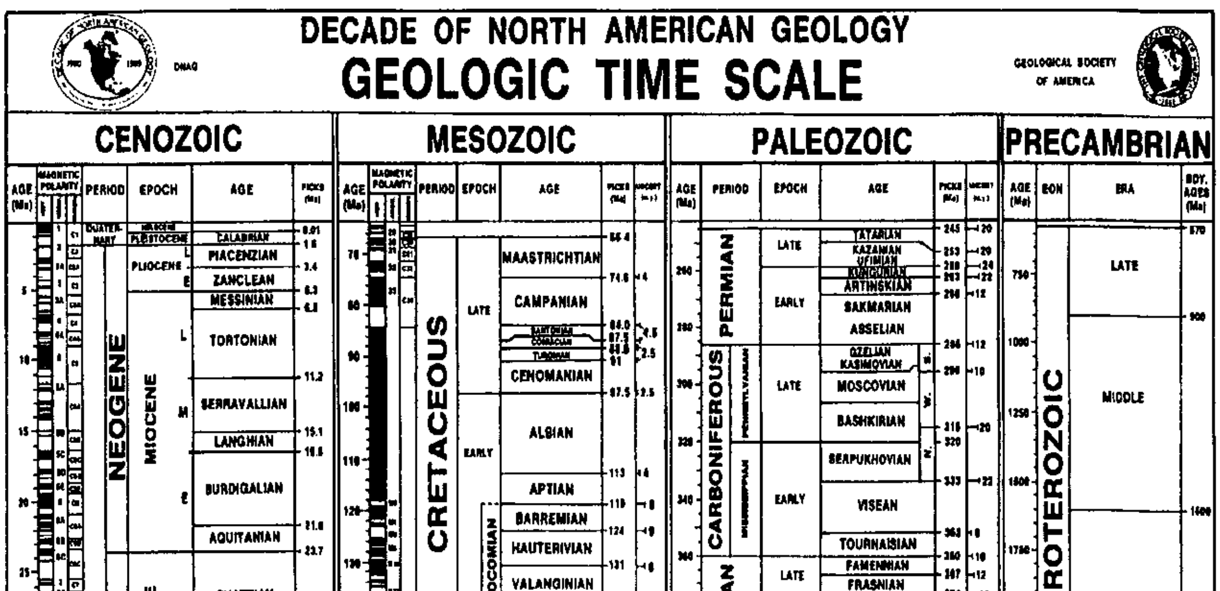
A brief discussion of the effects of soil instability is included. The problem is of particular importance in the Mississippi and other major river valleys of the Central United States."

Palmer, A.R. 1983. "The Decade of North American Geology 1983 Geologic Time Scale." Geology, Vol. 11, No. 9, pp. 503-504.

p. 503;

" Preparation of the 27 synthesis volumes of *The Geology of North America* for the Decade of North American Geology (DNAG) is now in progress. In order to encourage uniformity among DNAG authors in the citation of numerical ages for chronostratigraphic units of the geologic time scale, an ad hoc Time Scale Advisory Committee was established by the DNAG Steering Committee in 1982. This advisory committee, consisting of Z.E. Peterman (Chairman) and J. F. Harrison, U.S. Geological Survey; R. I. Armstrong, University of British Columbia; and W. A. Berggren, Woods Hole Oceanographic Institution, was asked to evaluate numerical dating schemes that were either recently published or in press and to provide recommendations for the best numbers to use in preparation of a DNAG time scale. The chart on the opposite side of this page was developed from the recommendations of the Time Scale Advisory Committee."

The figure on the following page is taken from p. 504 of the referenced document.


DECADE OF NORTH AMERICAN GEOLOGY
GEOLOGIC TIME SCALE
DNAG
GEOLOGICAL SOCIETY OF AMERICA
CENOZOIC
MESOZOIC
PALEOZOIC
PRECAMBRIAN
AGE (Ma)
MAGNETIC POLARITY
PERIOD
EPOCH
AGE
PICKS (Ma)
EON
ERA
BDY. AGES (Ma)
QUATERNARY
PLEISTOCENE
CALABRIAN
PLIOCENE
PIACENZIAN
ZANCLEAN
MESSINIAN
NEOGENE
MIOCENE
TORTONIAN
SERRAVALLIAN
LANGHIAN
BURDIGALIAN
AQUITANIAN
CHATTIAN
CRETACEOUS
LATE
EARLY
MAASTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALANGINIAN
PERMIAN
TATARIAN
KAZANIAN
UFIMIAN
KUNGURIAN
ARTINSKIAN
SAKMARIAN
ASSELIAN
CARBONIFEROUS
PENNSYLVANIAN
MISSISSIPPIAN
GZELIAN
KASIMOVIAN
MOSCOVIAN
BASHKIRIAN
SERPUKHOVIAN
VISEAN
TOURNAISIAN
FAMENNIAN
FRASNIAN
PROTEROZOIC
LATE
MIDDLE

Piper, A.M. 1973. Subrosion in and about the Four-Township Study Area near Carlsbad, New Mexico. Report to Oak Ridge National Laboratories, Oak Ridge, TN.

SCOPE AND ACKNOWLEDGEMENTS, p. 1;

" This paper concerns one aspect of the feasibility of storing wastes from the nuclear-fired power industry in bedded salt of the Salado formation near Carlsbad, New Mexico. The center of concern is a four-township study area--Ts. 21 and 22 S., Rs. 31 and 32 E.--which has been selected by the Oak Ridge National Laboratory as a candidate locality for a pilot repository. The paper is based wholly on prior investigations by others, and so is no more than an appraisal of information at hand. Figures 1 and 2 (in pocket) illustrate selected features in the vicinity of the study area.

The one aspect here considered is the vulnerability of the candidate area and storage horizon to future subrosion--specifically, to dissolution and removal of common salt and other evaporites by circulating ground water, also to other agents by which thickness, composition, texture, and structure of rock units may be modified in place. Principle among these other agents are: (1) subsidence or collapse of strata overlying a zone of dissolution; (2) volume expansion of anhydrite as it converts to gypsum in the presence of water, such expansion commonly shattering the texture of enclosing strata that are lightly loaded or merely inflating those strata if they are heavily loaded; (3) plastic flow of common salt under unequal load, tending to close voids created by dissolution; and (4) up-doming of strata as underlying anhydrite-bearing beds inflate or as salt flows.

Principles of dissolution are examined in another paper (Piper, 1973). Only the three general requirements are restated here, because they are misunderstood commonly. These are: (1) a continual source of unsaturated water, generally of land origin, either physically above or under a hydraulic head higher than strata of soluble evaporite; (2) an aquifer system passing from the water source to the soluble evaporite, and beyond to (3) a discharge area at the land surface, either local or remote, and either physically lower than, or under hydraulic head below, the particular evaporite zone. . . ."

Piper, A.M. 1974. The Four-Township Study Area near Carlsbad, New Mexico: Vulnerability to Future Subrosion. Report to Oak Ridge National Laboratories, Oak Ridge, TN.

SCOPE AND ACKNOWLEDGEMENTS, p. 1;

" In an earlier paper (Piper, 1973-b) the writer summarized information then available as to the present extent and prospective future progress of subrosion in and about a four-township study area near Carlsbad, New Mexico--specifically, Ts. 21 and 22 S., Rs. 31 and 32 E. This paper extends that summary according to additional information now at hand from recent, and current investigations by others. Both papers concern one aspect of storing wastes from the nuclear-fired power industry in bedded salt of the Salado formation.

The one aspect of concern has been the vulnerability of the four-township study area and the candidate storage horizon to future subrosion. The writer's earlier paper was reasonably definitive in regard to natural vulnerability from the west; the present paper seeks chiefly to assess vulnerability from the north, east, and south.

The writer must acknowledge his great indebtedness to . . ."

Popielak, R.S., Beauheim, R.L., Black, S.R., Coons, W.E., Ellingson, C.T., and Olsen, R.L. 1983. Brine Reservoirs in the Castile Formation, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico. TME 3153. Westinghouse Electric Corporation, Carlsbad, NM.

EXECUTIVE SUMMARY, p 1;

" The Waste Isolation Pilot Plant (WIPP) project is a U. S. Department of Energy (DOE) research and development facility to demonstrate the safe disposal of radioactive wastes resulting from the defense activities and programs of the United States. This demonstration consists of two parts. First, about six million cubic feet of TRU waste will be emplaced in the thick bedded-salt deposits of the Salado Formation in southeastern New Mexico at a depth of about 2150 feet. Second, the WIPP will provide for research relative to the interactions of defense high-level waste with bedded salt, though all high-level waste will be removed prior to facility decommissioning.

A potential location was selected for the WIPP in the northern Delaware Basin of New Mexico, and three exploratory core holes were drilled (AEC-7, AEC-8, and ERDA-6; Figure 1). While drilling the third such hole (ERDA-6), substantial geologic structural deformation was noted, and brine and gas sufficiently pressurized to flow to the surface were encountered. The unpredictability of the geology led to relocation of the site to its present location in 1974 (Figure 1). Since relocation, an extensive site characterization program has been conducted, and the adequacy of the site has generally been demonstrated.

In 1981, an agreement was signed between the State of New Mexico, the DOE, and others which included several studies intended to address the State's concerns relative to the suitability of the proposed WIPP site. Some of these studies addressed an area of geologic interest north of the proposed site, and pressurized brine reservoirs in the Delaware Basin. The work was begun in October 1981 and included the reopening and testing of ERDA-6, and the deepening and testing of WIPP-12, an exploration borehole which also encountered pressurized brine and gas. This report provides an account of these studies.

These studies and preparation of the brine reservoir report were performed by the WIPP Technical Support Contractor (TSC), primarily by D'Appolonia Consulting Engineers, Inc. (a member of the WIPP-TSC) under subcontract to the Westinghouse Electric Corporation (the TSC prime contractor). Sandia National Laboratories, Albuquerque, N.M., provided critical review of the studies and report; the U. S. Geological Survey also made comments.

The occurrence of pressurized brine reservoirs in the Castile Formation (underlying the Salado Formation) of the Delaware Basin has been documented over the past 40 years by reports of reservoir encounters by hydrocarbon exploration drilling. In general, these reservoirs were known to be contained in fractured anhydrite with associated hydrogen sulfide gas and were thought to be related to antiforms in the Castile.

Various theories were advanced to explain the origin of reservoirs, which include dissolution of evaporites by recent ground waters, dehydration of gypsum to form anhydrite, entrapment of ancient seawater during evaporite deposition, and ancient dissolution and reprecipitation of evaporite minerals. Should certain of these theories be correct, the suitability of the WIPP site could be in question. Thus, the purpose of this study was to determine the characteristics and origin of these reservoirs and evaluate their potential impact on the integrity and stability of the WIPP site.

Data used in the performance of this study were obtained from drilling and hydrological testing in boreholes ERDA-6" and WIPP-12 and from chemical analyses of samples of reservoir brine and gas collected at these two wells. Information was also obtained from a review of published and unpublished literature on the geology and hydrology of the basin. The principle data reviewed and analyzed in this report are contained in "Data File report - ERDA-6 and WIPP-12 Testing" (D'Appolonia, 1982, 1983)."

SUMMARY OF FINDINGS, p2, col 2, para 2;

" The analyses and interpretations by three disciplines -- geology, hydrology, and chemistry -- have been integrated to form a model of brine reservoir genesis, and to assess the current and future status of brine reservoirs as they relate to the WIPP site. The development of the brine reservoirs began in the Permian Period about 235 million years before present. The Castile evaporites, consisting primarily of anhydrite and halite as shown in Figure 2, were deposited at that time. During the initial chemical sedimentation (or precipitation) period, the solids were poorly consolidated and highly porous. Much or all of this pore space was filled with Permian seawater that had been enriched in dissolved solids, oxygen-18, and probably deuterium by evaporation. As sedimentation in the basin continued, the seawater became trapped as an interstitial fluid between individual grains of anhydrite and halite. As compaction increased, grain boundary accretion of halite probably surrounded some of the pore fluids and gave rise to fluid inclusions in halite crystals. Examination of ratios of major and minor element concentrations in the brines leads to the conclusion that the reservoir brines originated from ancient seawater with no evidence for fluid contribution from present meteoric waters."

p. 4, col. 2, para. 2;

" The ERDA-6 and WIPP-12 brine reservoirs, which are located in fractured anhydrites above thickened halite (Figure 2), may be modeled as fractured heterogeneous systems. The volumes of the ERDA-6 and WIPP-12 brine reservoirs are estimated, within an order of magnitude, to be about 630,000 barrels and 17,000,000 barrels, respectively. The vast majority of brine is stored in low-permeability microfractures, and therefore is not readily released in the event the reservoirs are intercepted. In fact, less than three percent of the reservoir fluids would flow unassisted to the surface if encountered during exploration drilling. About five percent of the overall brine volume in each reservoir is stored in large, open fractures.

SUMMARY OF FINDINGS, p 5, col 1, para 2;

" At present, the Castile brine reservoirs appear to be isolated. There is no evidence to suggest hydraulic or chemical connection between reservoirs, or between reservoirs and other ground-water systems, either at the present or in the past. The persistence of high and different hydraulic heads in Castile brine reservoirs for at least one million years (the age of the most recent tectonic activity) is the principle hydrologic evidence for their isolation. The four Castile brine reservoirs for which accurate data are available show differences in hydraulic head ranging from 280 to 871 feet of water. Similarly, measured heads in the brine reservoirs are at least 1330 feet higher than heads in aquifers in the subjacent Delaware Mountain Group, and at least 1530 feet higher than heads in the overlying Rustler Formation (Figure 4). Hence, there is no physical mechanism for the brine reservoirs to receive recharge from these underlying and overlying units."

p 5, col 1, para 3;

" As regards chemical mechanisms, the gas and brine chemistries of the two reservoirs are distinctly different from each other and from local ground waters. For example, large differences in the reservoir gas compositions exist between WIPP-12 and ERDA-6. The gas in WIPP-12 is composed mostly of methane and has little or no carbon dioxide. The ERDA-6 reservoir contains substantial quantities of carbon dioxide, and more hydrogen sulfide than WIPP-12. Differences observed in the brine composition include boron, bromide, magnesium, potassium, and lithium concentrations. Connection between reservoirs would eliminate or mitigate these differences, especially with respect to the highly mobile gases. Accordingly, if connected in the past, the current brine (and associated gas) compositions of the two reservoirs would be more similar.

In addition to being isolated, the brines appear to be in chemical equilibrium with their surroundings, and they are stagnant. For example, the brines are chemically saturated with the primary phases of the reservoir host rock (anhydrite and calcite). WIPP-12 brine also appears to be saturated with halite, the principle phase of the confining strata. Furthermore, calculations indicate bulk system equilibrium among solid, liquid, and gas.

In summary, the brine reservoirs appear to be local, isolated features that have reached equilibrium with their environment. Evidence for long-term hydraulic and chemical isolation includes:

- Hydraulic heads that are substantially different from reservoir to reservoir and higher than the heads of local ground waters.
- The containment of gas by the reservoirs.
- Brine and associated gas chemistries that differ from reservoir to reservoir.
- Geographic separation and non-uniform distribution of reservoirs, i.e., extensive drilling has taken place in this area, but only a few wells have intercepted pressurized brines. There is no evidence for a continuous, extensive aquifer in the Castile.
- Bulk chemical equilibrium between the brine, gas, and reservoir rock in the ERDA-6 and WIPP-12 reservoirs."

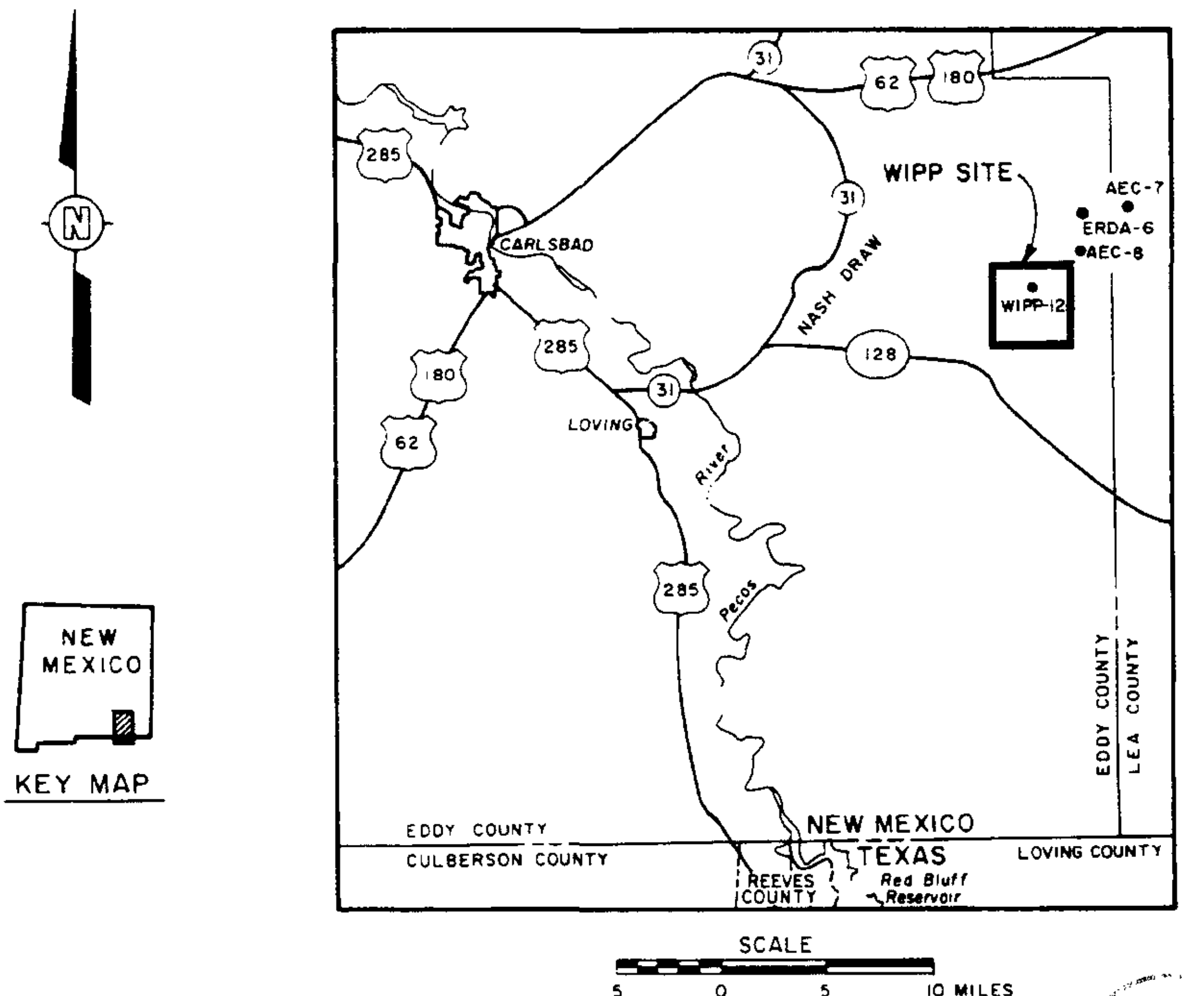


Figure 1 — Location of WIPP Site and Boreholes AEC-7, AEC-8, WIPP-12 and ERDA-6

p. H-45, Reservoir Pressure;

" The maximum pressure measured for the Erda-6 brine reservoir at the wellhead is 604 psig. Extrapolated to a reservoir depth of 2711 feet below ground surface with a fluid pressure gradient of 0.5326 psi/ft of brine, this corresponds to a reservoir pressure of 2048 psig. As shown in Figure H-12, this pressure corresponds to a potentiometric surface at 5551 feet above mean sea level when calculated for the specific gravity of pure water. This is the highest hydraulic head of any ground-water body known in the Delaware Basin.

Following the end of testing in November 1981 and a BOP change in February 1982, the wellhead shut-in pressure at ERDA-6 rose steadily as a result of both reservoir recovery and gas cap formation in the wellbore. A series of apparent gauge-related malfunctions have left the pressure data collected before and after the gas cap release on March 8, 1983 of uncertain validity. The highest pressure measured before the gas cap release was 558 psig on March 5, 1983. Because of a possible fluid leak from a diaphragm assembly attached to the gauge, this value may be too low. The first fully reliable pressure measurement made after the gas cap release was 552 psig on March 19, 1983."

p. H-52, Reservoir Pressure;

" The maximum pressure for the WIPP-12 reservoir at the wellhead is 208 psig. Extrapolated to a reservoir depth of 3017 feet below ground surface with a fluid pressure gradient of 0.5378 psi/ft of brine, this corresponds to a reservoir pressure of 1831 psig. As shown in Figure H-12, this corresponds to a potentiometric surface at 4680 feet above mean sea level calculated for the specific gravity of pure water. Section 3.4.1 contains a detailed discussion of hydraulic heads throughout the Delaware Basin.

Following the end of testing in June 1982, the wellhead shut-in pressure at WIPP-12 rose steadily as a result of both reservoir recovery and gas cap formation in the wellbore. Just prior to releasing the gas cap on March 7, 1983, the wellhead pressure was about 175 psig. On March 7, 1983, approximately 173 ft^3 of gas (at STP) were released from the well (D'Appolonia, 1983). Under the pressure (175.2 psig) and temperature (58°F) conditions then existing in the wellbore, this gas would have occupied a volume of about 14 ft^3, corresponding to maximum gas cap thickness of about 33 feet. Some minor fraction of the gas released probably came from gas exsolution from the brine during the release, however, and is not representative of gas cap volume in the wellbore. From March 8 through at least March 20, 1983, the wellhead pressure at WIPP-12 remained steady at about 162 psig. After more than nine months of recovery, the WIPp-12 reservoir should be near equilibrium. Future increases in wellhead pressure will be predominantly the result of renewed gas cap formation."

Powers, D.W., and Holt, R.M., 1995. Regional Geological Processes Affecting Rustler Hydrogeology. Prepared for U.S. Department of Energy by IT Corporation, Albuquerque, NM.

5.3 History of LOading and Unloading of the Culebra, p. 75, para. 3;

" The loading and unloading history of the Culebra since deposition has been estimated as overburden based on inferences from various local and regional geological trends and data (Figure 33). The history is presented with several alternatives, depending on the inferences that are drawn, ranging from minimal to upper bound estimates. The estimates are made with a reference point and depth to the Culebra at the air intake shaft (AIS) (Holt and Powers, 1991)."

NOTE: Figure 6, Well Control Base Map is included on the following page.

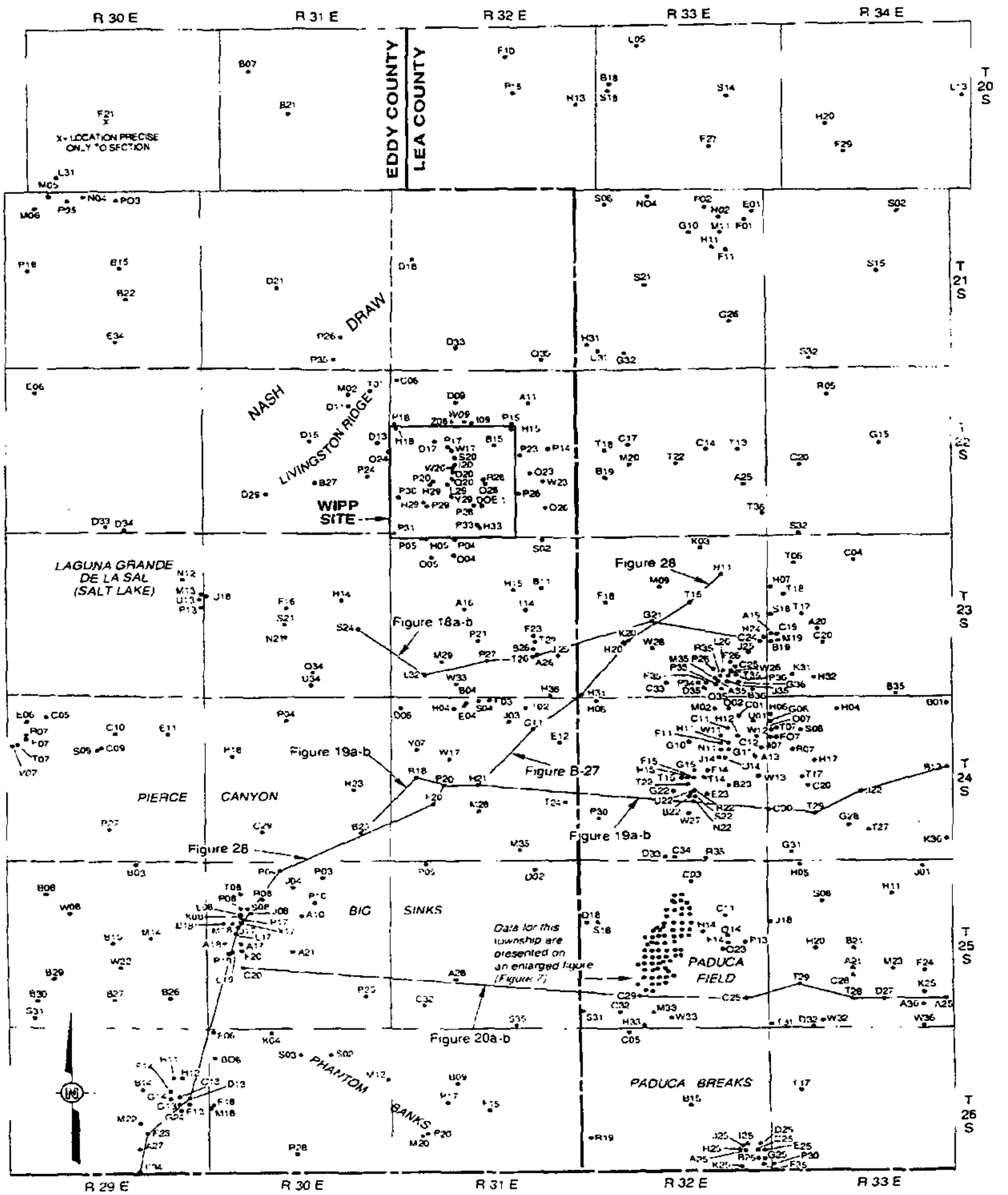


Figure 6
Drillhole Base Map

Powers, D.W., and Holt, R.M. 1993. "The Upper Cenozoic Gatuña Formation of Southeastern New Mexico." In Carlsbad Region, New Mexico and West Texas, New Mexico Geological Society, Forty-Fourth Annual Field Conference, Carlsbad, NM, October 6-9, 1993. D.W. Love et al., eds., pp. 271-282. New Mexico Geological Society, Roswell, NM.

ABSTRACT, p 271;

" The Gatuña Formation of southeastern New Mexico has been studied in the field for two landfill projects and the Waste Isolation Pilot Plant project. Shafts, drilling and field mapping reveal the distribution, thickness and sedimentary features of the unit in an area where it was poorly known or assigned to other units. The Gatuña is at least 300 ft thick in the study area. The formation was deposited in the north and east as clastic beds ranging from conglomerates to laminar claystones. Fining upward cycles are common, though depositional features and facies associations are consistent with braided river/stream environments, not meandering rivers. Laminar and thinly bedded siltstones to claystones were deposited in flood plain to playa environments. Pedogenic features superimposed on many fining upward cycles include soil fractures, slickensides, MnO_2, illuviated clay, bioturbation, probable ped structures and desiccation cracks. The upper Gatuña more consistently includes pedogenic development. Beds of poorly indurated 'orange' sand, consisting of rounded and well-sorted grains, are interpreted as eolian deposits. From southern Nash Draw to Orla, the Gatuña is fine-grained and gypsoferous, including displacive crystals and probable subaqueous deposits. These outcrops represent low energy environments, including playas, which were near local base level. The age of the upper Gatuña is reasonably constrained by the Lava Creek B ash (0.6 Ma) within the Gatuña along Livingston Ridge. The age of basal deposits is poorly or not constrained. An ash within probable Gatuña near Orla, TX, is about 13 Ma based on both radiometric and geochemical data. The Gatuña represents an important piece of the geological history of southeastern New Mexico. Further studies could include efforts to better determine the age of the formation; to obtain paleontological data; and to map Gatuña structural relationships to older and younger beds in detail to determine the timing of and spatial evidence for, dissolution of evaporites and collapse of overlying beds, including the Gatuña."

Further discussion, p. 281, col. 1, para. 3;

" Thick deposits at the eastern part of Pierce Canyon at one time represented a stacked sequence of at least 300 ft prior to slumping and rotation. The base of this section is at an elevation of about 3050 ft. This implies that the pre-rotation top of Gatuña was at an elevation of at least 3350 ft. The top of Gatuña Canyon deposits are at about 3400 ft. as are very tin deposits of Gatuña at the WIPP site. Given the suggestion (Holt and Powers, unpubl. report to U. S. Department of Energy, 1988) that there has been very little, if any, dissolution of underlying halite at the WIPP site, the elevations suggest a general pre-Mescalero high point of Gatuña deposition."

Powers, D.W., Sigda, J.M., and Holt, R.M. 1996. "Probability of Intercepting a Pressurized Brine Reservoir Under the WIPP." Unpublished report, July 10, 1996. Albuquerque, NM: Sandia National Laboratories. (Copy on file in the SWCF.)

> NOTE: The above listed document was not available for inclusion in the Reference Expansion as of the printing date. Page changes will be provided as the above document becomes available for inclusion.

Pratt, H.R., Stephenson, D.E., Zandt, G., Bouchon, M., and Hustrulik, W.A. 1979. Earthquake Damage to Underground Facilities. Proceedings of the 1979 RETC, Vol. 1, AIME, Littleton, CO.

ABSTRACT;

" The potential seismic risk for an underground facility is considered in the evaluation of its location and design. The possible damage resulting from either large-scale displacements or high accelerations should be considered in evaluating potential sites of underground facilities.

Scattered through the available literature are statements to the effect that below a few hundred meters shaking and damage in mines is less than at the surface; however, data for decreased damage underground have not been completely reported or explained. In order to assess the seismic risk for an underground facility, a data base was established and analyzed to evaluate the potential for seismic disturbance.

Substantial damage to underground facilities is usually the result of displacements primarily along pre-existing faults and fractures, or at the surface entrance to these facilities. Evidence of this comes from both earthquakes as a function of depth is important in the evaluation of the hazard to underground facilities. To evaluate potential displacements due to seismic effects of block motions along pre-existing or induced fractures, the displacement fields surrounding two types of faults were investigated.

Analytical models were used to determine relative displacements of shafts and near-surface displacement of large rock masses. Numerical methods were used to determine the displacement fields associated with pure strike-slip and vertical normal faults.

Results are presented as displacements for various fault lengths as a function of depth and distance. This provides input to determine potential displacements in terms of depth and distance for underground facilities, important for assessing potential sites and design parameters."

EXISTING DATA BASE ON EARTHQUAKE DAMAGE, p. 23, para. 4, line 2;

" Observations from 71 tunnels responding to earthquake motions were compared. Dynamic behavior was compared with intensity and magnitude as a function of distance. The studies compared calculated accelerations at the ground surface with tunnel damage and showed that the tunnels are less susceptible to damage than surface structures or facilities. Peak accelerations at the surface of less than 0.2 gravity (g) did not damage the tunnels; between 0.2 and 0.5 g, damage was only minor; and damage was significant only above 0.5 g (Figure 2). [2,3] Most of the damage was located near a portal."

Ramey, D.S., 1985. Chemistry of Rustler Fluids. EEG-31. New Mexico Environmental Evaluation Group, Santa Fe, NM.

EXECUTIVE SUMMARY, p. ii;

" Water chemistry determinations were performed by the U. S. Geological Survey on water samples collected from the three fluid-bearing zones of the Rustler Formation from 20 testholes at and adjacent to the WIPP from 1976 to 1980. Analysis of the data demonstrates that the three fluid-bearing zones are chemically separate from one another at the WIPP site, but progressively merge towards the west into Nash Draw.

The fluids present at the Rustler-Salado contact approach saturation with respect to sodium chloride. Magnesium replaces sodium as the prevalent cation east of the WIPP site; this boundary may represent the approximate limit of salt dissolution in the Rustler Formation.

Three zones (areally) of differing predominant chemical constituents are present in the Culebra Dolomite. Groundwater flow paths cross these zones, changing the Culebra water from a sodium chloride brine to a moderately saline calcium sulfate water. The Culebra waters are undersaturated with respect to halite and have the capacity of dissolving more halite from the Rustler or the Salado formations.

The major ions present in the fluids in the Magenta Dolomite are predominantly sodium and chloride. A few wells have sulfate, rather than chloride as the predominant anion.

Additional work is needed to improve the degree of understanding of the chemical characteristics of the fluids in the Rustler Formation especially with regard to the Culebra Dolomite. More information is needed to understand the chemical changes that occur along proposed groundwater flow paths of the Culebra. It is important that the current groundwater chemistry sampling program obtain representative and replicable groundwater quality data."

Section 6. <u>CONCLUSIONS AND RECOMMENDATIONS</u>, p 41; para 2;

" Three zones of differing predominant chemical constituents are present in the Culebra Dolomite. These zones do not support previously reported directions of water movement and there appears to be an inconsistency between the apparent chemistry and the previously reported flow paths. The Culebra waters are undersaturated with respect to halite and have the capacity of dissolving more halite from the Rustler, or if a connection is produced, from the Salado or repository horizon.

Rawson, D., Boardman, C., and Jaffe-Chazan, N. 1965. The Environment Created by a Nuclear Explosion in Salt. PNE-107F. U.S. Atomic Energy Commission Plowshare Program, Project Gnome, Carlsbad, NM.

ABSTRACT, p 5;

" The Gnome event, a 3.1 $\pm$ 0.5 kiloton nuclear explosion, was conducted at a depth of 361 m in bedded rock salt near Carlsbad, New Mexico. This explosion melted approximately 3.2 x 10^6 kilograms of rock salt and produced a standing cavity with a volume of about 27,200 cubic meters. The cavity has a pronounced bulge at its equator. The development of this asymmetry was controlled by the preshot character of the rock: horizontal weaknesses in the form of bedding planes and clay layers. The molten salt mixed with the condensing radioactive debris and about 11.6 x 10^6 kg of rock from the cavity walls, to form a radioactive 'puddle' of melt and rock breccia at the base of the cavity. This zone is blanketed by about 13.6 x 10^6 kg of rubble that resulted primarily from ceiling collapse, thus shielding the 'puddle' so that when personnel entered the cavity, gamma radiation levels were rarely in excess of 20 mR/hr.

During the dynamic cavity growth period of about 100 msec, radial cracks propagated closely behind the outgoing compressional shock wave. Molten rock had not yet mixed well with vaporized fission products and consequently melt injected into these cracks was not radioactive or slightly so. The maximum observed extent of these fractures, measured from the center of the explosion, is 40 m laterally, 38 m above and 25 m below.

Leakage of radioactive gases through the rock is detectable by the presence of radiation damaged salt. Generally, there was no evidence of leakage beyond 40 m and the maximum observed extent at 65.5 m is thought to be associated with fracturing to a natural cavity.

Close-in stemming failed and cavity gases vented dynamically into the emplacement drift. Back-up stemming confined the dynamic venting but allowed the low pressure release of steam and gaseous fission products. The formation of radial cracks and bedding plan partings, coupled with the emplacement configuration to accommodate a neutron-physics experiment, caused the stemming failure.

Asymmetry of rock displacements, fractures observed, and the permanent surface displacements indicate localized uplift of the rock between the cavity and the ground surface. It is interpreted that this uplift was caused by spall of the upper few hundred feet of rock which momentarily decreased the overburden pressure. The cavity pressure then exceeded overburden pressure and the cavity expanded preferentially upwards.

A zone of increased permeability was defined to extend at least 46 m laterally and 105 m above the point of the explosion. The permeability increase was established by complete circulation loss of the drill fluid and is primarily associated with motions and partings along bedding planes - the major preshot weakness in the rock."

1.1 BACKGROUND, p 8;

" Project Gnome was the first scientific experiment with nuclear explosives designed to provide information pertaining to the non-military uses of these explosives. A 3.1 $\pm$ 0.5 kt nuclear device was detonated at a depth of 361 m underground in bedded salt on December 10, 1961. The test site for Project Gnome was located about 48 km southeast of Carlsbad, New Mexico."

Register, J.K. 1981 Rubidium-Strontium and Related Studies of the Salado Formation, Southeastern New Mexico. SAND81-7072. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p. vii;

" The Salado Formation, a member of the Ochoan Series, is a bedded salt deposit found in the Delaware Basin of southeastern New Mexico and west Texas. It is comprised primarily of halite and sylvite with minor amounts of sulfate minerals. Rubidium-strontium age determination of the evaporite minerals in the Salado indicate an age of final equilibration of 214 $\pm$ 15 m.y. This age is fairly consistent with the geologic age of the formation, precluding substantial alkali-alkaline earth migration since deposition. Polyhalite and anhydrite samples from the Salado give $^{87}Sr/^{86}Sr$ values of about .7078, which are consistent with reported values for Permian seawater. The REE and trace element concentrations of the polyhalite and anhydrite samples are very low, reflecting the composition of seawater.

Rubidium-strontium age determinations of the clay minerals extracted from the salt suggest a minimum age of 390 $\pm$ 77 m.y. This age probably represents the minimum age of the provenance of the clay minerals. The REE and trace element concentrations as well as the mineralogy of the clay minerals indicate a detrital origin for the clay minerals with some clay-brine interaction. Clay minerals seem generally depleted in the light REE (relative to NAS) which most likely were replaced by Ca^{2+} and Na^{+} from the evaporitic brines."

Register, J.K., and Brookins, D.G. 1980. "Rb-Sr Isochron Age of Evaporite Minerals from the Salado Formation (Late Permian), Southeastern New Mexico." Isochron/West No. 29, pp. 39-42.

p. 39;

" The bedded evaporites of southeastern New Mexico have been extensively studied in conjunction with potash deposit exploration, and, more recently, for consideration for a Waste Isolation Pilot Plant (WIPP) for radioactive waste disposal. An important facet of the latter study is the chemical and isotopic integrity of the evaporite minerals. Experience elsewhere with evaporite minerals (see discussion in Brookins and others, 1980) suggests post-formational, open-system conditions resulting in anomalously young ages for both halide and sulfate minerals by the K-Ar and Rb-Sr methods. Many of these young dates elsewhere (i.e. Federal Republic of Germany) have been attributed to metamorphic events or, alternatively, to both episodic and/or continuous loss of radiogenic ^{40}Ar and ^{87}Sr by unspecified, though subtle, events. Tremba (1969) and Bodine (1978) have suggested episodic and continuous recrystalization events for the southeastern New Mexico evaporites.

It is the purpose of this report to present our Rb-Sr isochron findings for 41 samples including sylvite-halite rich mixtures, polyhalite-rich samples, and anhydrites. The locations are given in Table 1, the data in Table 2, and the mineralogy in Table 3. Figure 1 shows the isochron. Sample procedures are given in Register (1979). The decay constant of 1.42 x $10^{-11}y^{-1}$ was used, and the York (1969) method for isochron construction was employed."

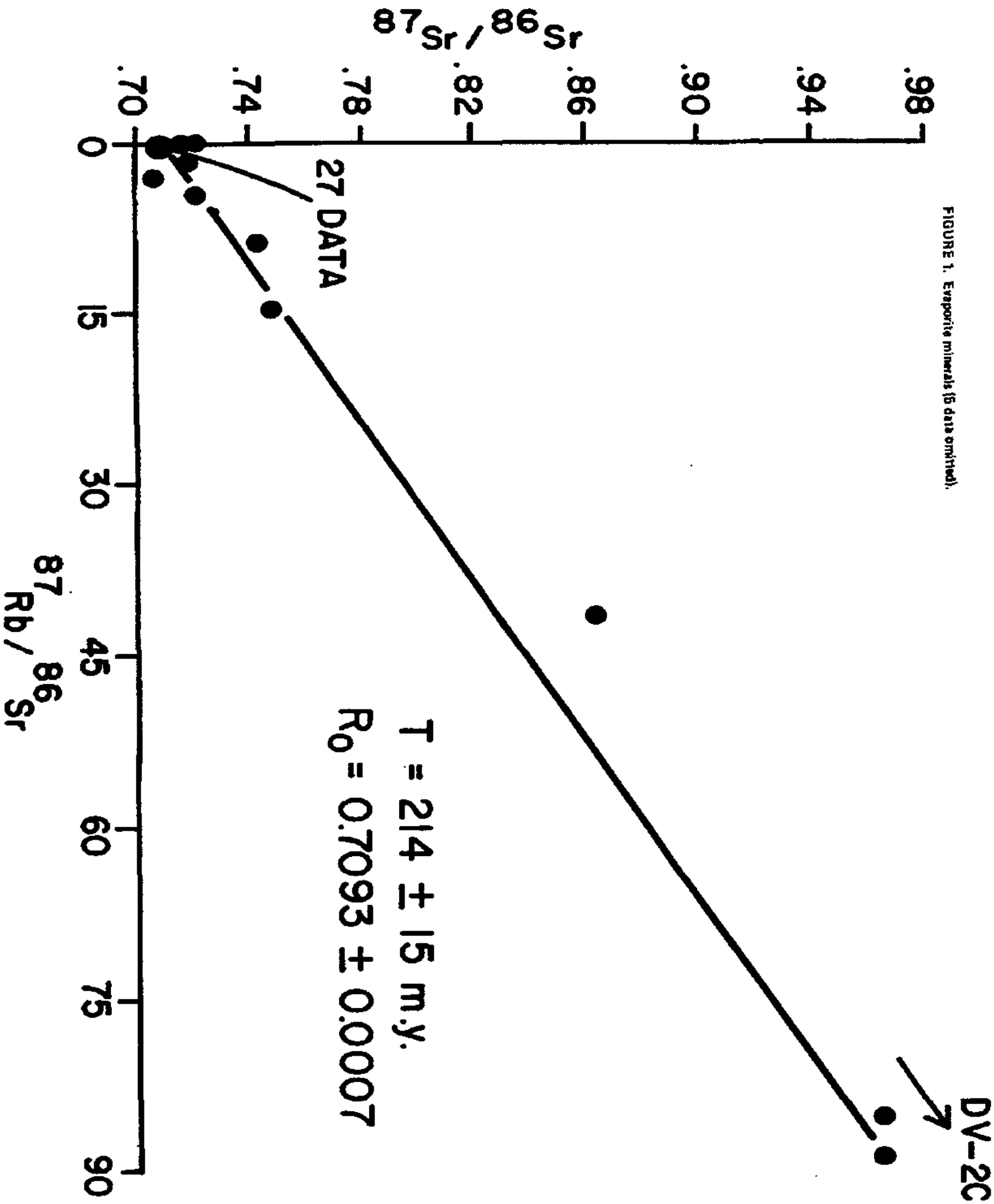


FIGURE 1. Evaporite minerals (6 data omitted).

Reiter, M. Barroll, M.W., and Minier, J. 1991. "An Overview of Heat Flow in Southwestern United States and Northern Chihuahua, Mexico." In Neotectonics of North America, D.B. Slemmons, E.R. Engdahl, M.D. Zoback, and D.D. Blackwell, eds., pp. 457-466. Geological Society of America, Boulder, CO.

The Rio Grande rift and northern Chihuahua, Mexico, p. 463, col. 1, para. 2;

" In the southern part of the Rio Grande rift there are a few heat-flow measurements and estimates that are intermediate in value (about 70 to 80 mW m_{-2}); most of the data are above the average heat flow (89 mWm_{-2}) for the entire Basin and Range Province (Fig. 7, bottom; see also Plate 1 in Reiter and others, 1986). Between Socorro and Las Cruces there are eight sites where the heat-flow estimates are about 90 to 100 mW m_{-2}. Four of the sites are located in the northern part of the Jornada del Muerto, north of the Jornada Basin. The other four sites are scattered widely. Higher heat-flow estimates (117 to 135 mW m_{-2}) are also made at sites scattered over the region from Socorro to Las Cruces. From these data it is suggested that the regional or background heat flow for the rift area between Socorro and Las Cruces is about 95 mW m_{-2}, a value that closely agrees with the interpretation of previous data by Decker and Smithson (1975). It is also interesting to note that the mean of 15 measurements in extreme southwest New Mexico is 94 $\pm$ 21 mW m_{-2}. Some of the sites with higher heat-flow estimates in the southern Rio Grande rift (117 to 135 mW m_{-2}) are near large normal faults that may act as conduits for hydrothermal circulation to enhance geothermal gradients; but again the actual cause of the elevated geothermal gradients is generally ambiguous . . ."

Richardson, G.B. 1904. "Report of a Reconnaissance of Trans-Pecos Texas, North of the Texas and Pacific Railway." Texas University Bulletin 23. Var Boeckmann-Jones Company, Austin, TX.

p. 43, para 4;
" The Castile gypsum outcrops in a belt between the Delaware Mountains and Rustler Hills, the width of which averages about 15 miles, though at the New Mexico-Texas boundary it is about 30 miles. This gypsum belt begins about 15 miles north of the railroad and extends into New Mexico. Within Texas the gypsum outcrops over 600 square miles. The name of the formation is derived from Castile Spring which is in the midst of the gypsum about 12 miles south of the State boundary."

p. 44, para 2;
" RUSTLER FORMATION.--The Rustler formation consists of a fine-textured white magnesium limestone and less abundant sandstone. The formation occurs in the Rustler Hills, in the dissected southwestern extension of the Rustler Hills between Cottonwood and Hurd's Pass "draws," and in a few isolated areas west of the hills."

Richter, C.F. 1958. Elementary Seismology. W.H. Freeman & Co., San Francisco, CA.

Construction of a Scale--First Form, p. 340;

" Of two earthquakes having the same hypocenter and recorded at the same stations, the larger should write larger seismograms at any one station. If the epicenters differ, the smaller shock may be so much closer to a given station that it writes larger seismograms there. Accordingly, the general procedure is first to determine the epicenter for each shock and then to plot the maximum ground motion at each station as ordinate with the corresponding epicentral distance as abscissa. Of two curves thus plotted for different earthquakes, one will probably be higher than the other, indicating that it represents the larger event.

Calculation of maximum ground motion calls for careful application of the principles given in Chapter 15. For the immediate practical purpose in southern California, considerable simplification was possible. All the stations used were equipped with torsional seismometers designed to have the same constants: T_0 = 0.8 second, V = 2800, h = 0.8. They should have had the same magnification for ground motion of the same character. For this reason, the plots were made using not computed ground motion but trace amplitudes in millimeters and tenths as measured directly on the seismogram; this method materially reduces working time when considering the numerous local earthquakes. Amplitudes were plotted on a logarithmic scale; since the measurements ranged from 0.1 millimeter to 10 to 12 centimeters, this gave a more manageable chart than a linear scale. Moreover, the results could now be stated numerically.

Figure 22-2 shows logarithmic plots for the data of observed earthquakes. The representative curves are roughly parallel to each other and to the dashed curve which is drawn at an arbitrary level. If this parallelism were exact, the difference between the logarithms of amplitudes of any two given shocks would be independent of distance; the amplitudes themselves would be in constant ratio. We could define a quantity M, to be called magnitude given by

$$M = \log A - \log A_0 \qquad (1)$$

where A is the recorded trace amplitude for a given earthquake at a given distance as written by the standard type of instrument, and A_0 is that for a particular earthquake selected as standard. The magnitude is thus a number characteristic of the earthquake and independent of the location of the recording stations.

The term magnitude was selected by analogy with the corresponding usage in astronomy. The scale of star magnitudes is also logarithmic, though on a less simple basis; in a sense it is reversed, since the greater the magnitude the fainter the star.† The earthquake magnitude scale follows the more obvious course of assigning the larger number to the larger earthquake. Logarithmic scales are in use in other fields; examples are the decibel scale in acoustics and the pH scale for hydrogen-ion concentration.

Three arbitrary choices enter into the definition of M: (1) the use of a particular type of seismometer with specified constants; (2) the use of ordinary logarithms to the base 10; (3) selection of the standard shock whose amplitudes are represented by A_0. This standard shock has also been called the zero shock, since, if $A = A_0$, $M = 0$. This clearly does not mean ' no earthquake'; a small earthquake might conceivably record with amplitudes smaller than those of the standard shock, which would give it a negative magnitude. The zero level was intentionally chosen low enough to make the magnitudes of the smallest recorded earthquake positive.

The zero level A_0 can be fixed by naming its value at a particular distance. This was taken to be one thousandth of a millimeter at a distance of 100 kilometers from the epicenter;"

Robinson, T.W., and Lang, W.B. 1938. "Geology and Ground-Water Conditions of the Pecos River Valley in the Vicinity of Laguna Grande de la Sal, New Mexico, with Special Reference to the Salt Content of the River Water." Twelth and Thirteenth Biennial Reports of the State Engineer of New Mexico for the 23rd, 24th, 25th, and 26th Fiscal Years, July 1, 1934 to July 30, 1938, Sate Engineer, Santa Fe, NM. WPO 37942.

INTRODUCTION, p 79;

" At the request and in cooperation with the State Engineer of New Mexico, a study of ground-water conditions in the Pecos River Valley southeast of Carlsbad, Eddy County, New Mexico, has been under way since the spring of 1937. The results of that study are presented in this report. The area involved lies largely in Townships 21, 22, 23 and 24 south, Ranges 26, 27, 28 and 29 east, New Mexico principle meridian. (See plate 1). Intensive work was done chiefly in the vicinity of the Laguna Grande de la Sal and the area lying between it and the Malaga Bend of the Pecos River, about five miles south. The area is crossed by the Pecos River flowing southeastward from Carlsbad. During the growing season, the entire flow of the Pecos River above Carlsbad is normally diverted for irrigation at Lake McMillan and Lake Avalon. During this period the Pecos River from Carlsbad south is fed chiefly by large springs. The largest spring, known as Carlsbad Spring, is located in the river channel just below Lake Avalon. The Black River enters the area from the west and flows eastward to its confluence with the Pecos River northeast of Malaga. It is also spring-fed, deriving most of its water from Blue Spring and Castle Spring, near Black River village. The drainage pattern is well developed on the west, and during rainy periods many normally dry arroyos and draws discharge flood water into the Pecos River. Drainage from the east is by poorly developed draws which carry water to the Pecos only during exceptionally heavy rainfall. A prominent feature east of the river is Laguna Grande de la Sal, which is a shallow salt lake in a playa covering about 3½ square miles.

Carlsbad, the largest town in the area and the county seat of Eddy County, had a population of 3,708 in 1930. However, owing largely to the development of the potash mines located about 20 miles east, the population in 1938 is about double that of 1930. Loving, located about 12 miles south, and Malaga, about 18 miles south of Carlsbad, each had less than 1,000 inhabitants in 1930. Carlsbad is served by the Atchison, Topeka, and Santa Fe Railroad and by main highways leading north to Roswell, New Mexico, southwest to El Paso, Texas, south to Pecos, Texas, and east to Hobbs, New Mexico.

Cotton and hay are raised in the irrigated section along the Pecos River, while cattle, sheep and goat raising predominate in the unirrigated upland areas to the east and west. The principle mineral industry is the mining and refining of potash. A large number of tourists are attracted annually to the famous Carlsbad Caverns, located about 25 miles southwest of Carlsbad, near the highway leading to El Paso, Texas.

A group of farmers who pump water from the river for irrigation report that in recent years the water, because of its salinity, has been injurious to their cotton crop. In September 1932 the U.S. Potash Company began operations, using the Laguna Grande de la Sal as a disposal area for the waste brine from their potash refining operations. The reported difficulty with salt, shortly after refinery operations began, naturally cast suspicion on the brine in the Laguna Grande. There is no visible outlet from the Laguna Grande, and therefore the problem arose as to whether the lake brine may be percolating underground to the Pecos River.

A study of the chemical character of the water of the Pecos River has been made by C.S. Howard and W.F. White, Jr., and numerous analyses were made of the surface and ground waters in this area (see report on chemical character of Pecos River under 'Quality of Water,' to be found elsewhere in this volume). The ground-water studies by T.W. Robinson were begun on April 13, 1937, and the geologic studies by W.B. Lang on October 15, 1937."

RUSTLER FORMATION, p. 83, para 5;

" The Rustler formation in this area is approximately 500 feet thick. It is divided into two sections: the upper part usually 200 feet thick, consisting of all beds lying above the main limestone to and including the top 30-foot anhydrite or gypsum member; and the lower part, a section that includes the 35-foot dolomitic limestone and everything down to the top of the Salado. The lower section . . ."

Deposits Overlying the Rustler Formation, p. 84;

" Gatuña formation.--The name Gatuña is here given to an assemblage of rocks of various kinds that were laid down in the Pecos Valley in poet-High Plains time and apparently after the completion of the maximum cycle of erosion in this valley. The deposits are of terrestrial origin and with them began the process of refilling the Pecos Valley. The dominant material of which they are composed is fine red sand. However the material is largely of local derivation and therefore the character of the source of the material has had a controlling influence on the composition and color of the resulting deposits. Conglomerates, stream gravels, gypsum and limestone, as well as bedded and unconsolidated sands and silts, comprise this formation. They are gray, purplish, and yellow as well as red. The inclusion of caliche wash has in most places contributed to this formation a slightly paler reddish color than that of the Pierce Canyon redbeds. The name is derived from Gatuña Canyon in northeastern Eddy County, New Mexico. The formation is of Quaternary age."

GENERAL RELATION OF THE GEOLOGY TO THE OCCURRENCE OF BRINE AT THE BASE OF THE RUSTLER FORMATION, p. 86;

" It was observed by the writer more than a decade ago during the investigation for potash, that some of the test wells in the vicinity of T. 21 S., R. 30 E., indicated the presence of a strong sodium chloride brine just above the salt of the Salado halite. Some other test wells that were dry at this zone yielded salt core slightly cellular or cuttings with an uncommon appearance that was interpreted as having been caused by solution. Later, wells drilled farther south in Nash Draw yielded abundant sodium chloride brine in the basal Rustler, but those west of the draw were dry. Thus it seemed likely that the structural conditions that caused the development of Nash Draw might also control the position of a body of salt water beneath it in the basal Rustler. The investigation has confirmed this assumption."

RUSTLER FORMATION, Character, Extent, and Relations of the Brine Horizon at the Base of Rustler Formation, p. 87;

" The water which occurs in the Rustler formation may be divided into two groups on the stratigraphic position of the water-bearing beds and the quality of the water. These two groups are (1) the water occurring in the brine horizon at the base of the Rustler formation, and (2) the water occurring above the brine horizon.

The brine horizon occurs at or very near the base of the Rustler formation, and as a rule it yields a strong sodium chloride brine. IN some of the oil tests and potash core tests only weak to moderate solutions of sodium chloride were reported. This difference in concentration may be due to the occurrence of weaker brine in the locality of the well, to a dilution of strong brines by fresher water from a higher bed that was not shut out when the well was drilled, or to admixture of water used in drilling. At the seven test wells, described in the appendix, (not included with this report), the material of the brine horizon is composed almost entirely of granular and selenitic gypsum. In some of the wells the bottom of the bed that yields the sodium chloride brine is separated from the salt of the underlying Salado halite by a very few feet of clay and in others it appears to be in contact with the salt. Such close association of the water in this horizon with the salt is obviously favorable for the production of a sodium chloride brine.

The presence of a rather extensive bed yielding a sodium chloride brine at the base of the Rustler formation was not generally recognized until the first test well had been drilled. Previous to the start of the investigation, brine had occasionally been reported in oil tests and potash core tests just above the Salado halite. As the brine was not reported in all wells it was at first believed to occur only locally. However with the drilling of the first test well, 23-29-22C1, by the U. S. Potash Company with a sodium chloride brine reported in two nearby oil tests, 23-29-14N1 (Fogarty No. 1) and 24-29-3F2 (Kerr No. 1) (plate 1), it became evident that there is a continuous horizon yielding a sodium chloride brine east and south of Laguna Grande de la Sal. Subsequent drilling of the other test wells and oil tests, 22-31-30K1 (Texas Welch) (?) and 24-28-28L1 (C. J. Frederick Reed No. 1), has shown that this brine horizon extends over a considerable area. The approximate area underlain by this brine horizon, as it is known at present from all available test wells, oil tests and potash core tests, is outlined o the accompanying map, plate 3. The area shown on the map covers about 122 square miles, but it is approximate only and is subject to revision when more well data are available.

As shown on the map, the area extends as a narrow strip northeast from the vicinity of Willow Lake to Laguna Grande, and then northeast and north to the head of Nash Draw, a distance of approximately 30 miles. It ranges in width from 2 to 8 miles. It is interesting to note that north of Laguna Grande the brine horizon appears to lie within the confines of Nash Draw, suggesting that solution of the Salado halite may have had some influence in the development of this flat valley.

The thickness of the brine horizon based on the six test wells which penetrated to the Salado halite, ranges from 61 feet in well 23-29-28B6 (U. S. P. C. No. 2 Test) to 10½ feet in 22-30-17M1 (U. S. G. S. No. 5 Test), and averages about 36 feet. The seventh test well, 23-29-22C1, (U. S. P. C. No. 1) did not penetrate the Salado halite. The thickness appears to decrease to the north. The average thickness based on all available data of the oil tests, potash core tests and the six test wells, is about 24 feet."

CONCLUSIONS, p 100;

" The discussion in the foregoing pages and the data presented in the appendix lead to the following conclusions: A body of concentrated solution of sodium chloride occurs at the base of the Rustler formation and overlies the extensive deposit of salt known as the Salado halite. This brine horizon extends from some locality north of Laguna Grande de la Sal to the vicinity of the Malaga Bend of the Pecos River. The brine in this horizon is under artesian pressure and has in general a southward hydraulic gradient. Below Fishing Rock, at the Malaga Bend, the artesian pressure is sufficient to raise the brine above the level of the river at normal stages. In the vicinity of the Malaga Bend the confining bed for the brine horizon is thin and incompetent. Salt water is percolating upward from the brine horizon and entering the Pecos River at the Malaga Bend locality.

It is believed that the salt in the brine of the brine horizon is derived chiefly from the underlying deposit of salt in the Salado Halite. The available evidence points to the conclusion that the lake brine does not reach the Malaga Bend through the brine horizon or by any other route."

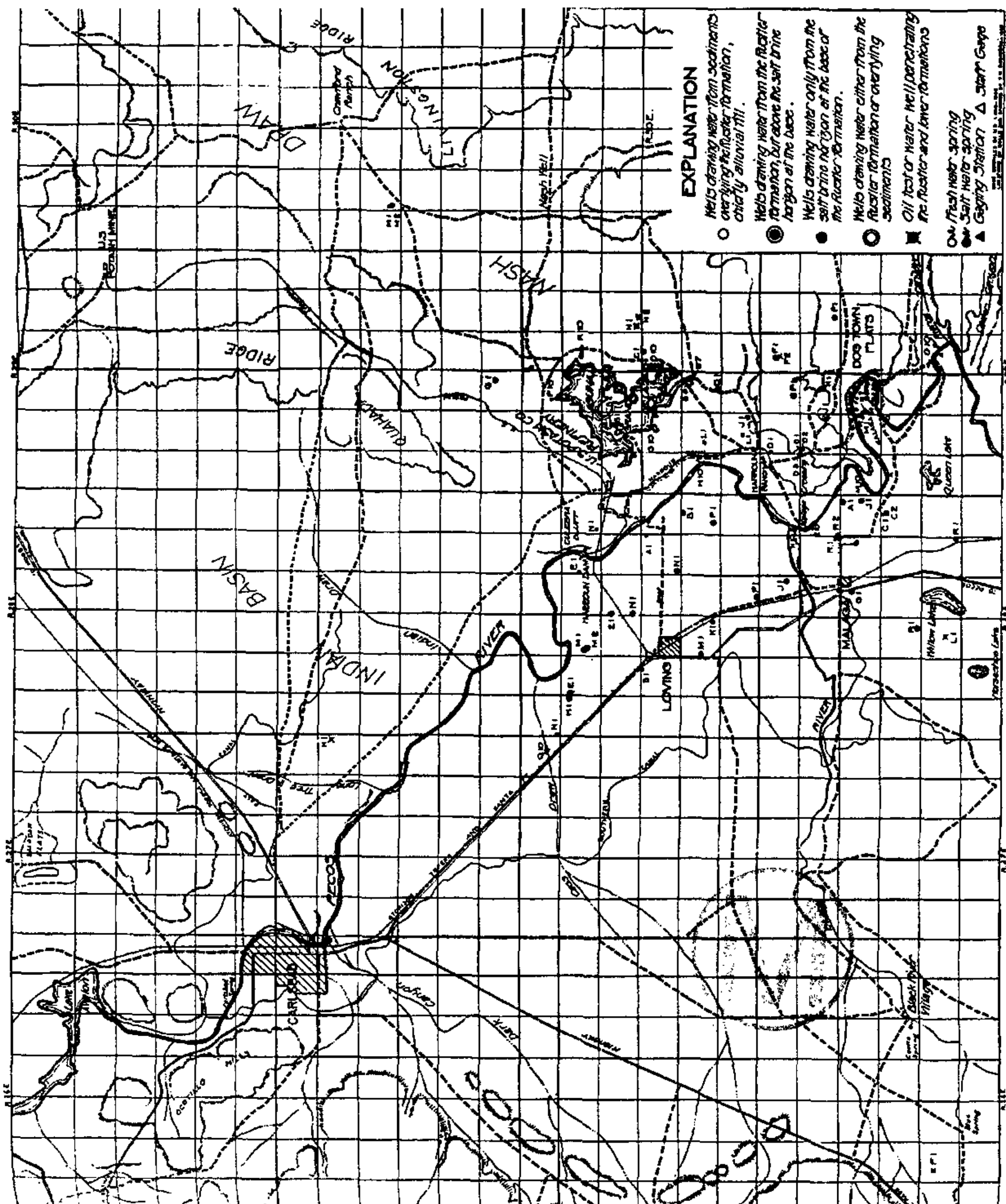


Plate 1. Map of the Pecos River area in the vicinity of Laguna Grande de La Sal showing wells and springs.

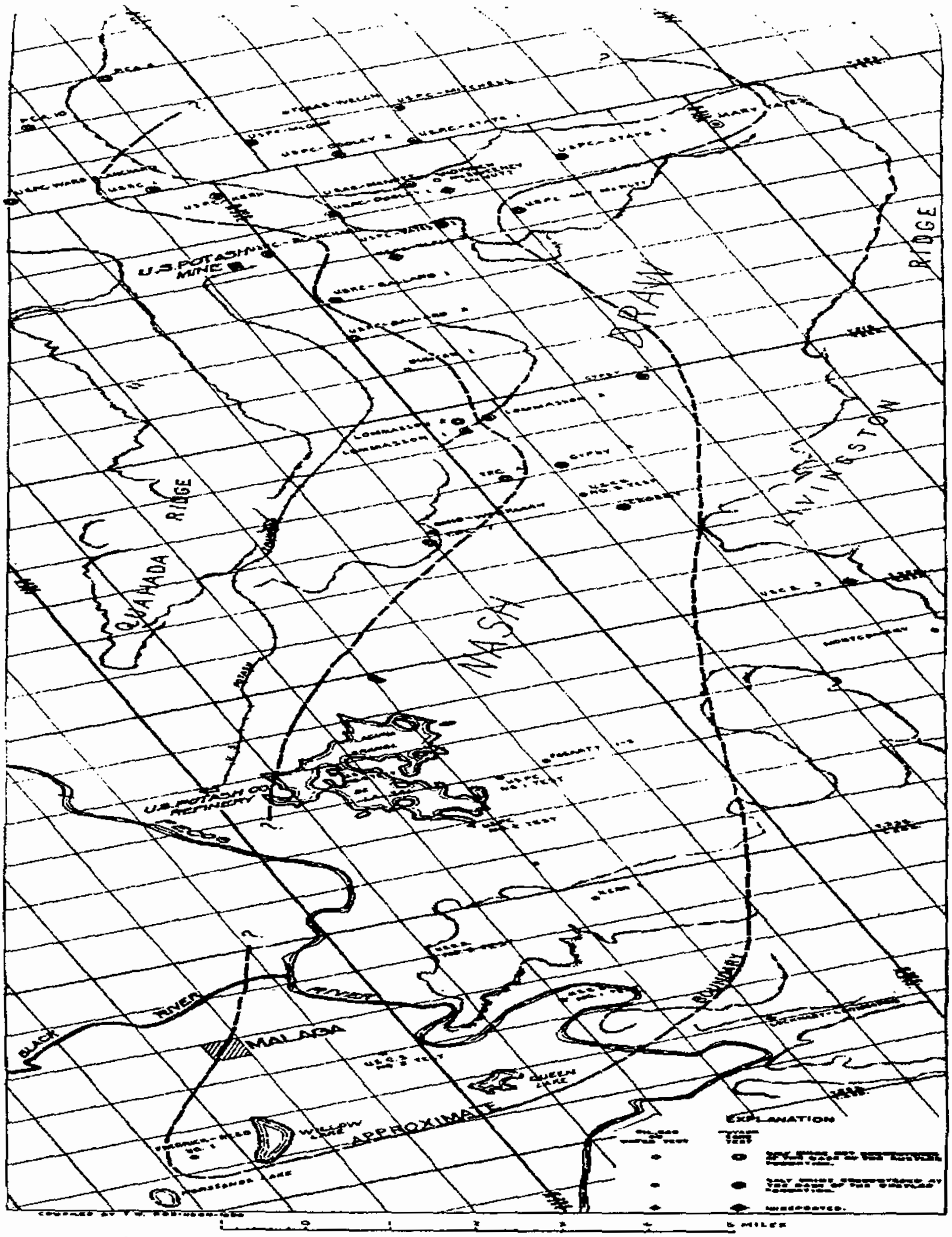


Plate 3. Map showing approximate area underlain by sodium chloride brine at the base of the Ru formation, in the vicinity of Laguna Grande de la Sal and adjacent area.

Robinson, J.Q., and Powers, D.W. 1987. "A Clastic Deposit within the Lower Castile Formation, Western Delaware Basin, New Mexico." In Geology of the Western Delaware Basin, West Texas and Southeastern New Mexico, D.W. Powers, and W.C. James, eds., El Paso Geological Society Guidebook 18, pp. 69-79. El Paso Geological Society, El Paso, TX.

ABSTRACT, p 69, col 1;

" In the vicinity of CP Hill, about 16 km south-southwest of Whites City, New Mexico, a brecciated sequence in the lower Castile Formation has been examined in detail. Four distinct units associated with the breccia sequence have been defined. Unit A is clast poor, structureless to thinly bedded, and contains kerogen. It occurs only over nodular anhydrite. Unit B is pseudo-bedded, with anhydrite matrix supporting tabular anhydrite clasts. Unit C contains abundant rounded polyclasts and is grain-rich. Unit D is similar to A, but clasts are finer in Unit D. These beds are arranged in vertical sequence and show lateral thinning in an apparent fan shape. The textures, grading, and vertical and lateral relationships suggest this breccia unit was deposited as a subaqueous debris flow."

DISCUSSION, p 77, col 1, para 2;

" Dissolution, as a more general alternative mechanism for the formation of evaporite breccias in the western part of the Delaware Basin, has been proposed by Anderson (1978) and explored in several subsequent publications (Anderson, et al., 1978; Kirkland and Anderson, 1980; Anderson, 1981, 1982). We are providing a depositional model to account for the features along the western margin of the Delaware Basin which have been attributed to dissolution. Nevertheless, the data available prior to this study, for the western margin is principally logs and a few cores, and this is insufficient to exclude a depositional origin for many breccias along the western margin.

The Castile is considered one of the prime examples of deep water evaporite deposits. Among the criteria taken to indicate deep water are (Kendall, 1986):

1. fine laminations of carbonate and sulfate over distance of many kilometers;
2. laminated halite, with finely laminated anhydrite and carbonate; and
3. gravity-displaced evaporites.

The debris flow deposit(s) described here fits into a setting in which the first two criteria appear to have been satisfied, and the presence of the debris flow deposit therefore might be taken as evidence that the third criterion is also satisfied. In this respect, the often repeated assertion that the Castile formed as a deep-water evaporite would seem to be strengthened.

Dean, Davies, and Anderson (1975) discuss nodular anhydrite within the Castile, and conclude that it is not diagnostic as a shallow-water indicator, partly because the Castile is considered a deep-water evaporite. Within the CP Hill area, the lower anhydrite is thicker where additional nodular anhydrite beds are present; depositional changes are consistent with the change in slope. These changes are also consistent with the disappearance of halite, and strongly suggest that halite was not, at least locally, deposited over this slope and to the west. There is a suggestion then that local brine depth or depth of halite-saturated brine was less than the local change in relief on the Anhydrite-I substrate. Among the pieces of evidence that need to be considered in this discussion is the limited amount of bromine in the Castile (Holser, 1966; Adams, 1969), indicating the brine may not have all resulted from marine water evaporation. We will continue to examine evidence and relative merits of the evidence for the concept of deep-water versus shallow-water deposition of the Castile along the western margin of the Delaware Basin.

The crackle breccias which occur above the main bedded or pseudo-bedded breccia units are consistent with downwarping of a rigid beam (AII). The downwarping is considered due to overburden and loss of partial support from below. Two possible mechanisms for loss of support are dissolution and compaction of the underlying debris flow deposit. A combination of the two are possible as well. We do not yet have specific data favoring or opposing either hypothesis."

CONCLUSIONS, p 78;

" A unit of intraformational clasts within the lower Castile near the western margin of the Delaware Basin exhibits clast rounding, bedding, clast orientation and grading, and a fan-shaped distribution that is generally consistent with a model as a subaqueous debris flow or series of flows. Internal units display common textural features that can be mapped within the fan. This depositional model for this deposit contrasts with a more general model of dissolution of evaporites considered to be the origin of breccia textures in the same stratigraphic interval along the broader western basin margin."

Rogers, A.M., and Malkiel, A. 1979. A Study of Earthquakes in the Permian Basin of Texas-New Mexico. Bulletin of the Seismological Society of America. Vol. 69, pp. 843-865.

ABSTRACT;

" A microearthquake seismograph network has been employed to study earthquakes occurring in the Permian Basin of Texas and New Mexico. The earthquakes are predominantly located on the Central Basin platform, although a few occur in the Delaware Basin. The majority of the earthquakes occur at the depths of sedimentary rocks, and the focal depths are also coincident with the depths at which hydrocarbon production and water-flood (secondary recovery) operations are conducted. Comparison of the historic earthquake activity with water-flood data shows that there was a possible increase in the number of large earthquakes ($M > 3.0$) in the mid-1960s when the number of water-flood projects and their injection pressures increased. The first felt event occurred in 1966. This tentative correlation suggests that the earthquakes are related to hydrocarbon production in this area."

INSTRUMENTATION, p. 847;

" The Kermit seismic network consists of 11 self-contained radio telemetry systems covering an area of 2200 km^2."

APPENDIX, p. 860;

" A list of all known earthquakes on the CBP from December 12, 1975 through June 26, 1977.

Selected Headings	*Explanation*
mag	Duration magnitude.
no	Number of station readings used to locate earthquake.
gap	Largest azimuthal separation between stations in degrees.
dmin	Epicentral distance in km to the nearest station.
ms	Root mean square error of time, in seconds.
erh	Standard error of the epicentral, in km.
erz	Standard error of the focal depth, in km.
q	Solution quality of hypocenter (Lee and Lahr, 1972)."

Rosholt, J.N., and McKinney, C.R. 1980. Uranium Series Disequilibrium Investigations Related to the WIPP Site, New Mexico (USA), Part II. Uranium Trend Dating of Surficial Deposits and Gypsum Spring Deposit Near WIPP Site, New Mexico. Open-File Report 80-879. U.S. Geological Survey, Denver, CO.

INTRODUCTION, p. 1;

" Just how suitable salt beds are for permanent disposal of radioactive wastes has been the subject of extensive studies covering diverse aspects over the past decade. The proposed site of the Waste Isolation Pilot Plant (WIPP) is located in southeastern New Mexico, about 42 km east of Carlsbad, where plans are to construct the storage facility in rock salt beds of the Permian Salado Formation. Detailed surface and subsurface geology at the site and of the surrounding area has been discussed previously (Bachman, 1976; Powers and others, 1978).

A basic concern for waste repositories in salt beds is their high solubility in ground waters. Different kinds of dissolution features are known in most evaporite basins including the Delaware Basin, the region of the proposed WIPP site. Some primary questions that can be posed are: 1. Is there active dissolution of salt at or near the site of WIPP? 2. Is the process of salt dissolution continuous or episodic? 3. If episodic, what is the correlation between time and depth? 4. When did the last salt dissolution cycle occur? 5. What is the rate of dissolution?

Rosholt and others (1966) and Rosholt (1978) demonstrated that a process of isotopic evolution of uranium and thorium occurs in most types of sediments, altered volcanic ashes and deeply buried granites provided that some groundwater is allowed to migrate through the porous zones of these materials during their geologic history. Often the analyses of the isotopes of the ^{238}U-^{234}U-^{230}Th-^{232}Th system yield an estimated age for the time of deposition (uranium-trend age estimate) over the range of the method from 2,000 to about 800,000 years ago (Rosholt, 1978). Accordingly, it was felt that a preliminary study of salt dissolution residue samples near the WIPP site may yield insight into the dissolution processes and/or it may provide a uranium-trend age estimate for the most recent salt dissolution that produced clay residuum and bands of gypsum. The application of uranium trend dating in the investigation of the age of surficial deposits in the area east of Carlsbad, New Mexico, is included in Part II of this report."

Table 5, p. 15;

" Uranium-trend ages of surficial deposits in Nash Draw and Hat Mesa, New Mexico quadrangles.

Deposit	U-trend slope	x-intercept 232Th index	Half period of $F_{(o)}$ (10^3 yr)	Age (10^3 yr)
Berino soil	-0.533	-0.480	140	330±75
Mescalero caliche				
Upper part	-2.34	+.036	590	420±60
Lower part	-.419	+.182	370	570±110
Gypsum spring	-.889	-.196	340	380±60"

Sanford, A.R., Jaksha, L.H., and Cash, D.J. 1991. "Seismicity of the Rio Grande Rift in New Mexico." In Neotectonics of North America. D.B. Slemmons, E.R. Engdahl, M.D. Zoback, and D.D. Blackwell, eds., pp. 229-244. Geological Society of America, Boulder, CO.

GENERAL FEATURES OF RIO GRANDE RIFT SEISMICITY, p. 230, col. 1, para. 2;

" Starting about 10 years ago, geophysical data began to accumulate that indicated that the RGR boundaries could be extended beyond those proposed by Chapin (1971) in Figure 1. Cordell (1978) summarized geophysical evidence for a broad astenospheric-lithospheric structure centered beneath the chain of grabens shown in Figure 1. Cordell found that the main feature of east-west gravity profiles through New Mexico is a broad negative Bouguer anomaly centered roughly on the axis of the rift. According to Cordell (1978), the anomaly is a consequence of subcrustal structure related to a Rio Grande rift system, which includes a broad uplifted region as well as the obvious grabens and basins usually considered to be RGR. The width of the anomaly appears to be at least 500 km along the New Mexico-Colorado border and broadens progressively to the south. Thus, the gravimetric signature of the rift system, and possibly the structure that produced it, extends beneath the presumably stable Colorado Plateau and Great Plains Provinces, well beyond Chapin's boundaries of the rift shown in Figure 1.

Other geophysical observations support the existence of a broad astenospheric-lithospheric structure beneath the RGR. Davis and others (1984) found a traveltime residual anomaly for teleseismic P-wave arrivals along a profile crossing the RGR. The anomaly has a maximum delay of 1.5 seconds and an east-west extent of approximately 340 km, of which about 60 km underlies the Colorado Plateau and about 70 km underlies the Great Plains.

Shown in Figure 2 is a magnetic map for New Mexico based on the composite magnetic anomaly map of the United States by Taylor and others (1983). The broad north-south-oriented low that appears to be associated with the RGR is one of the strongest and most clearly defined in the conterminous United States. The boundaries for this anomaly are somewhat subjective but clearly fall beneath the Colorado Plateau and the Great Plains and well beyond the maximum boundaries of the RGR in Figure 1.

Gable and Hatton (1983) presented geologic evidence for surface uplift during the past 10 m.y. over a broad region centered on the RGR (Fig, 3). The general character of the uplift extends uninterrupted north through Colorado and south-southeast through west Texas. The east-west extent and generally north-south orientation of the uplift suggests a relation between it and the asthenospheric-lithospheric structures underlying it.

On the basis of geophysical, topographical, and geological information, Eaton (1986) concluded that the Southern Rocky Mountains extend southward through the entire length of New Mexico. Accordingly, the broad geophysical anomalies and surface uplift described above are the signature of the Southern Rocky Mountains, and the RGR is a system of axial grabens along this major north-trending structure."

Saulnier, Jr., G.J., and Avis, J.D. 1988. Interpretation of Hydraulic Tests Conducted in the Waste-Handling Shaft at the Waste Isolation Pilot Plant (WIPP) Site. SAND88-7001. Sandia National Laboratories, Albuquerque, NM. WPO 24164.

ABSTRACT, p ii;

" A series of sub-horizontal boreholes from 8- to 41-feet deep were drilled from four depth levels in the waste-handling shaft at the Waste Isolation Pilot Plant (WIPP) site in southeastern New Mexico. The waste-handling shaft is one of three shafts built at the WIPP site to provide surface access to the underground waste repository under construction 2150 feet below the ground surface. The boreholes were drilled at the 782- and 805-foot depth levels in a mudstone and a claystone of the unnamed lower member of the Rustler Formation; at the 850-foot depth level in bedded halite in the upper Salado Formation; and at the 1350-foot depth level in halite, anhydrite, and polyhalite of the Salado Formation. Examination of the cores recovered from one borehole at each level indicated no direct evidence of construction-induced fracturing. Pulse-injection tests were conducted in packer-isolated intervals in six of the boreholes to estimate the formation's hydraulic conductivity and apparent formation pressure, and to determine whether or not there was evidence of construction-enhanced permeability up to one shaft diameter from the shaft wall.

The pulse-injection tests . . ."

Section 6.0 SUMMARY AND CONCLUSIONS, 6.1 Test Results, p 6-11, para 2;

" The hydraulic conductivities of the mudstone, claystone, and evaporite beds are low and range from 6.0×10^{-15} to 1.0×10^{-13} m/s."

Schiel, K.A. 1988. "The Dewey Lake Formation: End Stage Deposit of a Peripheral Foreland Basin." Master's thesis. University of Texas at El Paso, El Paso, TX.

ABSTRACT, p iv;

" The red siltstones and fine grained sandstones of the Dewey Lake Formation (Late Permian?) have always been relegated to a rather insignificant role in the geologic history of the Permian Basin. The present study suggests that they are, in fact, an important key to understanding the tectonic evolution of the southwestern United States.

Field work, in southeastern New Mexico, reveals that the Dewey Lake is fluvial in origin. Broad, shallow channels filled with thin horizontal laminations and flanked by laterally thinning wings comprise a large portion of the formation. Floodplain deposits, consisting of interbedded siltstone and silty claystone, are also very common.

The Dewey Lake displays many of the sedimentologic and morphologic characteristics associated with ephemeral fluvial systems. Some of these characteristics are an abundance of horizontal laminations and silty claystone drapes, the existence of interbedded siltstone and silty claystone interpreted to be the distal portion of sheet floods, and the presence of broad channels with laterally thinning wings. The Dewey Lake is, therefore, believed to have been deposited on a very extensive northwest sloping fluvial plain. Movement of sediment across this plain occurred only sporadically, during brief and localized flash floods.

It has previously been theorized that the Dewey Lake was extensively eroded prior to the deposition of the Santa Rosa Formation (Middle to Late Triassic). The results of the present study suggest that the thickness variations in the Dewey Lake are not a reflection of post depositional erosion but syndepositional differences in the subsidence rates of the Central Basin Platform and Delaware Basin. Increased subsidence of the Delaware Basin is reflected by the fact that the base of the Dewey Lake Formation is offset 100 m (300 ft) along the major northwest trending fault zone separating the Delaware Basin and Central Basin Platform. The Delaware Basin, therefore, appears to have been tectonically active throughout the deposition of the Dewey Lake Formation.

If the thickness variations in the Dewey Lake are due to subsidence rather than erosion then the contact between the Dewey Lake and the overlying Santa Rosa Formation is conformable. The Santa Rosa has been dated as Middle to Late Triassic in northeastern New Mexico; if this date is applicable to the Santa Rosa in southeastern New Mexico it dictates that the deposition of the Dewey Lake Formation continued into the Early Triassic.

A major unconformity separates Lower Permian and Cretaceous strata in the Fort Worth, Val Verde and Marfa Basin of Texas. This unconformity, which also exists in northwestern Chihuahua, clearly indicates that a large region of central Texas and northern Mexico was uplifted and eroded during the latest Permian ? and early Mesozoic. The location and timing of this uplift suggests that it was the source of the silt and fine sand comprising the Dewey Lake Formation. A close geographic and temporal relationship between this uplift and Late Triassic rift basins suggests that it originated as a pre-rift bulge.

The very extensive nature of this uplift suggests that the alluvial plain to the north (i.e. the Dewey Lake and Quartermaster Formations) extended significantly beyond the area

of west Texas and eastern New Mexico. The western portion of this plain is theorized to be the redbed facies of the Moenkopi Formation (Early Triassic). Apparent similarities in age, stratigraphic position, lithology and paleoscope all support the concept that the Dewey Lake and Moenkopi Formations are components of a single lithologic unit."

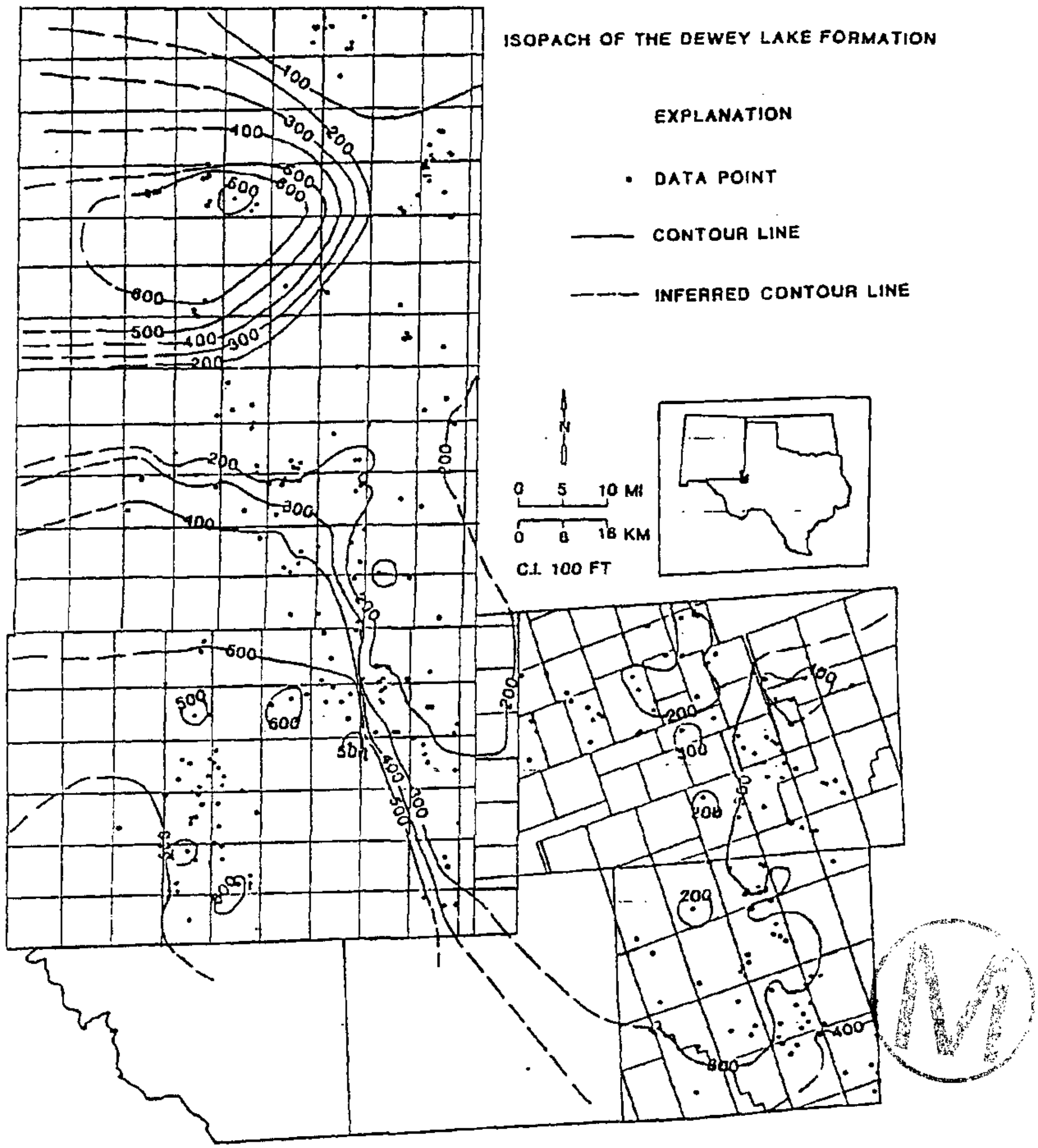


Figure 21 Isopach map of the Dewey Lake Formation.

SUMMARY AND CONCLUSIONS, p 143;

" Broad, winged channels filled with thin, horizontal laminations dominate the Dewey lake Formation. The lateral interfingering and vertical stacking of these channels creates an unusual depositional architecture not seen in either the typical meandering, anastomosing or braided fluvial models. It, however, is not unique. Similar sedimentologic and morphologic characteristics have been noted in other formations and interpreted to represent a fluvial system dominated by ephemeral flood events. The depositional environment of the Dewey Lake is, therefore, envisioned to be a large, arid to semi-arid fluvial plain, which experienced infrequent and localized flash floods. As the flood waters rushed across some portion of the plain they would carve and quickly fill broad, shallow channels. Later floods would erode and fill other channels to create interfingering and stacked architecture now exposed in the Dewey Lake Formation."

Schiel, K.A. 1994. "A New Look at the Age, Depositional Environment and Paleogeographic Setting of the Dewey Lake Formation (Late Permian)." West Texas Geological Society Bulletin, Vol. 33, No. 9, pp. 5-13. WPO 20465.

ABSTRACT, p 5;

" The Dewey Lake Formation (Late Permian?) was studied, using surface and subsurface techniques, to more clearly define its depositional environment and tectonic/paleogeographic setting. The Formation contains numerous wide, shallow channels filled with horizontally laminated siltstone and flanked by laterally thinning 'wings' of micro-cross laminated siltstone. This morphology indicates that the Dewey Lake was deposited in a fluvial plain dominated by localized, ephemeral flows. The 'wings' represent distally thinning, floodplain deposits, formed as the channel filled with sediment and the water overflowed onto the surrounding plain.

The Dewey Lake is generally restricted to the Late Permian; however, the supporting evidence is weak. Lateral thickness variations in the Dewey Lake reflect syndepositional subsidence (i.e, the Delaware Basin was still active), not post-depositional erosion. Ash beds in the lower Quartermaster Formation (lateral equivalent), with ages near the Permo-Triassic boundary, date the initiation of sedimentation, not its duration. These observations suggest that although deposition of Dewey Lake sediments may have begun in the latest Permian, it continued through the Early Triassic.

The silts and fine grained sands comprising the Dewey Lake were derived from an uplift, to the south/southeast, encompassing the Pennsylvanian Ouachita/Marathon thrust belt and fore-deep basins. Triassic uplift of this region is indicated by an erosional unconformity between Late Permian and Cretaceous strata in several fore-deep basins and Triassic conglomerates in the Glass Mountain and Llano Uplift regions interpreted as alluvial fans. Timing and location of this uplift suggest that it may have originated as a pre-rift bulge. Lithologic, stratigraphic, and sedimentologic similarities between the Dewey Lake and Moenkopi Formation suggest that the alluvial plain north of this uplift may have extended throughout the southwestern United States."

p 9;

" Summary of depositional Environment Analysis.

The process of channel carving and filling, during the course of ephemeral flow events, create the unique morphology of the Dewey Lake.

- Runoff from a local shower carves a shallow channel.
- As the channel fills with sediment (Facies 3), water overflows onto the surrounding plain.
- Friction reduces the velocity and climbing cupsate ripples (Facies 4) form along the channel margin (Figure 4A). Further away from the channel the velocity is even lower and less silt is deposited, creating the channel 'wings'.
- As the flow wanes, silty clay drapes the area. This drape thickens away from the channel forming the silty claystone portion of Facies 5.

The abundance of Facies 4 and 5 suggests that many channels were rapidly filled with sediment, which caused overflow onto the surrounding plain. There are, however, several channels in Figure 3 which contain two or more distinct filling episodes. In many cases the initial channel fill consists of the silty claystone of Facies 7. This suggests that some channel forms remained after the cessation of flow. One explanation may be that these 'open' channels were near the origination of flow; hence, there was no 'upstream' sediment to fill the channel.

A few channel orientations,and several sedimentary structure measurements, suggest that flow was to the north/northwest. Therefore, the source area was located to the south/southeast.

The Dewey Lake Formation was deposited in a large, arid fluvial plain subject to ephemeral flood events. The size and location of these flows were dictated by meteorological conditions. Events were probably infrequent and local in nature. Time between flood events in a single locality could easily have been years, or decades. Much of the sediment deposited during any one event was eroded and redeposited down gradient during subsequent channel-carving events (Figure 4B). Preservation of sediment at one locality would ultimately be dictated by the amount of tectonic subsidence between events, and the erosive power of the following event."

Sewards, T., Williams, M.L., and Keil, K. 1991. Mineralogy of the Culebra Dolomite Member of the Rustler Formation. SAND90-7008. Sandia National Laboratories, Albuquerque, NM. WPO 23879.

ABSTRACT, p i, para 4;

" Clay is the second most abundant mineral present and is concentrated along textural features, particularly the surfaces of fractures and vugs, thus making its presence of particular import to the characterization of hydrological transport within the formation. Clay abundances range from less than 1.0% to nearly 60% of the bulk samples.

The clay mineral assemblage includes corrensite (ordered mixed-layer chlorite/smectite), illite, serpentine, and chlorite. Corrensite is the dominant clay mineral, usually constituting about 50% of the clay assemblage;illite is the next most abundant constituent, and serpentine and chlorite are relatively minor components. Because of its high cation exchange capacity (CEC), the presence of corrensite is of particular importance as it can be an effective sorbent of radionuclides."

Section VII. CLAY MINEROLOGY, p VII-1, para 1;

" Clay fraction separates (<2 micron) were obtained from three samples and analyzed by XRD using oriented mounts (Drever, 1973) to both identify the clay mineral present and determine the modes of each clay mineral. XRF analysis was used to determine the bulk composition of the clay separates. AEM was used to study the textural relationships of the clay mineral in one sample, H6B #3."

NOTE:
XRD = X-Ray Diffraction
XRF = X-Ray Fluorescence
AEM = Analytical Electron Microscopy

Siegel, M.D., Lambert, S.J., and Robinson, K.L., eds., 1991. Hydrogeochemical Studies of the Rustler Formation and Related Rocks in the Waste Isolation Pilot Plant Area, Southeastern New Mexico. SAND88-0196. Sandia National Laboratories, Albuquerque, NM. WPO25624.

ABSTRACT, p i;

" Chemical, mineralogical, isotopic, and hydrological studies of the Culebra dolomite member of the Rustler Formation and related rocks are used to delineate hydrochemical facies and form the basis for a conceptual model for post-Pleistocene groundwater flow and chemical evolution. Modern flow within the Culebra in the Waste Isolation Pilot Plant (WIPP) area appears to be largely north-to-south; however, these flow directions under confined conditions are not consistent with the salinity distribution in the region surrounding the WIPP Site. Isotopic, mineralogical, and hydrological data suggest that vertical recharge to the Culebra in the WIPP area and to the immediate east and south has not occurred for several thousand years. Eastward increasing $^{234}U/^{238}U$ activity ratios suggest recharge from a near-surface Pleistocene infiltration zone flowing from the west-northwest and imply a change in flow direction in the last 30,000 to 12,000 years.

Culebra groundwaters are in chemical equilibrium with gypsum and are undersaturated with halite and anhydrite. A partial-equilibrium model for the chemical evolution of the groundwater suggests that Na, Cl, Mg, K, and SO_4 are added to the Culebra by dissolution of evaporite salts in adjacent strata. Equilibrium is maintained with gypsum and calcite, but dolomite supersaturation increases as the salinity of the water increases. Stable-isotope compositions of carbonates are consistent with this model and indicate that no recrystallization of dolomite in equilibrium with the groundwater has occurred. Major and minor element correlations are consistent with several plausible mechanisms of water/rock interaction, including sorption of lithium and boron by clays and dissolution of Mg-rich clays."

EXECUTIVE SUMMARY, p ES-1, para 3;

" An extensive geochemical data base, including analyses of major and minor solutes, redox data, mineralogical studies of intact core samples, and isotopic studies of waters, carbonates, and sulfates, has been assembled for the Rustler Formation and adjacent units in the northern Delaware Basin. These data were evaluated to compare the aqueous geochemistry with host rock mineralogies, to delineate hydrochemical facies in the Culebra member of the Rustler Formation, and to determine the consistency of these facies with groundwater flow patterns derived from site stratigraphy and hydrology. The resulting synthesis of data and current hypotheses concerning the origin, composition, and history of waters in the Culebra member of the Rustler Formation and related units provides a tentative conceptual model for groundwater flow in the Rustler during the last 12,000 to 16,000 years. This model can form part of the basis for assessing the long-term performance of the geological containment system at the WIPP, which is developed in the underlying evaporites of the Salado Formation."

EXECUTIVE SUMMARY, p ES-3, para 3;

" Mineralogical and isotopic studies of sulfates in overlying layers also show that no significant amounts of either solutes or water have permeated vertically downward from the surface to recharge the Culebra. Specifically, much of the anhydrite in the Tamarisk member between the Magenta and Culebra members has not been hydrated to gypsum by recrystallization in the presence of fresh water, D/H ratios in gypsum throughout the Rustler are not consistent with a pervasively large water/rock ratio accompanying such hydration, and comparison of $^{87}Sr/^{86}Sr$ ratios of gypsums and carbonates in Rustler, Dewey Lake, and surface rocks shows that secondary sulfates and carbonates in the Rustler did not form in a hydrological regime that was uniformly interconnected with overlying rocks and the surface. Thus, the available mineralogical, hydrological, and isotopic data indicate no significant vertical connection between the Culebra and overlying strata.

The apparent discrepancy between modern flow direction and solute distribution can be explained by a change in flow direction in the last 30,000, or perhaps 12,000 years. Such a model is consistent with generally eastward-increasing ^{234}"$U/^{238}U$ activity ratios that indicate recharge from a near-surface Pleistocene infiltration zone, flowing from the west-northwest. The model is also consistent with the cessation of recharge in the late Pleistocene, as indicated by the radiocarbon dates. A likely explanation for the less saline waters south of the WIPP Site is that at the time of influx of the present generation of Culebra groundwater from the west-northwest, Rustler halite was absent adjacent to the Culebra in that area, and did not provide a source of NaCl. Thus, the postulated paleoflow direction (from the west-northwest) is consistent with both flow perpendicular to the $^{234}U/^{238}U$ contours and flow parallel to the hydrochemical facies boundary between more saline water in the north and less saline water south of the WIPP."

EXECUTIVE SUMMARY, p ES-5, para 2;

" Isotopic studies of minerals and waters provide some support for this model. Stable-isotope compositions of carbonate minerals indicate that calcite has precipitated in equilibrium with the groundwater now found in the Culebra in some areas, but that dolomite has not extensively recrystallized or exchanged isotopes with meteoric groundwater of any age. There is also isotopic evidence that calcium sulfate has recrystallized (dissolved and reprecipitated) in the presence of Rustler groundwaters.

The results of principle component analysis (PCA) suggest that reactions with clay minerals may exert an observable influence on the water's minor-element chemistry throughout the study area. When the effects of solute addition associated with halite dissolution are factored out prior to the PCA, a Mg-SiO_2-alkalinity association is left that is negatively correlated with a pH-B-Li association. These correlations are consistent with several plausible mechanisms, including uptake of Li by vacant octahedral sites in a clay lattice, sorption of B by surface sites of clays, and dissolution of a reactive amorphous Si-Mg-rich layer in corrensite, the dominant Culebra clay mineral.

Investigations that could further elucidate the hypotheses proposed here include collection and analysis of isotopic and chemical data from additional boreholes, systematic examination of the mineralogy of samples from highly transmissive zones (containing core rubble rather than intact core), and more rigorous calculations of the extent of mass transfer that could result from precipitation, dissolution, ion exchange, and sorption."

CHAPTER 1: SUMMARY OF HYDROGEOCHEMICAL CONSTRAINTS ON GROUNDWATER FLOW AND EVOLUTION IN THE RUSTLER FORMATION, p 1-1. para 2;

" Isotopic, mineralogical, and hydrological data suggest that vertical recharge to the Culebra in the WIPP area and to the immediate east and south has not occurred for several thousand years. These data are consistent with the view that the apparent discrepancy between modern flow direction and solute distribution can be explained by a change in flow direction during the last 30,000, or perhaps 12,000 years. This model is consistent with generally eastward- increasing $^{234}U/^{238}U$ activity ratios that suggest recharge from a near-surface Pleistocene infiltration zone, flowing from the west-northwest. Culebra groundwater are in chemical equilibrium with gypsum and undersaturated with respect to halite and anhydrite. A partial-equilibrium model for the chemical evolution of the groundwater suggests that Na, Cl, Mg, K, and SO_4 are added to the Culebra by dissolution of evaporite salts in adjacent strata. Equilibrium is maintained with gypsum and calcite, but dolomite supersaturation increases as the salinity of the water increases. Isotopic studies of minerals and waters provide some support for this model. Stable-isotope compositions of carbonates indicate no recrystallization of dolomite in equilibrium with the groundwater now found in the Culebra, but local precipitation of calcite has apparently occurred. There is isotopic as well as mineralogical indication that calcium sulfate has recrystallized (dissolved and reprecipitated) in the presence of Rustler groundwater."

Section 1.4.8 Isotopic Studies of Rustler Waters, p 1-71, para 2;

" By comparison, vadose Capitan waters from the Carlsbad cavern system, groundwater from a water table in alluvium, and near-surface accumulations that homogenize seasonal variations in isotopic composition also have meteoric isotopic signatures, but have isotopic compositions more positive in δD-$\delta^{18}O$ space than confined Rustler and Capitan waters (Lambert and Harvey, 1987). The envelopes of δ-values for these two populations of differing hydrologic character do not overlap (Figure 1-25). The data a Nativ and Smith (1987) reveal that Ogallala groundwaters underlying the high plains to the east, climatically similar to the Delaware Basin, the only groundwaters containing tritium levels indicative of recent (post-1950) meteoric derivation (>10 tritium units [TU] all have δD values >-42% (Figure 1-25), comparable to near-surface unconfined meteoric waters in the Delaware Basin (Figure 1-26). High Plains data for Figure 1-26 are from Nativ and Smith (1987); WIPP data are from Lambert and Harvey (1987) and Lambert (1987). Significantly high tritium concentrations (>10 TU), indicating derivation from a meteoric source since 1950, are restricted largely to groundwaters having δD values more positive than about -42%. Ogallala waters from nearby southeastern New Mexico have δD values between -39 and -41%, corresponding with δD values of modern groundwater recharge in the Texas High Plains.

Hydrogen-isotope characteristics of groundwaters from the nearby climatically similar Delaware Basin (WIPP data) are shown for comparison. The isotopic signatures of confined Rustler and Capitan waters are distinct from that of both Ogallala water with discernable modern input and of vadose Capitan and alluvial water. Thus, it is likely that the isotopic compositions of confined Rustler and Capitan groundwaters in the northern Delaware Basin are not characteristic of groundwaters that would be receiving modern meteoric recharge under the present climatic conditions. . . .

Only four out of 16 well-water occurrences gave internally consistent radiocarbon 'age' calculations based on the internally consistent interpretive model and assumptions of Evans et. al. (1979) for water-bearing carbonate rocks. The model of Evans et. al. takes into account dilution of atmospheric carbon by dissolution of carbonate rock, and carbon isotope exchange between water and host rock. The mean of these four is 14,000 years; 95% confidence limits are ±5,000 years. This is a minimum age estimate. It is not possible to estimate an upper age limit because of the unavoidable possibility of at least small amounts of unmitigable contamination even in these four samples. These tightly clustered ages, given their individual confidence limits, while spread out from north to south across the WIPP Site, do not allow consistent age gradients or travel times to be inferred across the WIPP Site based on differences in radiocarbon ages (Figure 1-27). Ten of the 16 well-water occurrences were completely contaminated due to unmitigable anthropogenic well-bore effects. The remaining two are ambiguous, but all 16 probably represent three-component mixing, including some contamination. The four dated groundwaters (three Culebra and one Dewey Lake) all have stable-isotope compositions belonging to the more negative population inδD-$\delta^{18}O$ space (Figure 1-25). Thus, it is inferred that Rustler and Dewey Lake groundwaters in this population have a significant component at least 12,000 radiocarbon years old. All the tritium measurements from the WIPP area, which are associated with the more negative (confined Rustler) isotopic compositions, are <3 TU, indicating little or no contribution from the atmosphere since 1950. Figure 1-27 shows tritium and radiocarbon in Rustler and Dewey Lake (DL) or Magenta (MA), measurements in Figure 1-27 (all from Lambert, 1987) apply to water from the Culebra member of the Rustler Formation. The uniformly low (<7 TU) tritium concentrations near the WIPP Site indicate no introduction of an atmospheric component since 1950 (cf. Isaacson et. al., 1974). Three Culebra and one Dewey Lake water were amenable to dating by the carbonate-aquifer model of Evans et. al. (1979), giving times of isolation from the atmosphere ranging from 12,000 to 16,000 radiocarbon years. These data indicate long residence times or long travel times from recharge areas, but provide no evidence of either modern vertical infiltration or monotonic age gradients indicating north-to-south flow. Three of these data, from water samples also having δD analyses, are depicted in Figure 1-26."

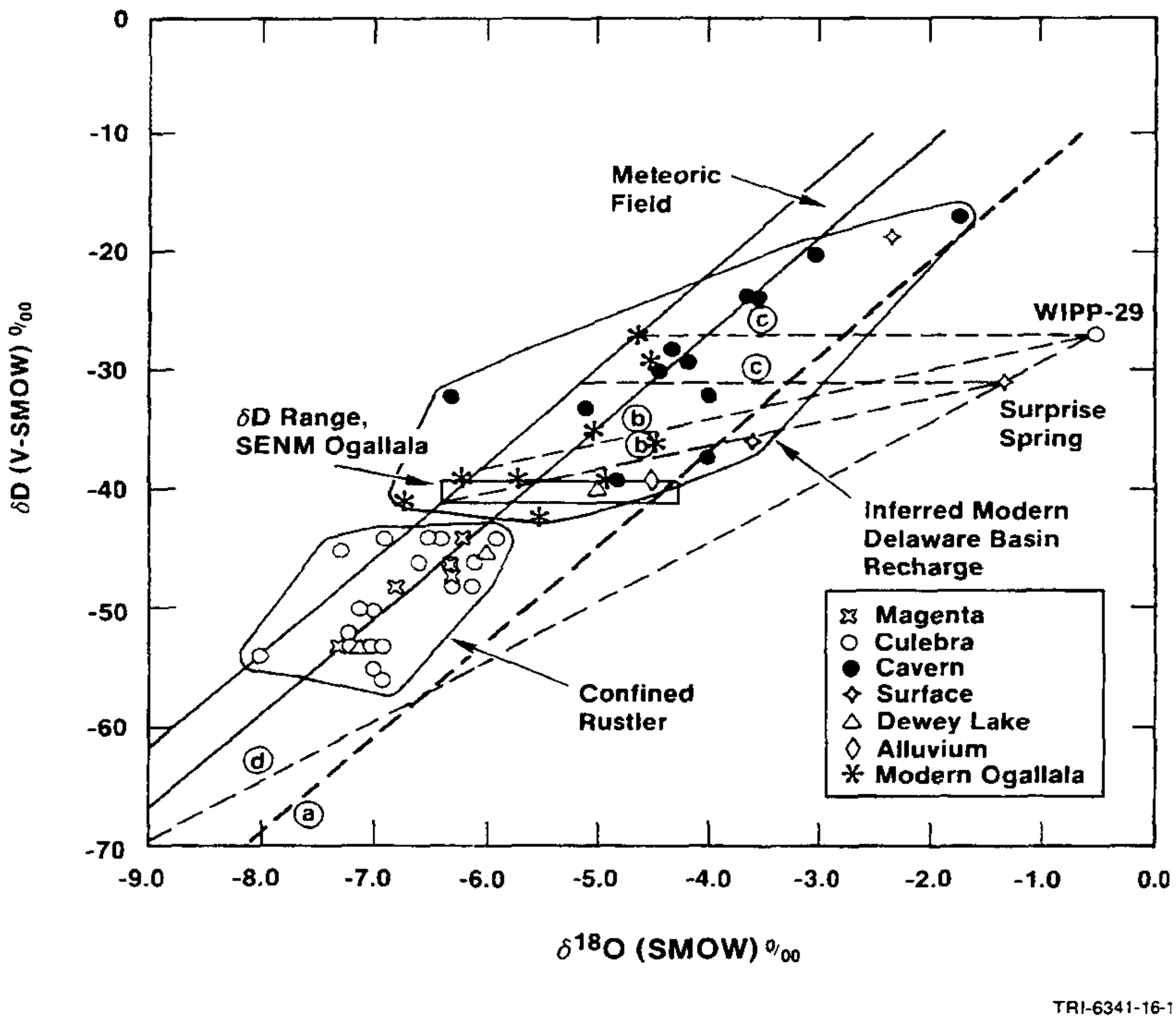


Figure 1-25. Stable-isotope compositions of groundwaters from the Rustler Formation (Figure 5-1, adapted from Lambert and Harvey, 1987).

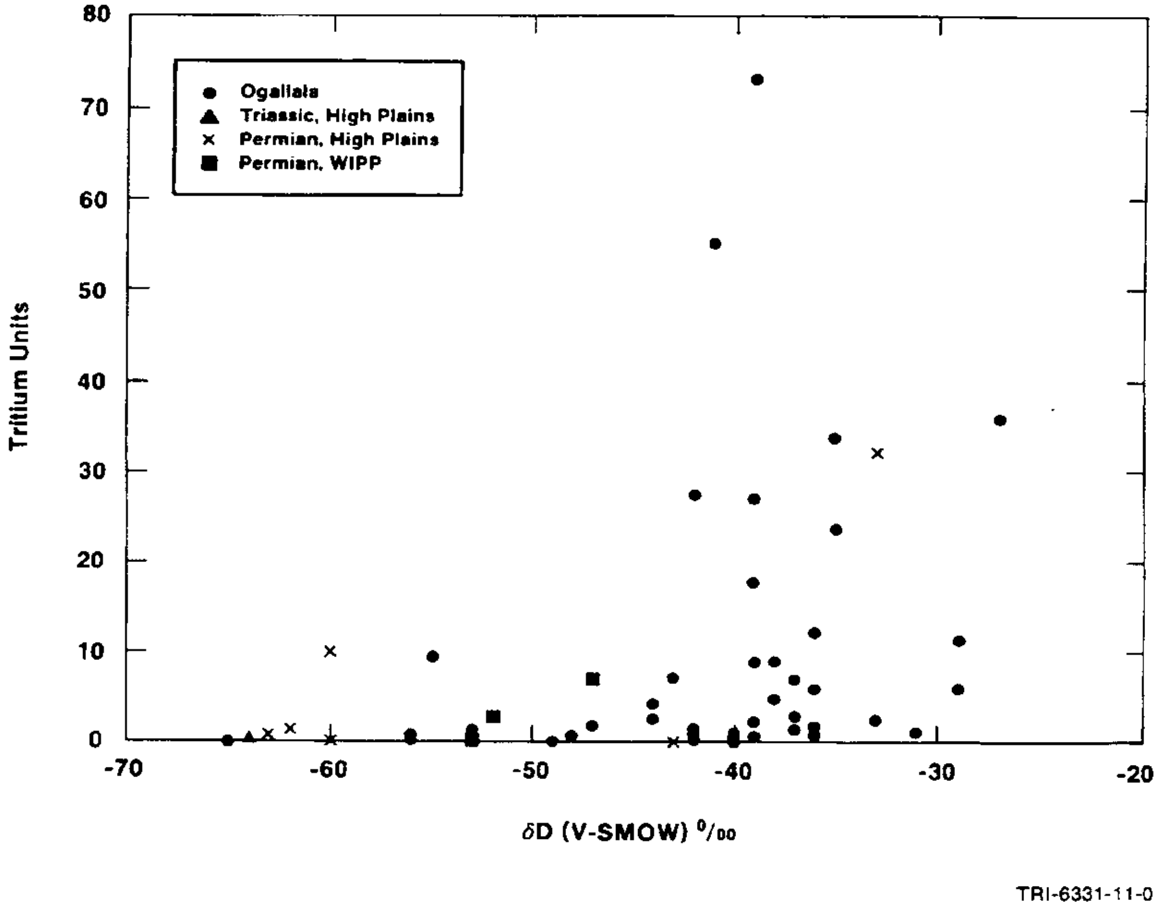


Figure 1-26. Tritium and deuterium concentrations in groundwaters from the Southern High Plains, Texas, and the Delaware Basin, southeastern New Mexico (Figure 5-2, from Lambert and Harvey, 1987).

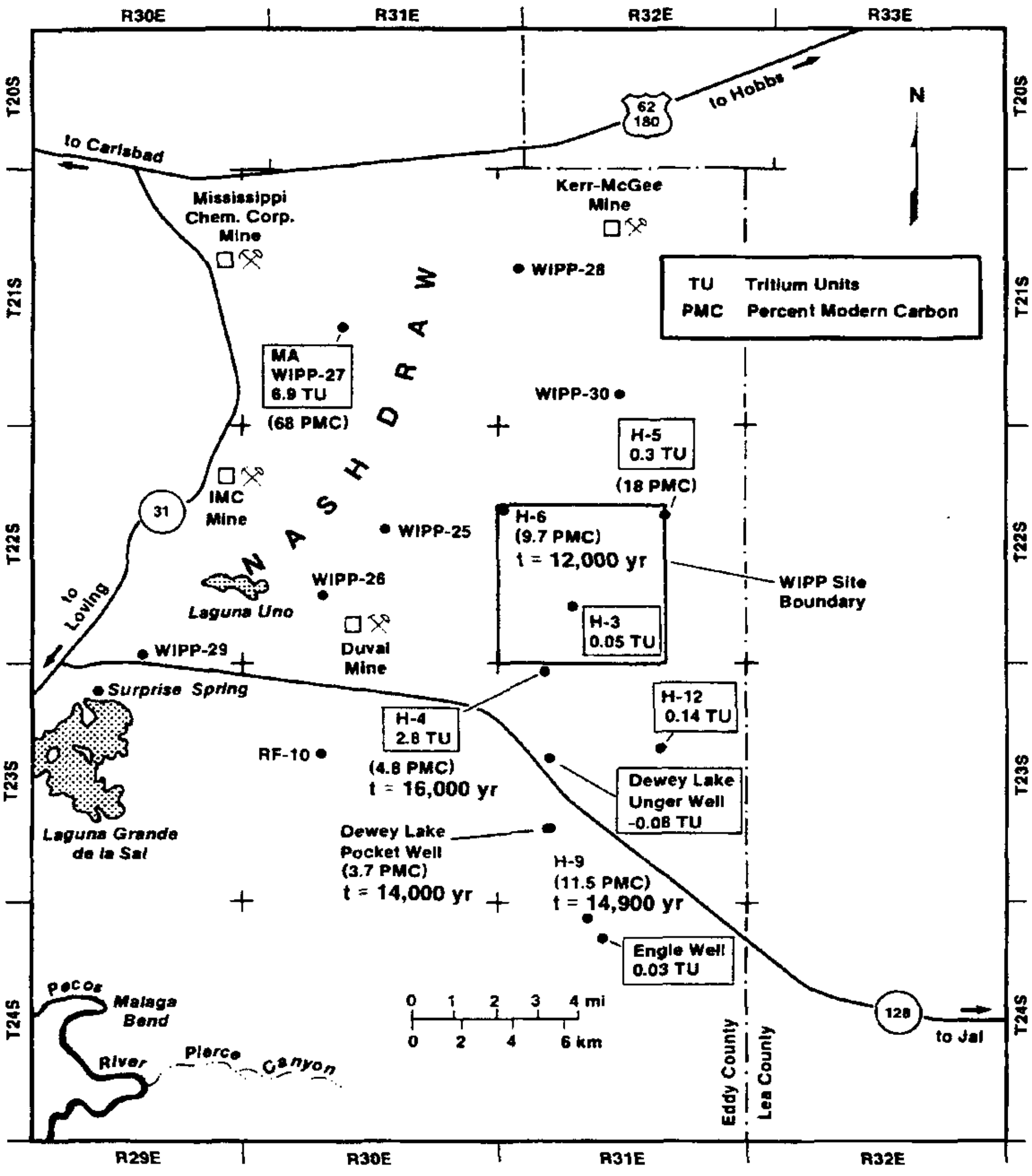


Figure 1-27. Tritium and radiocarbon in Rustler and Dewey Lake groundwaters (Figure 5-11, adapted from Lambert and Harvey, 1987).

CHAPTER 2, SOLUTE RELATIONSHIPS IN GROUNDWATERS FROM THE CULEBRA DOLOMITE AND RELATED ROCKS IN THE WASTE ISOLATION PILOT PLANT AREA, SOUTHEASTERN NEW MEXICO, ABSTRACT, p 2-1;

" This chapter summarizes solute concentrations in waters of the Culebra member of the Rustler Formation. The solute relationships are used to delineate hydrochemical facies, to compare flow directions suggested by water chemistry with those indicated by modern hydrologic potentials, and to formulate a hypothesis for the chemical evolution of the Culebra groundwaters. Descriptions of waters from the Magenta dolomite, Rustler/Salado contact zone, the Dewey Lake Red Beds, and the Bell Canyon Formation are also included.

Four hydrochemical facies have been delineated in the Culebra. Zone A contains saline (about 3.0 m) NaCl brine and is found in the eastern third of the study area, roughly coincident with the region of low transmissivity and the occurrence of halite in several units of the Rustler Formation. Zone B contains a dilute Ca-SO_4-rich water (I <0.1 m) in the southern part of the study area and is coincident with a zone of high transmissivity where halite is absent from the Rustler. Zone C contains waters of variable composition and ionic strengths (0.3 to 1.6 m); it extends from the central part of the Waste Isolation Pilot Plant (WIPP) Site (four-mile zone), where halite is present in the unnamed member of the Rustler, to the eastern side of Nash Draw where no Rustler halite has been found. Zone D contains WIPP-27 and WIPP-29 and is defined on the basis of anomalously high salinities (3-6 m) and K/Na ratios (0.2), probably related to contamination from potash refining operations in the area."

2.3.2.1 Definition of Hydrochemical Facies in the Culebra Dolomite, p 2-57, para 2;

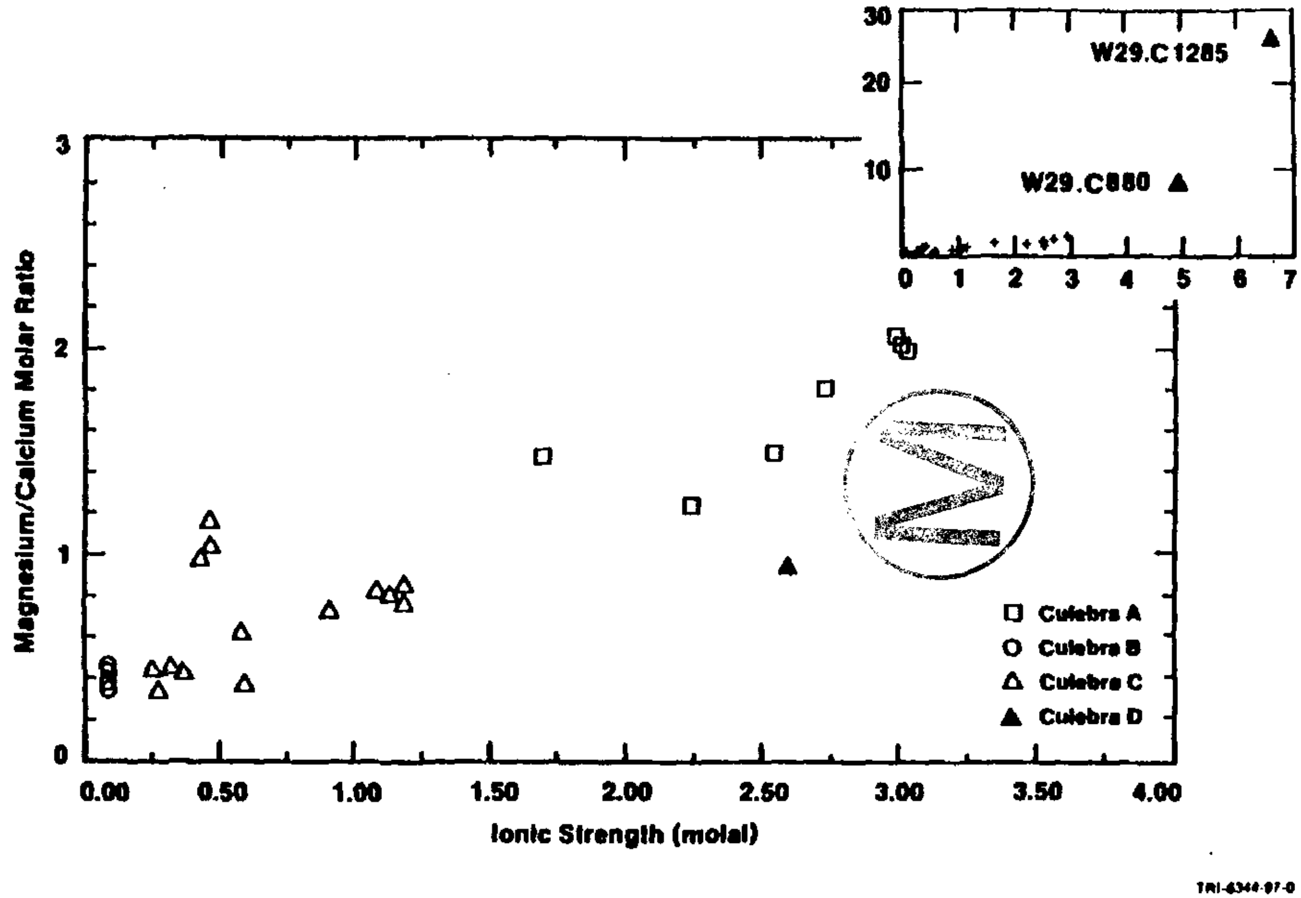
" Based on the major solute compositions given in table 2-2, four hydrochemical facies have been delineated and are shown in Figure 2-17. Compositions of waters from several other locations (indicated by open circles, open squares, or parentheses around the well name) were not included in the original data set used to define the facies, but their compositions are consistent with the facies boundaries. Compositions of waters in each zone are described in Figure 2-18.

> Zone A (DOE-1, H-5, H-11, H-12, P-17) contains saline (-2 to 3 molal) NaCl brines with Mg/Ca molar ratios of about 1.2 to 2(cf. Figure 2-19). This water is found in the eastern third of the study area; the zone coincides roughly with the region of low transmissivity, although at some wells (e.g., DOE-1 and H-11B3) the transmissivities are greater than 1 ft^2/day. On the western side of the zone, halite in the Rustler has been found only in the lower unnamed member; in the eastern portion of the zone, halite has been observed above and below the Culebra.
>
> Zone B (H-7, H-8, H-9, Engle) contains relatively dilute $CaSO_4$-rich groundwater (ionic strength <0.1 m). This water is found in the southern part of the study area. This zone coincides with a region of high transmissivity; halite is not found in the Rustler in this zone. Chemical data from Bodine et al. (Chapter 4) suggest that

several stock wells (Windmill, Indian, South and Two-Mile) and the Gnome (USGS) wells are also part of this zone.

Zone C contains waters of variable composition with low to moderate ionic strength (0.3 to 1.6 m). These waters occur in the western part of the WIPP Site and the eastern side of Nash Draw. Mg/Ca molar ratios of the fresher waters in this zone ($I < 1.25$ m) range from about 0.3 to about 1.2. This zone coincides with a region of generally high transmissivity (except wells WIPP-30, H-1, H-2, H-4, H-14, and H-16). In the eastern part of this zone, halite is present in the unnamed lower member of the Rustler; on the western side of the zone, halite is not observed in the formation. The most saline (Na-Cl rich) water is found in the eastern edge of the zone, close to borehole locations where halite is observed in the Tamarisk member.

Zone D (WIPP-27, WIPP-29) is defined based on inferred contamination related to potash-refining operations in the area. The Culebra groundwaters from these wells have anomalously high salinities (3-7 m) and K/Na weight ratios (0.2) compared to other wells in the study area (salinities < 3 m; K/Na weight ratios 0.01 to 0.09). At WIPP-29, the composition of the Culebra water has changed over the course of a 7-year monitoring period."



L-19 Relationship between Mg/Ca molar ratios and ionic strengths of Culebra groundwaters.
The Mg/Ca molar ratios were calculated from the UNC Geotech data given in Table 2; ionic strengths are also given in Table 2. Hydrochemical facies is indicated for each sample.

CHAPTER 5: ISOTOPIC CONSTRAINTS ON THE RUSTLER AND DEWEY LAKE GROUNDWATER SYSTEM

Section 5.2.4 Groundwaters Modified by Rock/Water Interactions, p 5-18;

" Confined groundwaters from the Rustler/Salado contact in Nash Draw have meteoric isotopic compositions typical of other Rustler waters. Toward the east, over the WIPP Site, however, the isotopic composition of water from the Rustler/Salado contact shows progressively more positive deviation in δ-value ('isotope shift') from typical Rustler meteoric values (Figure 5-4). Shift-contours roughly parallel the boundaries drawn by Snyder (1985) (dotted line in Figure 5-4) delineating the stratigraphic positions of halite occurrence in the Rustler. The zero-shift contour parallels the scarp defining Nash Draw at Livingston Ridge. The magnitude of the shift is correlative with measured decreases in transmissivity (cf. Mercer, 1983), increasing distance from the eastern dissolution scarp of Nash Draw (cf. Bachman, 1985; 1987), and an increasing amount of halite surviving in the Rustler Formation (cf. Snyder, 1985).

Assuming an eastward-progressing halite-dissolution front, total removal of halite by dissolution in the Rustler has been faster than eastward scarp retreat, development of increased permeability due to subsidence-induced fracturing, and flushing of isotopically shifted water. The isotope shift is attributable to an increasing amount of rock/water interaction accompanying a diminishing water/rock ratio (cf. Clayton et. al., 1966). The precise mechanism of isotope exchange and the reactant solid phase have not been identified, but the potential effect of anhydrite hydration to gypsum or the contribution of a relatively large reservoir of exchangeable water of crystallization in existing gypsum relative to a smaller amount of groundwater should not be overlooked."

p. 5-54, para. 2;

" The Sr_{DL} data show a very wide range in Sr isotopic composition. This reflects the role of denitral Sr brought into the Delaware Basin during sedimentation and also reflects later exchange with waters. The surface caliche and gypsite spring deposits (Sr_{CL}) yield high $^{87}Sr/^{86}Sr$ values consistent with prediction based on mixed provenance for these occurrences. Note that the Pleistocene gypsite spring deposit (Bachman, 1981) contains high $^{87}Sr/^{86}Sr$ material more closely associated with a large component of shallow derivation, similar to the Dewey Lake veins, and is not the result of direct remobilization of the Rustler sulfates at depth. In turn, gypsum veining in the Dewey Lake Red Beds cannot be derived directly and solely from partial dissolution of Rustler sulfates, without the admixture of an apparently surficial component having a significantly higher $^{87}Sr/^{86}Sr$ ratio than the Rustler sulfates."

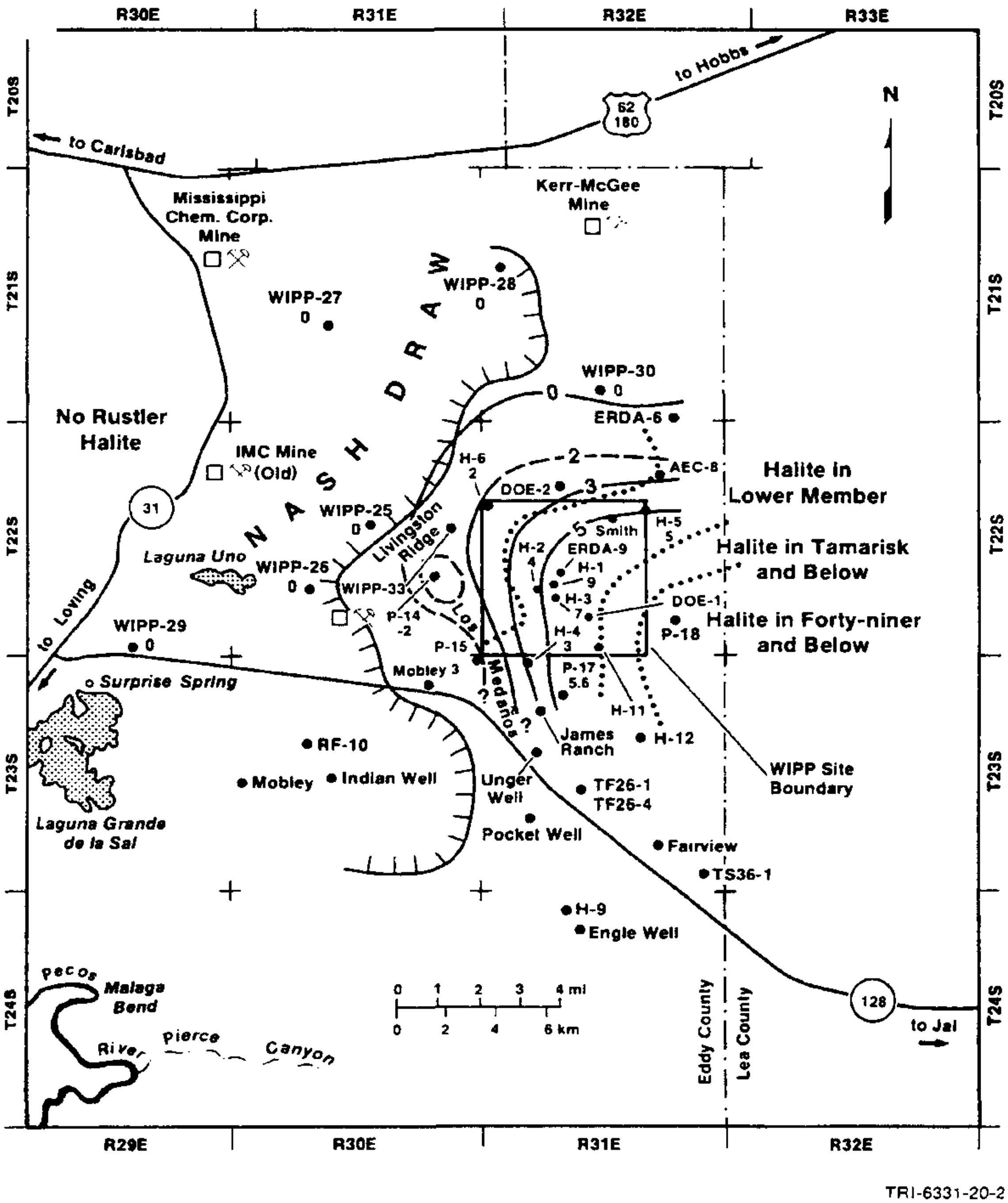


Figure 5-4. Contour map of oxygen-isotope shift in confined groundwaters at the Rustler/Salado contact, relative to -7‰ (from Lambert and Harvey [1987]).

5.6.4 Inferred Influences of Meteoric Water, p 5-65;

" The reproducibility of δD measurements on gypsums, together with the reproducibility of the water yield of the rock samples (Table 5-3), indicates little if any post-coring exchange of hydrogen isotopes in the water of crystallization of gypsum under conditions of sample storage and laboratory analysis. The analyses were carried out over a period of time during which the temperature and relative humidity were undergoing radical day-to-day changes in the laboratory, accompanying a change in the configuration in the building ventilation system (from summer to winter). The reproducibility of replicate measurements suggests a minimal influence of ambient laboratory conditions on the gypsum D/H ratios. Thus, the D/H ratios in gypsum are taken to represent the in situ isotopic compositions and are assumed to have been determined by the last episode of recrystallization of gypsum in the presence of a given water and a given water/rock ratio.

The gypsum/water fractionation factor (Equation A) was used together with the ranges of δD values of the two different populations of water samples (confined Rustler-type versus less confined shallow-type) to calculate the expected δD values of recrystallized gypsum under varying water/rock ratios. Since the former population of waters (Rustler-type) ranges in δD value between -44 and -58‰ (Section 5.2.3), a very small water/rock ratio would yield a range of -64 to -78‰. These ranges are depicted in Figure 5-19. Similarly, the latter population of waters (shallow-type) range in δD between -17 and -41‰, yielding this same range for gypsums expected to have formed in the presence of this water, gives a small water/rock ratio. A large water/rock ratio would yield the range -37 to -61‰. These ranges are depicted in Figure 5-20.

Taken together, Figures 5-19 and 5-20 show that the δD values of the Rustler gypsum and Dewey Lake selenite vein material at AEC-8 and gypsum from the WIPP-33 Forty-niner and WIPP-34 Magenta are consistent with recrystallization in the presence of a water that isotopically resembles typical Rustler meteoric water, inferred to be late Pleistocene or older (Figure 5-20). However, they are not consistent with recrystallization in the presence of shallow-type water inferred to be modern (Figure 5-20). Also, the WIPP-19 sample cannot be easily generated from Rustler-type water alone, regardless of water/rock ratio. Note that if 0.985 instead of 0.980 is used for the α-value in Equation 1, these constraints apply to one of the WIPP-34 Forty-niner data points also. If the Rustler-type waters more depleted in deuterium are at least as old as late Pleistocene (Section 5.3.5.3), and no waters of similar isotopic composition have entered the subsurface since, then the time of recrystallization also is at least that old, since such groundwaters are not characteristic of modern recharge (Section 5.2.3). These constraints preclude both total preservation of these gypsums as primary seawater precipitates and their recrystallization in response to infiltration typified by local modern meteoric isotopic compositions. Whereas Rustler dolomites generally have not recrystallized in isotopic equilibrium with Rustler water (except at WIPP-33; see Figure 5-6), much of the gypsum in the Ochoan section has done so."

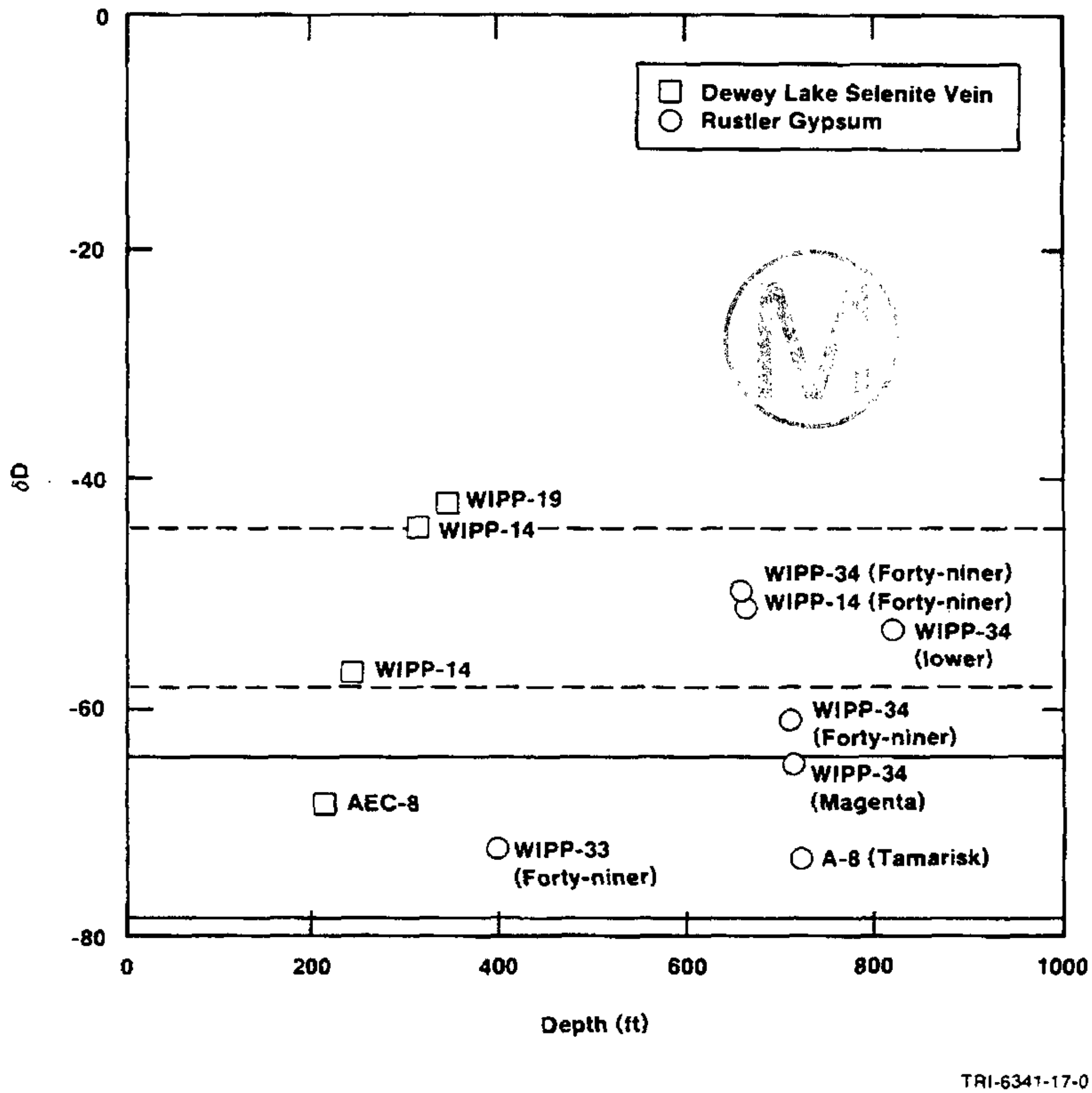


Figure 5-19. δD values of the water of crystallization in gypsums as a function of depth.

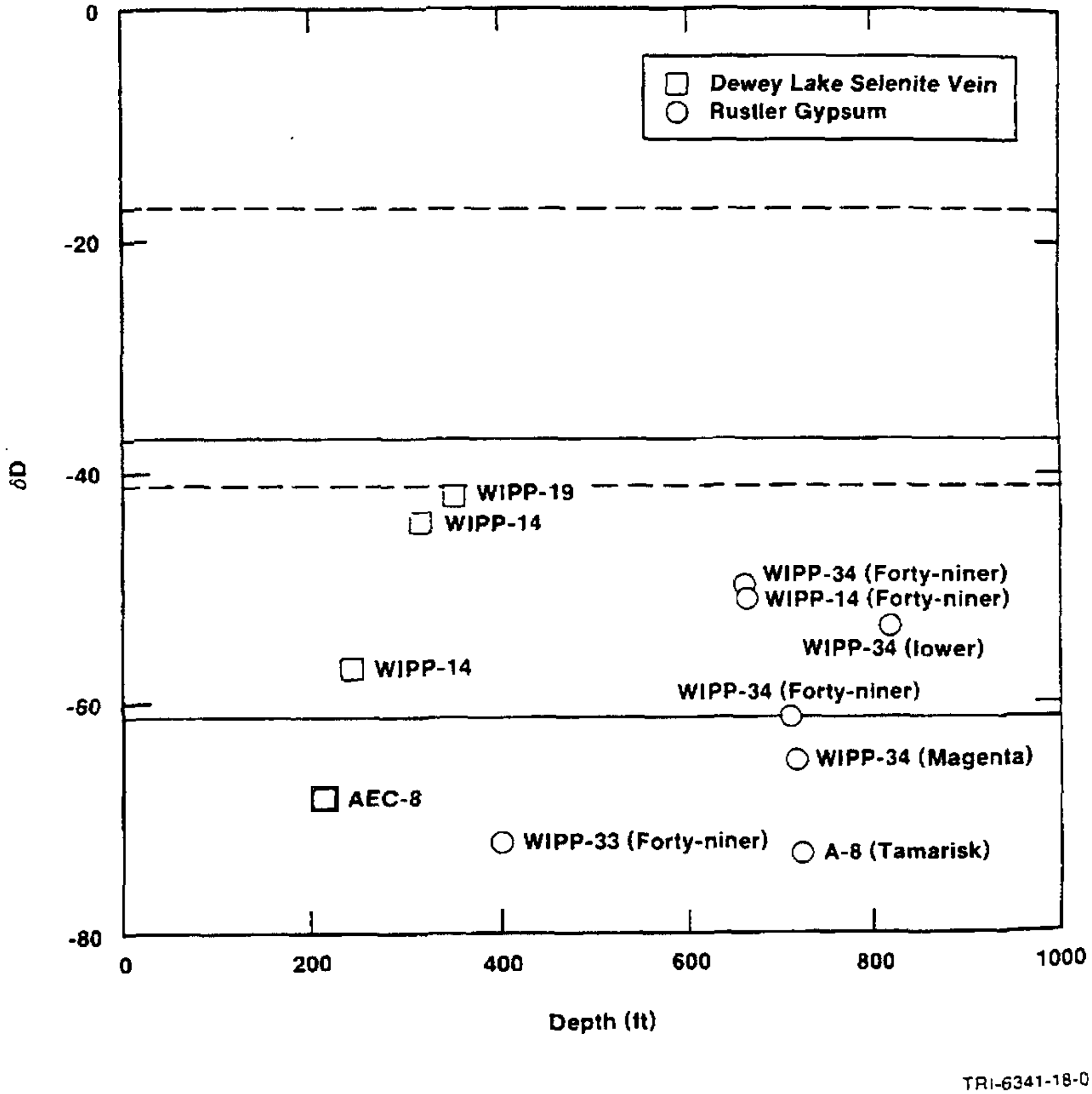


Figure 5-20. δD values of the water of crystallization in gypsums as a function of depth.

Snider, H.I. 1966. "Stratigraphy and Associated Tectonics of the Upper Permian Castile-Salado-Rustler Evaporite Complex, Delaware Basin, West Texas and Southeast New Mexico." Ph.D. dissertation. University of New Mexico, Albuquerque, NM.

ABSTRACT, P 1;

" The Delaware basin of west Texas and southeast New Mexico is roughly pear-shaped with a northwest-southeast length of about 140 miles and a width of 100 miles in the northwest tapering to 60 miles in the southeast--an area of about 10,000 square miles. In late Permian time the basin was essentially encircled by a carbonate depositional environment or reef zone.

The Upper Permian evaporite complex within the Delaware basin consists of Castile, Salado, and Rustler Formations. The Castile Formation contains laminated calcareous anhydrite, halite, and limestone. The Castile Formation was subdivided into seven units: Anhydrite I, Halite I, Anhydrite II, Halite II, Anhydrite III, Anhydrite IV, and Anhydrite V. The lowest four units can be traced over two-thirds of the basin. The upper three units can only be differentiated in the eastern part of the basin. The Salado Formation consists of halite and anhydrite with minor clastics, magnesite, and potassium minerals in the north and east parts of the basin. In the south and west parts of the basin, the Salado consists mainly of anhydrite dolomite, and clastics. The Rustler Formation contains anhydrite, dolomite, clastics, and halite.

The distribution of halite may reflect tectonism during Castile time. Little to no halite is found on the intrabasin shelf, while thick halite beds are found in the Ochoa trough. Halite units of the Castile Formation may have overlapped to the south due to differential subsidence or 'tilting' southward of the Ochoa trough. A reversal of this tilting occurred in Salado time.

Evidence of local movement in Castile units is abundant. Four models are analyzed to account for salt structures found: 1. salt movement contemporaneous with deposition--'down building'; 2. post-depositional halite piercement; 3. post-depositional lateral movement of upper halite over lower halite stock, dome, or anticline; and 4. gravity flow of upper halite over a lower halite structure--'anticline on anticline.' Tectonic 'triggering' is suggested as the major cause of Castile halite movement. Regional movement resulting in structures similar to 'salt pillows' or 'salt stocks' is believed to have occurred in the northeast part of the Delaware basin in Lea County, New Mexico."

p. 39;

" The thickness of the Castile Formation ranges from 1,250 feet in the western part of the Delaware basin to more than 2,000 feet in the east-central part and in the extreme northeastern part of the Delaware basin (Fig. 14, in pocket). A net footage map of halite in the Castile Formation (Fig. 15, in pocket) shows the range of thickness from no halite in the western, southern, and southeastern parts of the Delaware basin to more than 650 feet in east-central and northeastern parts. A net footage map of non-halite strata, primarily laminated anhydrite (Fig. 16, in pocket) shows a range of thickness from 1,000 to 1,500 feet over most of the basin. Thicknesses of non-halite greater than 1,500 feet are generally found along the basin margin to the east and to the south."

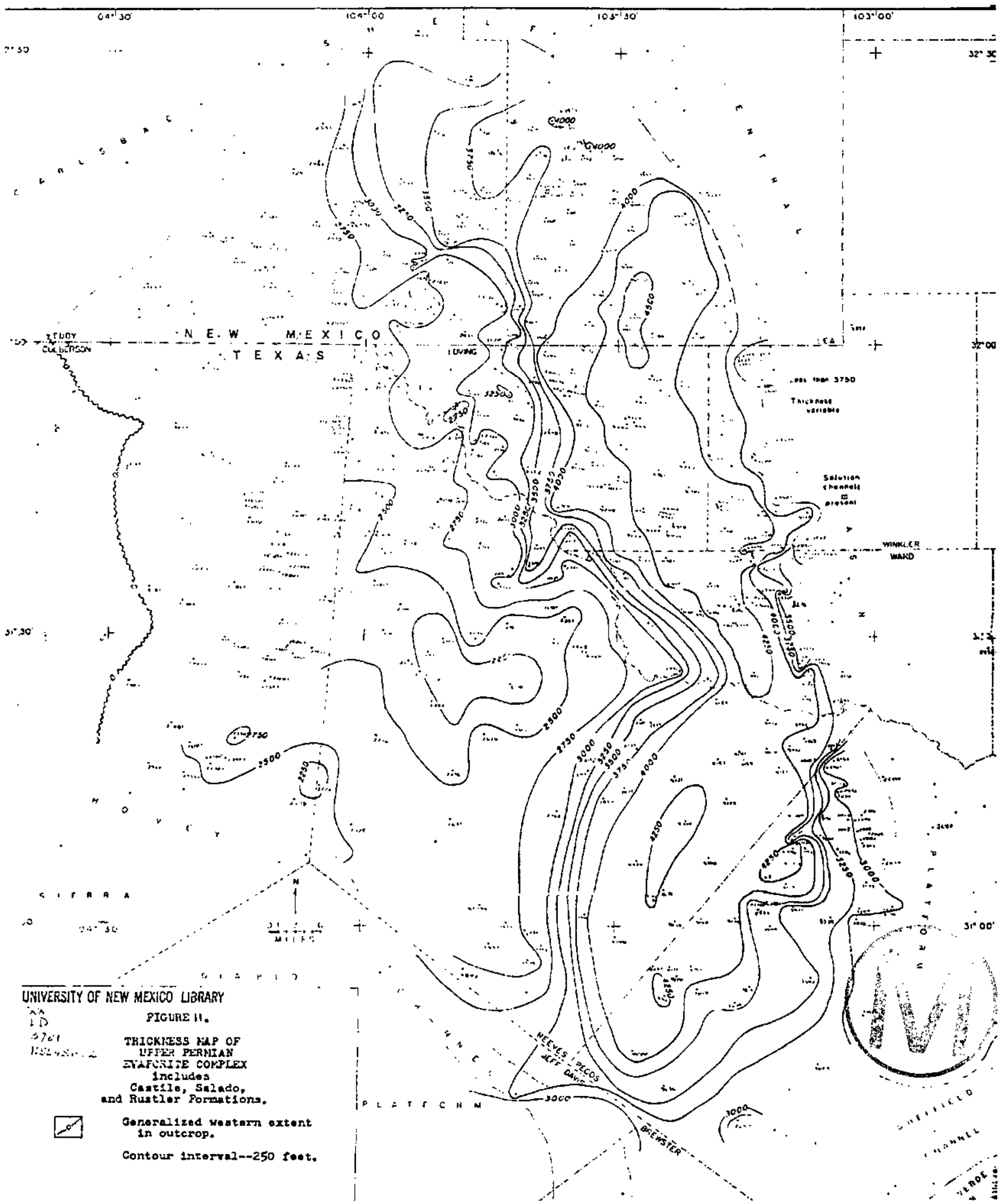


FIGURE 11.

THICKNESS MAP OF UPPER PERMIAN EVAPORITE COMPLEX includes Castile, Salado, and Rustler Formations.

Generalized western extent in outcrop.

Contour interval--250 feet.

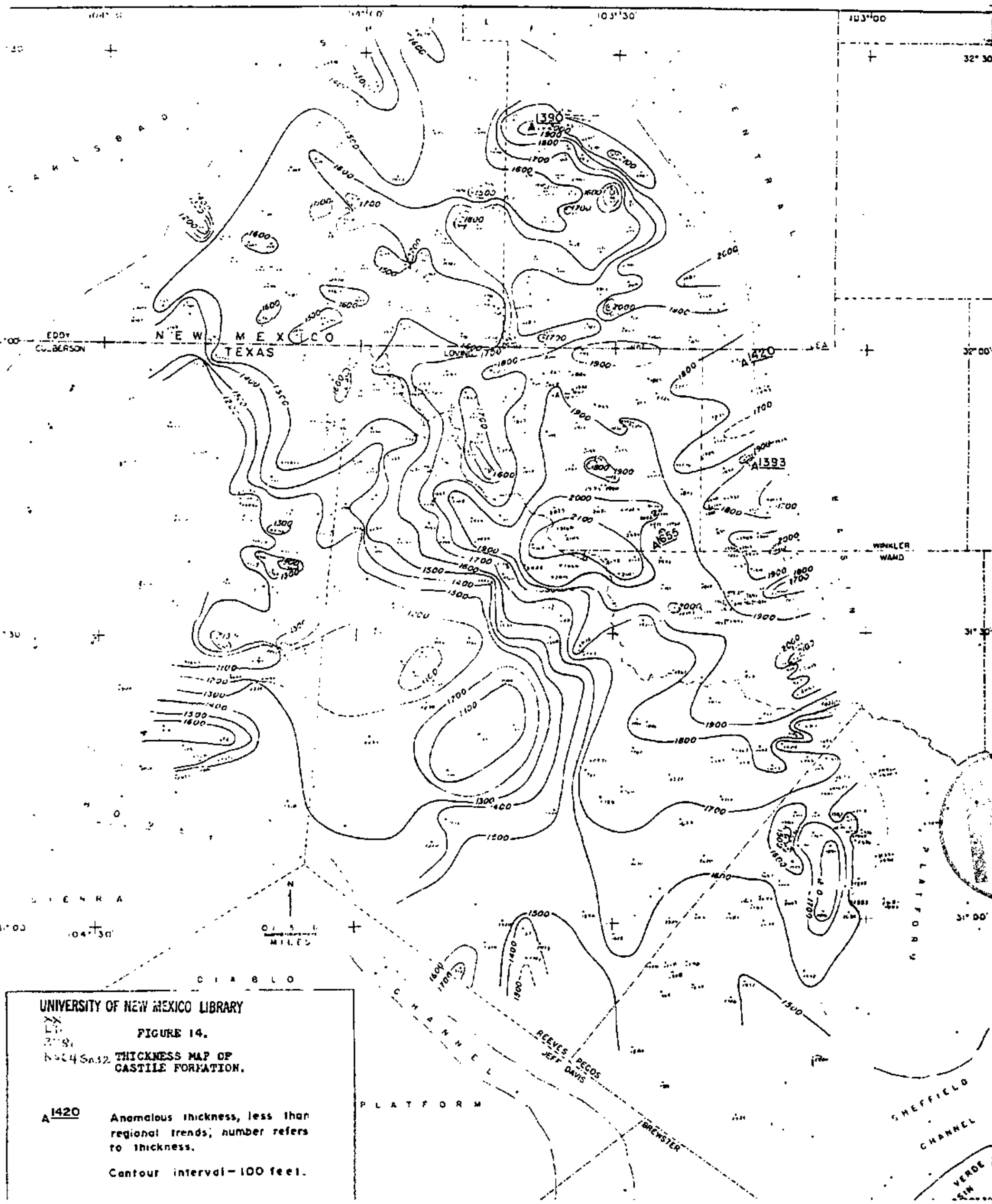


FIGURE 14.
THICKNESS MAP OF CASTILE FORMATION.

Snyder, R.P., 1985. Dissolution of Halite and Gypsum, and Hydration of Anydrite to Gypsum, Rustler Formation, in the Vicinity of the Waste Isolation Pilot Plant, Southeastern New Mexico. Open-File Report 85-229. U.S. Geological Survey, Denver, CO.

ABSTRACT, p 1;

" Data from selected drill holes spaced at intervals of 1.5 to 15 km (5,000 to 50,000 ft) in southeastern New Mexico demonstrate a progressive removal of halite by dissolution, hydration of anhydrite to gypsum, and removal of gypsum by dissolution in the Permian Rustler Formation. Thickness of the Rustler decreases as halite is removed, but increases after complete removal due to the hydration of anhydrite to gypsum."

Introduction, p 1, para 2;

" The U.S. Department of Energy (DOE) has selected a site in southeastern New Mexico for the development of a Waste Isolation Pilot Plant (WIPP). The site (fig. 1), 40 km (25 mi) east of Carlsbad, is to be used as a test area for the underground storage of military radioactive waste in bedded salt (halite). Evaporites, mostly halite and anhydrite, constitute the major rock types at the WIPP site to a depth of about 1,280 m (4,200 ft).

Circulating ground water has removed halite, and thus has caused concern about the integrity of the stored waste. The Rustler Formation of Permian age is the uppermost unit at the site that contain evaporites. In addition to halite and anhydrite, the formation also contains two dolomite beds that are known aquifers.

More than 70 holes (Mercer, 1983, p. 7) have been drilled on or near the WIPP site to study the structure, stratigraphy, lithology, and hydrology of the area. The data for this study are from five of these holes plus one hole drilled for the U.S. Bureau of Land Management (BLM) southwest of the site. Lithologic descriptions of the units penetrated were obtained from cores and cuttings supplemented by interpretation of geophysical logs.

STRATIGRAPHY AND LITHOLOGY OF THE RUSTLER FORMATION, p 3, para 7:

" The Culebra Dolomite Member, a 6 to 9.1 m (20 to 30 ft) thick finely crystalline vuggy dolomite overlies the unnamed lower member. The vugs are diagnostic of the Culebra, and may have been formed by gas bubbles during or shortly after deposition (Vine, 1963, B-14). The vugs in some drill holes contain halite or gypsum. The Culebra is one of two known aquifers in the Rustler Formation near the WIPP site. Mercer (1983, p. 60) suggests that direction of ground-water movement in the fractured Culebra Dolomite is affected by directional differences in hydraulic conductivity (anisotropy), and that the regional direction of flow may show little or no relationship to localized direction of flow. The contours on the potentiometric-surface map (Mercer, 1983, fig. 17) show a southward flow trend in the vicinity of the WIPP site.

p 6, para 4, line 1;

" In drill hole W-21, about 3,505 m (11,500 ft) west of P-10, each of the three halite/anhydrite bearing members show evidence of dissolution and hydration. About half the halite is the unnamed lower member has been removed, and the anhydrite beds are partly converted to gypsum. The halite in the Tamarisk and Forty-niner Members has been completely removed, leaving only silt and clay residue; and much of the anhydrite has been altered to gypsum. The polyhalite bed, represented in drill holes P-10 and P-18, is missing from the Tamarisk member in this hole. Thickening of anhydrite beds as they alter to gypsum is apparent in the Tamarisk and Forty-niner Members (fig. 2). Vine (1963) described a massive siltstone in Forty-niner Member outcrops found west of Livingston Ridge. Jones and others (1960) identified this siltstone as dissolution residue."

p. 8, para. 4;

" An isopach map of the Rustler Formation (fig. 4) shows a general pattern of dissolution of halite and hydration of anhydrite. On the east and progressively westward for about 3.2 km (2 mi) the formation thins. In this area only halite is being removed, generally from the Forty-niner Member. Figure 4 divides the WIPP area into four zones; from east to west they are: (1) no halite dissolved from Rustler Formation, (2) halite dissolved from Forty-niner Member, (3) halite dissolved from Tamarisk Member, and (4) halite dissolved from lower unnamed member. In the first two of these zones the Rustler Formation thins progressively westward, but in the third and fourth zones the formation thins and thickens depending on how much anhydrite has altered to gypsum."

CONCLUSIONS, p. 10;

As one progresses westward across the WIPP site there is both a progressive dissolution of halite and a gradual hydration of anhydrite to gypsum. Seemingly, halite from the uppermost member, the Forty-niner, is removed first, followed by removal of halite from the middle Tamarisk Member, and then finally from the unnamed lower member. The intervening dolomite member are not directly affected by these processes, but as halite is removed from below each of them, the dolomites settle and fracture and transmit ground water more readily. At some stage in the removal of halite, possibly when the dissolution reaches a point where the anhydrites settle and crack allowing ground water to flow through them, the anhydrites begin hydrating to gypsum. This process tends to thicken the formation even though halite is being removed. The mutual interaction between these two processes results in an erratic thickening and thinning of the Rustler Formation as seen on the isopach map (fig. 4).

The increase in transmissivity in the Magenta and Culebra Dolomite Members seems to 'feed upon itself;' fracturing increases as more halite is removed and more anhydrite alters to gypsum, more ground water moves through these aquifers removing more halite and altering more anhydrite. Eventually all the gypsum formed is also removed by dissolution. . . ."

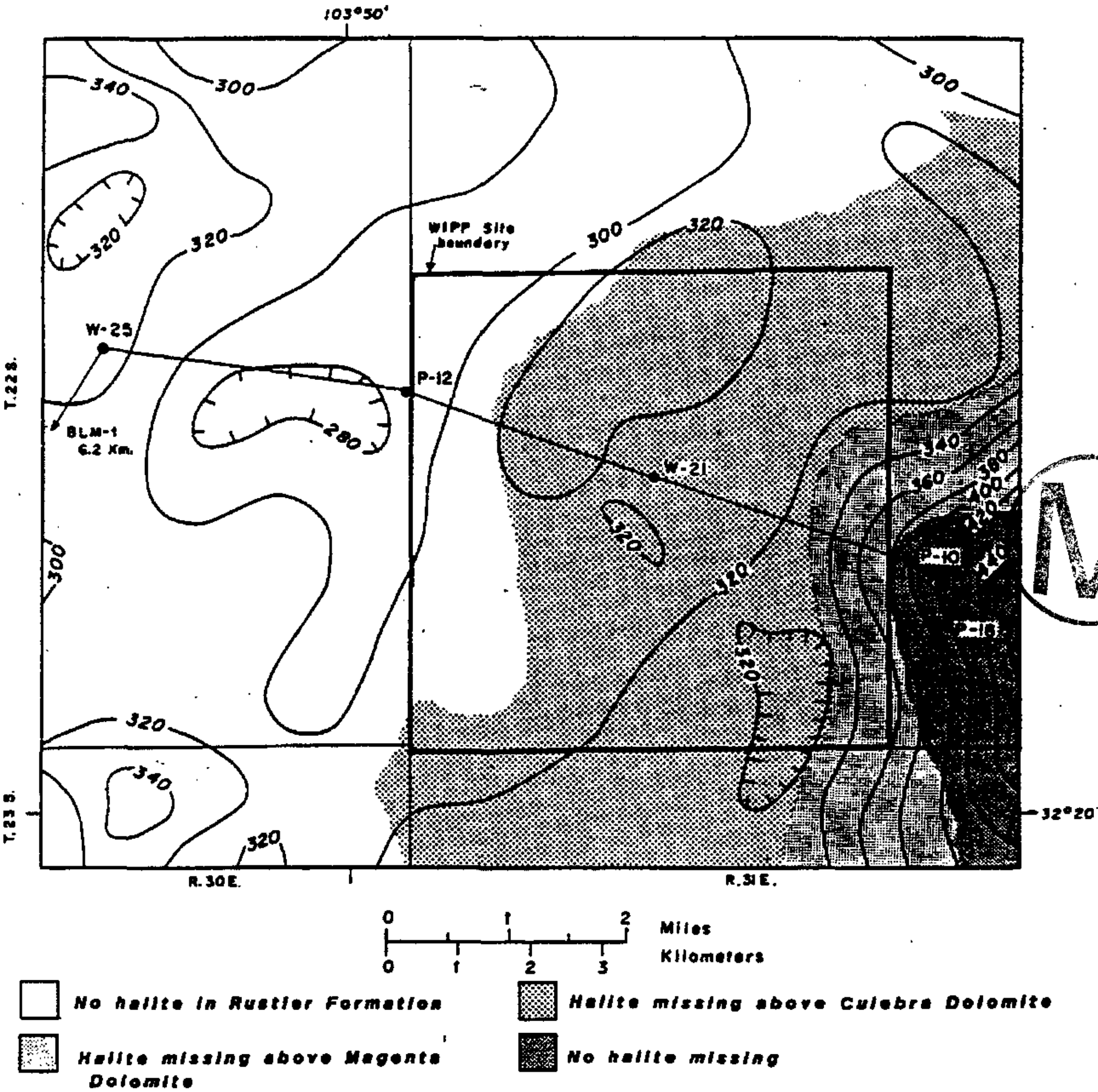


Figure 4.--Isopach map of the Rustler Formation in the vicinity of the WIPP site showing dissolution zones. (Hachures indicate closed lows.)

Snyder, R.P., Gard, Jr., L.M., and Mercer, J.W. 1982. Evaluation of Breccia Pipes In Southeastern New Mexico and Their Relation to the Waste Isolation Pilot Plant (WIPP) Site, With Section on Drill-Stem Tests. Open-File Report 82-968. U.S. Geological Survey, Denver, CO.

INTRODUCTION, p. 1;

" The Waste Isolation Pilot Plant (WIPP) site is located about 40 km (25 mi) east of Carlsbad, N. Mex. (fig. 1). The site geography has been described in detail by Powers and others (1978) and U.S. Department of Energy (1980, 1981). Site selection was based principally on the existence of a thick section of Permian evaporites, mainly halite. The purpose of establishing this site is to demonstrate whether or not an evaporite environment is acceptable for the disposal of trans-uranic waste generated by the Nation's defense programs.

The primary concern regarding safe disposal of nuclear waste is to isolate the waste from the biosphere until it is no longer a danger to mankind. One of the most probable methods of accidental release of radiation from nuclear waste isolated in a geologic medium is leaching and transport of the waste by moving ground water. It is therefore of primary importance to identify any potential channelways that might allow water to enter a repository site located on bedded salt of the Salado Formation of southeastern New Mexico. The presence of the thick Permian (225 m.y.) rocks attests to the fact that major dissolution of the halite by unsaturated ground water has not occurred at the WIPP site.

Focus of Current Study

This report describes several dissolution features in the Delaware Basin and elsewhere that have been referred to as breccia pipes. Breccia pipes (also called breccia chimneys) as they occur in evaporites are vertical cylindrical pipes or chimneys that may or may not involve more than one geologic formation. The chimneys are filled with downward-displaced brecciated rock. In this context, the rock is brecciated by having collapsed into a void at depth that was probably created by ground-water solution and removal of deep-lying evaporite or carbonate rocks in an underlying aquifer system (Anderson and Kirkland, 1980; Bachman, 1980). Such features have been described in evaporite deposits in many areas of the world.

The current study was done for the U.S. Department of Energy (DOE) in response to a suggestion that because breccia pipes are thought to be the result of deep dissolution, they may represent channelways for future ingress of ground water, and that they should be considered in risk assessment programs for the evaluation of proposed waste repositories in bedded evaporite rocks. To this end, features referred to as breccia pipes in southeastern New Mexico have been assessed in relation to the integrity of the WIPP site. Reports by Anderson (1978), Bachman (1980), and Vine (1960) described dissolution and karst features in the Pecos region of southeastern New Mexico and discussed the origin and history of breccia pipes. The present report is intended to supplement these studies and provide detail that was not available to them at the time their reports were written.

Using the data from exploratory work, answers may be found to the following questions concerning breccia pipes:

1. Do breccia pipes penetrate through the evaporite section?
2. What is the physical description of a pipe?
3. How are they formed?
4. How deep do they go?
5. When are they formed, and are they forming at present?
6. Are they permeable?
7. Where are they formed, can they form at the WIPP site?
8. Do they represent a threat to the WIPP site?"

Possible Effect on WIPP Site, p 65;

" Numerous domes and sinks dot the landscape in the Delaware Basin. Some of these features can be shown to be remnants of near-surface dissolution or surface erosion; others are from dissolution and cavity formation in the Capitan Limestone. Known locations where deep dissolution occurs and forms structures called breccia pipes are limited to areas over the buried Capitan reef, no closer than 16 km (10 mi) to the WIPP site. The four known occurrences are Hills A, B, C, and the Wills-Weaver site.

Collapse of these structures, at least to the surface, occurred sometime before 400,000-500,000 years ago.

Locales on and around the WIPP site that were investigated for evidence of pipe formation, with none being found, include the sites of drill holes WIPP 13, WIPP 32, WIPP 33, and WIPP 34. Numerous surface features were mapped and found to be near-surface erosion and dissolution features.

No examples of breccia pipes that could lead to breaching of a repository at the WIPP site have been found to date and are not likely because the Capitan Limestone is not present beneath the site."

Stensrud, W.A., 1995. Culebra Transport Program Test Plan: Hydraulic Tests at Wells WQSP-1, WQSP-2, WQSP-3, WQSP-4, WQSP-5, WQSP-6, and WQSP-6a at the Waste Isolation Pilot Plant (WIPP) Site. On file in the Sandia WIPP Central Files.

1.1 Summary, p. 1;

" This Test Plan describes the purpose, objectives, design, equipment, and methodologies for hydraulic tests to be performed by Sandia National Laboratories (SNL) in seven Water Quality Sampling Program (WQSP) wells at the Waste Isolation Pilot Plant (WIPP) site located in southeastern New Mexico (Figure 1-1). The wells were drilled by the Waste Isolation Division (WID) of Westinghouse Electric Corporation during September and October 1994 to provide locations for long-term water-quality monitoring. The locations of the WQSP wells are shown on Figure 1-2."

Thompson, G.A., and Zoback, M.L. 1979. Regional Geophysics of the Colorado Plateau. Technophysics, Vol. 61, Nos. 1-3, pp. 149-181.

ABSTRACT, p. 149, Para. 2;

" The Colorado Plateau (CP) is a relatively coherent block surrounded on three sides by the extensional black faulted regime of the Basin and Range Province (BRP) and the Rio Grande Rift (RGR). The CP appears to be part of an inter-related system including the Sierra Nevada, BRP, and the RGR which has undergone major uplift and extension during the last 20 m.y. The final elevation in any area probably depends upon which processes dominate there.

In most geophysical properties the CP is intermediate between the BRP/RGR and the stable platform of the southern Great Plains. However, many BRP/RGR geophysical characteristics appear to extend well inward of the classical Plateau physiographic boundary. Geologically these 50-100 km wide zones of transition are marked by normal faulting and late Tertiary and Quaternary volcanism. The interior of the Plateau is characterized by a 40 km-thick crust, a P_n velocity of about 7.85 km/sec, and an average heat flow of 1.5-1.6 HFU. Available data on the modern stress field in the Plateau interior indicate high horizontal stresses and a stress field oriented differently from that in the surrounding BRP/RGR, inconsistent with the theory that the plateau is merely an inherited, more coherent subplate subjected to the same stresses as it's surroundings."

Seismic refraction data, p. 152, Para. 2;

" A major and surprising result emerged from seismic refraction experiments beginning with the work of Tatel and Tuve (1995). Compared to stable regions the crust in the elevated, tectonically active region from the Rocky Mountains to the Sierra Nevada Range is abnormally thin, and upper mantle velocities are anomalously low. Within this region, the crust of the CP is thicker than that of the BRP and RGR, which have been subjected to extentional tectonism; however, the changes in thickness do not everywhere correspond with province boundaries. Currently available refraction data are not adequate to define all the major variations within provinces, especially within CP.

Our profile line (Fig. 2) crosses or passes near only three reversed refraction lines. On the figure we have indicated published sources of data and whether the lines were reversed or unreversed; also measurements projected from off the profile are so indicated. Major conclusions from the data of Fig. 2 are: (1) crustal thickness beneath the CP, about 40 km (measured from sea level), is intermediate between that of the BRP, about 30 km, and southern Great Plains, about 50 km; (2) upper mantle (P_n) velocities are 7.8-7.9 km/sec across most of the BRP, CP, and RGR, in marked contrast to 8.2 km/sec beneath the southern Great Plains; (3) the P_n velocity is lowest, about 7.4 km/sec, in the eastern BRP and through a transition zone of the CP to the limits of normal faults that shred the western edge of the CP; and (4) average upper crustal velocity is significantly greater beneath the CP (6.2-6.4 km/sec) than beneath the BRP and RGR (5.9-6.1 km/sec)."

UNM (University of New Mexico). 1984. A Handbook of Rare and Endemic Plants of New Mexico. New Mexico Native Plants Protection Advisory Committee, eds. University of New Mexico Press, Albuquerque, NM.

PREFACE, p xiii;

" The New Mexico Native Plant Protection Advisory Committee is an *ad hoc* group of professionals in the field of botany, representing the academic community, land managers, and private industry. The committee has served informally at the discretion of the governor, under the direction of the secretary of natural resources of New Mexico since 1977. The New Mexico Natural Heritage Program serves as secretary for the committee.

Although the committee has provided the U.S. Fish and Wildlife Service and the New Mexico Natural Heritage Program with information and advice regarding the status of our rarer plant species, this is the first major work produced as a committee effort.

In compiling data for this book, the committee has attempted to provide a single source of information on rare and endemic plants useful both to land managers and to the general public. Plants covered either are principally found in New Mexico or require special management attention. All plants nominated for protection under the Endangered Species Act are included, regardless of their relative abundance."

U.S. Congress, 1992. Waste Isolation Pilot Plant Land Withdrawal Act. Public Law 102-579, October, 1992. 102nd Congress, Washington, D.C.

"An Act
To withdraw land for the Waste Isolation Pilot Plant, and for other purposes.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,"

SEC.3.LAND WITHDRAWAL AND RESERVATION FOR WIPP.;

" (a)LAND WITHDRAWAL, JURISDICTION, AND RESERVATION.--

(1)LAND WITHDRAWAL.--Subject to valid existing rights, and except as otherwise provided in this Act, the lands described in subsection (c) are withdrawn from all forms of entry, appropriation, and disposal under the public land laws, including without limitation the mineral leasing laws, the geothermal leasing laws, the material sale laws (except as provided in section 4(b)(4) of this Act), and the mining laws.

(2)JURISDICTION.--Except as otherwise provided in this Act, jurisdiction over the Withdrawal is transferred from the Secretary of the Interior to the Secretary.

(3)RESERVATION.--Such lands are reserved for the use of the Secretary for the construction, experimentation, operation, repair and maintenance, disposal, shutdown, monitoring, decommissioning, and other authorized activities associated with the purposes of WIPP as set forth in section 213 of the Department of Energy National Security and Military Applications of Nuclear Energy Authorization Act of 1980 (Pub.L. 96-164; 93 Stat. 1259, 1265), and this Act.

(b) REVOCATION OF PUBLIC LAND ORDERS.--Public Land Order 6403 of June 29, 1983, as modified by Public Land Order 6826 of January 28, 1991, and any memoranda of understanding accompanying such land orders, are revoked.

(c)LAND DESCRIPTION.--

(1)BOUNDARIES.--The boundaries depicted on the map issued by the Bureau of Land Management of the Department of the Interior, entitled 'WIPP Withdrawal Site Map,' dated October 9, 1990, and on file with the Bureau of Land Management, New Mexico State Office, are established as the boundaries of the Withdrawal.

(2)LEGAL DESCRIPTION AND MAP.--Within 30 days after the date of the enactment of this Act, the Secretary of the Interior shall--

(A) publish in the Federal register a notice containing a legal description of the Withdrawal; and

(B) file copies of the map described in paragraph (1) and the legal description of the Withdrawal with the Congress, the Secretary, the Governor of the State, and the Archivist of the United States."

U.S. Department of Commerce. 1980. Census of Population, General Population Characteristics of New Mexico. Bureau of the Census.

ABSTRACT;
" This report is a one page profile for specific single geographic areas giving detailed information of race, sex, age, households, and some housing characteristics. Geographic levels include the nation, states, SMSA'a, counties, and named places with 2,500 or more population. The report profile was developed to serve the information needs of the Employment and Training Administration; however, it can be used to satisfy other Population and Housing data requirements. This report series was prepared from data contained in Summary Tape File 1. This is one of five Summary Tape Files the Census Bureau plans to make available from the 1980 Census. A separate report is available for each state and the District of Columbia. Write to NTIS for price list and order form."

Intorduction, Abstract, p. iv;
" This report is a one-page profile of selected data from Summary Tape File 1 (STF1) of the 1980 Census of Population and Housing for various government units and census desugnated areas. STF1 summarizes only complete-count (100-percent) data items, i.e., responses to questions that were in the short form distributed to the entire United States population. Data items include age, sex, race, Hispanic origin, marital status, household type and household relationship. Housing items include information on occupancy status, tenure, vacancy rate, contract rent, value, number of condominiums, and plumbing facilities."

Introduction, Geographic coverage, p. iv;
" Areas covered by report 1A include:
- The United States
- State or State equivalent
- Standard Metropolitan Statistical Area (SMSA)
- County or County equivalent
- Places with population of 2,500 or more
- Comprehensive Employment and Training Act (CETA) Prime Sponsor Areas"

Report 1A: Population Characteristics, Table: Population and Housing Characteristics, Eddy County, p. 9;
" Population by Race, including Hispanics 47,855"

Report 1A: Population Characteristics, Table: Population and Housing Characteristics, Lea County, p. 14;
" Population by Race, including Hispanics 55,993"

U.S. Department of Commerce. 1990. Census of Population, General Population Characteristics of New Mexico. Bureau of the Census.

INTRODUCTION; p. 1-1, para. 2;

" Data from the 1990 census are presented in several different report series. These series are published under the following three subject titles:

1. 1990 Census of Population (1990 CP)

2. 1990 Census of Housing (1990 CH)

3. 1990 Census of Population and Housing (1990 CPH)

The types of data and the geographic areas shown in reports differ from one series to another. In most series, there is one report for each State, the District of Columbia, Puerto Rico, and the Virgin Islands of the United States (Virgin Islands), plus a United States summary report. Some series include reports for American Indian and Alaska Native areas, metropolitan areas, and urbanized areas. See appendix F for detailed information about the various report series; additional 1990 census data products such as computer tapes, microfiche, and laser disks; other related materials; and sources of assistance

The data from the 1990 census were derived from a limited number of basic questions asked of the entire population and about every housing unit (referred to as the 100-percent question), and from additional questions asked of a sample of the population and housing units (referred to as the sample questions). Two primary versions of questionnaires were used: a short form containing only the 100-percent questions and a long form containing both the 100-percent questions and the additional sample questions. Appendix E presents facsimiles of the questionnaire pages and the respondent instructions used to collect the data included in this report. Appendix F lists the subjects that are covered by the 100-percent and sample components of the 1990 census.

Legal provision for this census, which was conducted as of April 1, 1990, was made in the Act of Congress of August 31, 1954 (amended August 1957, December 1975, and October 1976), which is codified in Title 13, United States Code."

Table 1; Summary of General Characteristics of Persons: 1990; p. 1;

"

COUNTY	All Persons
. . .	
Eddy County	48,605 . . .
Lea County	55,765 . . ."

Vine, J.D., 1963. "Surface Geology of the Nash Draw Quadrangle, Eddy County, New Mexico." U.S. Geological Survey Bulletin 1141-B, U.S. Government Printing Office, Washington, D.C. WPO 29558.

ABSTRACT, p B1;

" Outycropping rocks and surficial deposits of the Nash Draw quadrangle were mapped to provide geologic information for the U.S. Atomic Energy Commission's Plowshare program. The quadrangle is near the north margin of the Delaware basin and about 15 miles east of Carlsbad, N. Mex. The region is sparsely inhabited and has an arid climate.

As much as 4,000 feet of salt and anhydrite of Permian age is present below the surface, but does not crop out in normal thickness in this area or elsewhere because of their high solubility. These rocks have been divided into the Castile formation below and the Salado formation above. Rocks exposed at the surface overlie these soluble rocks and include the Rustler formation of Late Permian age, the Pierce Canyon redbeds of Permian or Triassic age, the Santa Rosa sandstone of Late Triassic age, and the Gatuna formation, caliche, and a variety of unconsolidated deposits of late Cenozoic age.

The Rustler formation of Late Permian age is subdivided into four easily distinguishable members, excluding about 120 feet of the lower part, which is not exposed at the surface in this area. The oldest member exposed is the Culebra dolomite member, about 30 feet thick, identified only in erratically distributed outcrops in collapse areas. The Culebra consists of microcrystalline gray dolomite or dolomitic limestone characterized by numerous spherical cavities 1 to 10 mm in diameter. It is conformably overlain by the Tamarisk member, named herein for exposures directly east of Tamarisk Flat. It consists of about 115 feet of massive gypsum at the surface, changing to anhydrite in the subsurface, and a bed, 5 feet thick, of siltstone near the base. Surficial deformation caused by hydration and solution are characteristic of all the outcrops. The Tamarisk member is conformably overlain by the Magenta member, about 20 feet thick and consisting of alternating wavy laminae of pale-red dolomite and pale yellowish-green anhydrite or gypsum. The top member of the Rustler formation conformably overlies the Magenta and is here named the Forty-niner member after Forty-niner Ridge, where it crops out. In surface exposures it consists of about 40 to 65 feet of broken and slumped massive gypsum and a bed of siltstone in the lower part. The siltstone beds in the Tamarisk and Forty-niner members probably represent the insoluble residue of salt beds reported from the subsurface to the east."

Overlying the Rustler formation with apparent conformity are the Pierce Canyon redbeds of Permian or Triassic age. These rocks consist of about 200 to 250 feet of laminated or minutely cross-laminated moderate reddish-brown siltstone. The contact between the Pierce Canyon redbeds and the overlying Santa Rosa sandstone is a disconformity, at least locally.

The Santa Rosa sandstone of Late Triassic age consists of pale-red sandstone and conglomerate lenses crossbedded in sets 3 to 15 feet thick separated locally by moderate reddish-brown siltstone and claystone. Only the lower 50 to 70 feet of Santa Rosa was recognized in the area.

The Gatuna formation of Pleistocene (?) age unconformably overlies all older rocks. In much of the area it consists of 3 to 5 feet of moderate reddish-orange sandstone, siltstone, and conglomerate. Locally, in karst depressions, the Gatuna attains a thickness of at least 100 feet. In some areas the lithology closely resembles the Pierce Canyon redbeds or the Santa Rosa sandstone.

Caliche forms a resistant layer at the ground surface, 5 to 10 feet thick, that protects older rocks from erosion in many areas. The caliche consists of calcareous material with a variable amount of imbedded sand grains, pebbles, and rock fragments. Caliche mounds and broken flexure ridges, 10 to 15 feet high, have formed narrow zones 50 to several hundred feet long.

Quaternary alluvium has been deposited along the sides of depressions. It is overlain by playa lake deposits, which are in turn overlain by conspicuous sand dunes as much as 100 feet high.

The regional structure is relatively simple and consists of a dip of a few feet per mile to the east and southeast.

Normally flat-lying strata are tilted, warped, and locally distorted at the surface by hydration and solution of the evaporite rocks in the subsurface. Nash Draw, a depression 4 to 6 miles wide and about 18 miles long, has resulted from the solution of salt in the Rustler and Salado formations and collapse of the overlying relatively insoluble rocks. Topography and surface structure conform in some areas with the configuration of the underlying solution surface at the top of the massive salt in the Salado formation; however, locally there is an inverse correspondence. Many circular karst features 1/10 to 1/2 mile in diameter are in the area. Some of these features are structural domes, but they contain a core of tilted or brecciated rock. These karst features result from the formation and collapse of sinkholes, differential solution at the top of the massive salt, and hydration of the anhydrite beds."

p B14, para 2, line 4;

" Overlying the lower part is the Culebra dolomite member, consisting of about 30 feet of uniformly fine textured microcrystalline gray dolomite or dolomitic limestone. Adams (1944, p 1614) credits W. B. Lang with naming the Culebra for Culebra Bluff on the east side of the Pecos River, about 4 miles northeast of Loving. The rock is characterized by numerous small nearly spherical cavities that range from about 1 to 10 mm in diameter. These cavities are present both in surface exposures of the Culebra and in core taken from the AEC drill hole 1 and therefore are presumed to be either a primary or a diagenetic phenomenon and not related to surface weathering. Some of the cavities are partly filled with secondary gypsum or calcite, but most are open. There seems to be little or no tendency for the cavities to be connected, as might be expected if they were formed by solution in a homogeneous rock. These features suggest that they were formed by the solution of a highly soluble mineral aggregate or by the inclusion of a gas or liquid at the time the sediment was soft. Locally, the Culebra is finely oolitic, and the individual oolites are less than 0.5 mm in diameter.

Exposures of the Culebra dolomite member are in the southern part of the Nash Draw quadrangle, east of Salt Lake where the rocks are locally deformed by solution collapse, which has caused the outcrop pattern to be irregular. The Culebra outcrops are brecciated locally. For this reason the Culebra was not seen in normal stratigraphic sequence with the underlying and overlying rocks in the Nash Draw quadrangle.

Overlying the Culebra dolomite member is the Tamarisk member of the Rustler formation. The Tamarisk consists of about 115 feet of massive gypsum in exposures but is chiefly anhydrite and locally gypsum in the subsurface, except for a bed 5 feet thick, of siltstone about 20 feet above the base. The siltstone is thought to represent the insoluble residue from a halite bed in the subsurface (Jones and others, 1960, fig. 1). This member forms a broad expanse of barren outcrop 2 to 3 miles wide and about 7 miles long east of Tamarisk Flat, from which the name is here taken."

SANTA ROSA SANDSTONE OF TRIASSIC AGE, p B25, para 3;

" The Santa Rosa sandstone disconformably overlies the Pierce Canyon redbeds. Only the lower 50 to 70 feet of the Santa Rosa sandstone is present in the northern and northeastern part of the Nash Draw quadrangle and therefore the total thickness of the formation could not be determined. In general, the Santa Rosa consists of large-scale trough-type crossbedded pale-red sandstone and conglomerate lenses, 3 to 15 feet thick, separated by thin partings of moderate reddish-brown siltstone and silty claystone (fig. 12). The conglomerate lenses contain both silty dolomite pebbles and chert or quartz pebbles. The sandstone is characteristically poorly sorted. The formation differs from the underlying Pierce Canyon redbeds by being coarser grained, less well sorted, and by having beds that are thicker and more lenticular."

GATUNA FORMATION OF PLEISTOCENE (?) AGE, p B27, para 6;

" The Gatuna formation unconformably overlies the Permian and Triassic rocks in the quadrangle, except where it has been removed by erosion. In most of the area the Gatuna formation is only about 3 to 5 feet thick and is directly overlain by Recent caliche that is more resistant than the Gatuna and masks the underlying rocks. Therefore, except where the Gatuna is thick or forms a broad enough exposure to map separately, it is shown together with the caliche on the geologic map (pl. 1). In general, the Gatuna formation consists of moderate reddish-orange friable sandstone, siltstone, and conglomerate, but locally includes gypsum, gray shale, and claystone. The Gatuna is as much as 100 feet thick locally."

GEOMORPHOLOGY, p. B38, para. 2, line 5;

" At least locally, the rocks exposed along the margins of Nash Draw exhibit dips in toward the center of the topographic depression, contrary to a structural picture consistent with an anticline (fig. 11). The structure of the marker beds within the Salado formation as revealed by well records indicates a gentle homoclinal structure (pl. 1). The anomalous dips seen in surface exposures are interpreted to represent surficial deformation later than the tectonic structures as a result of collapse into the Nash Draw depression. Nash Draw is, therefore, thought to be an undrained physiographic depression superimposed over a gentle homoclinal structure. The depression probably resulted from regional differential solution of beds in the upper part of the Salado formation. Nash Draw is separated by a gentle divide area from a large depression to the north called Clayton Basin.These depressions are probably similar in origin to the solution-subsidence troughs of the Gypsum Plain in southern Eddy County, N. Mex., and adjacent parts of Texas, described by Olive (1957). However, the solution-subsidence troughs of Olive are more regular in outline, smaller, and are formed in the Castile formation.

In the northern part of Nash Draw, bedrock is largely covered by a mantle of windblown sand, dunes, caliche, and alluvium. In the central and southern part of Nash Draw however, the Rustler formation is highly deformed in outcrops. The deformation is thought to be due primarily to large-scale collapse of the Rustler formation as a result of solution within the anhydrite, gypsum, and halite beds of the Rustler, and at the top of the Salado formation. Evidence for solution within the Rustler can be found almost everywhere that it is exposed. Sinkholes of all sizes abound in the Rustler formation, ranging from small cavernous joints that trap unwary livestock to large shallow depressions, partly filled with alluvial or playa deposits but commonly with identifiable sinks within the depressed area (fig. 13). Where dips in the Rustler can be determined, they are generally in the direction of the larger depressions. In plan, these depressions range from small circular features a few tens or hundreds of feet across to large irregular, or arcuate, features more than a mile across. Many of the larger depressions, including the basin that holds Salt Lake, are probably formed by the coalescing of smaller ones. Some of the depressions tend to line up. These may indicate the probable location of subterranean cavernous water courses."

p. B40;

" Areas of rock deformation that are circular or semicircular in plan and range from a few hundred to a few thousand feet in diameter are a common form of solution or karst feature in this area. Sedimentary strata including caliche are well exposed on the flanks of some of these features and dip away from the center giving them the appearance of structural domes. Generally, such domes contain a core of brecciated or randomly rotated rack that has been displaced downward with respect to the flanking rock. Typically the brecciated rock in the core is overlain by a greater thickness of the Gatuna formation than is present in the adjacent areas. The core of brecciated rock and Gatuna overlain by an unknown arch of caliche on several of these features, which suggests that the brecciation predates the deposition and doming of the caliche. The breccia probably formed as a result of collapse into a sinkhole. Examples of several well-exposed domes directly north of the Nash Draw quadrangle have been described in a separate report (Vine, 1960)."

Weart, W.D., 1983. Summary Evaluation of the Waste Isolation Pilot Plant (WIPP) Site Suitability. SAND83-0450. Albuquerque, NM: Sandia National Laboratories.

p. 9, col. 2, para. 3;

" The WIPP site investigations have been guided by an established set of site selection criteria.[2] These criteria, and the factors that address the criteria, are listed in this section. The criteria are broad statements of desired conditions and must be addressed in practice by identifying and quantifying pertinent site factors. When this has been done, a judgment can be made on how well the criteria are satisfied. The basic criteria listed below are from the WIPP GCR;[2] more specific site evaluation factors are from the Site Validation Program document.[5]

p. 10;

"

Listing of Site Criteria and Qualification Factors

Site Criteria

Geologic Criterion--The geology of the site will be such that the repository will not be breached by natural phenomena while the waste poses a significant hazard to man. The geology must also permit safe operation of the WIPP.

Hydrology Criterion--The hydrology of the site must provide high confidence that natural dissolution will not breach the site while the waste poses a significant hazard to man. Accidental penetrations should not result in undue hazards to mankind.

Tectonic Stability Criterion--Natural tectonic processes must not result in a breach of the site while the wastes represent a significant hazard to man and should not require extreme precautions during the operational period of the repository.

Physical-Chemical Compatibility--The repository medium must not interact with the waste in ways which create unacceptable operational or long-term hazards.

Economic/Social Compatibility Criterion--The site must be operable at reasonable economic cost and should not create unacceptable impact on natural or the biological/sociological environment.

The specific site qualification factors which must be examined in order to assess how well these criteria are fulfilled are listed as follows.

Site Qualification Factors (Criteria)[5]

1.0 Topography

The site must:

1.1 Permit access for transportation.

1.2 Possess relief low enough to avoid significant differences in lithostatic stress at waste disposal level.

1.3 Preclude inundation from surface floods.

2.0 Depth

The waste disposal horizon must be:

2.1 Deep enough to remain below the influence of surficial phenomena (infiltration of surface waters, erosion/denudation).

2.2 Within the depth where lithostatic stresses will not produce excessive rock deformation rates.

3.0 Thickness of Host Rock

The thickness of waste disposal host rock must be sufficient to:

3.1 Provide a thermal and mechanical buffer zone above and below the facility.

4.0 Lateral Extent

The lateral extent of the waste disposal host rock must be sufficient to:

4.1 Provide the required lateral continuity and distance from the disposal facility to structural or erosional breaches or dissolution boundaries.

5.0 Lithology

The lithology of the waste disposal host rock must:

5.1 Be relatively low in brine content with respect to any horizon selected for heat-producing waste experiments.

5.2 Be relatively pure mineralogically to reduce the chemical interaction which must be considered.

6.0 Stratigraphy

6.1 The individual beds of rock in the disposal zone must be continuous enough to permit location of the facility at essentially one stratigraphic horizon.

6.2 The location and characteristics of interbedded materials, such as clay, must not preclude construction of stable excavations nor provide transport pathways which would significantly reduce the containment capacity of the waste disposal rock.

7.0 Structure

7.1 The site shall be free of active or capable faults.

7.2 The dips of strata at the disposal level shall not exceed the acceptable grade for excavations unless the stratigraphy/lithology allow construction of the disposal facility in beds either side of the selected horizon.

8.0 Dissolution

8.1 The disposal horizon must be free and remain free from dissolution for at least 10,000 years, based upon rates of dissolution determined from an assessment of previous rate of dissolution.

9.0 Subsidence

9.1 Subsidence caused by dissolution or mining should be avoided if it adversely affects the waste facility.

10.0 Surface Water

10.1 The site must be free of flooding hazard which could affect unplugged penetrations to the waste facility.

11.0 Groundwater

11.1 Facility and related shafts must not adversely affect existing aquifers which are, or could be, sources of water supply for humans or animals.

11.2 The underground facility must be able to be isolated from waterbearing strata and must not, itself, be located in a water-bearing stratum (stratum which will yield water to a drillhole under the influence of gravity alone).

11.3 The hydraulic conductivity of the facility stratum must be sufficiently low (10^{-6} cm/sec or less) to prevent flow of water through that stratum from any source which could develop after facility construction.

11.4 Calculated hydrologic transport of radionuclides through the waste disposal facility and overlying strata must be slow enough that a significant hazard to humans would not exist even if the disposal stratum were breached.

12.0 Tectonic Stability

12.1 The magnitude of maximum historical seismic events must demonstrate a low seismic risk to the site.

12.2 Major faults and pronounced linear structural trends should be avoided.

12.3 Major flow structures (anticline) should be avoided or evaluated for presence of brine.

12.4 Diapirism will be avoided for WIPP siting.

12.5 Areas of active regional uplift or subsidence should be avoided.

12.6 Areas of active or recent volcanism or igneous intrusion should be avoided.

12.7 Areas of high geothermal gradient should be avoided.

13.0 Physical-Chemical Compatibility

13.1 The disposal stratum should not contain more than 3% water content.

13.2 Beds of unusual composition and/or containing minerals with bound water should not occur within 20 feet of the waste horizon.

13.3 The mineralogy of the disposal horizon rock must not be chemically reactive with the waste or waste packages in a way that will reduce the effectiveness of the rock as a barrier to nuclide transport.

13.4 Radiation effects must not compromise the effectiveness of the disposal horizon rock as an enclosing medium.

14.0 Natural Resources

14.1 The site should be located so that losses of natural resources are reduced to acceptable levels, which shall be determined by the value of the resources and alternative sources of those commodities.

15.0 Man-Made Penetrations

15.1 Boreholes or shafts which penetrate through the disposal level to underlying aquifers should be at least 1 mile from the facility.

16.0 Transportation

16.1 Transportation routes should be capable of satisfying transport needs to the site with ready development. Transportation routes should avoid population centers as much as possible.

17.0 Accessibility

17.1 The site should be readily accessible for transportation and utilities.

18.0 Land Acquisition

18.1 The site should be located on federal land to the greatest extent possible.

19.0 Population Density

19.1 The site should be located in a low population area.

20.0 Ecological Effects

20.1 The site should not contain ecological conditions, the disruption of which is irreversible or uncontrollable due to construction or operation of the facilities.

20.2 Archaeological and historical features of significance should be preserved.

21.0 Sociological Impacts

21.1 Construction and operation of the facility at the selected site should not create unmanageable impacts on local governmental, educational, or social institutions.

Before discussing the WIPP site in relation to these criteria, a few comments are in order.

- First, very few of the qualification factors, by and of themselves, disqualify a site. The reason is that assurance of waste isolation relies on the synergy of many factors; one (or a few) unsatisfied factor can often be adequately compensated for by other favorable factors. Only an unsatisfied factor that clearly leads to failure of isolation or that is in opposition to DOE policy would result in *a priori* site rejection. For the same reason it is usually inappropriate to establish quantitative limits for the site factors. These factors may be considered as favorable or unfavorable, or as sufficient but perhaps not necessary for site acceptability.
- Second, these factors were prepared at a time when the WIPP mission considered the possibility of HLW disposal and therefore had to include the aspects important to long-term irradiation and to high-temperature effects. These factors, while they will be addressed (and identified), do not apply to TRU waste isolation.
- Finally, these factors were developed and are worded to apply to sites in the bedded salt of the Delaware Basin. Without omitting any of the generic guideline aspects, they are specific to the WIPP geologic and geographic environment. WIPP siting factors should not be applied to other locations and to other geologic settings. The recently published DOE Draft Siting Guidelines,[47] which apply only to siting of commercial HLW repositories, have been examined; the WIPP siting factors are consistent with these guidelines in scope and intent."

p. 27, col. 1, para 5;

"Conclusions Regarding Site Suitability

The preceding discussion has considered all of the site qualification factors that have been identified for the WIPP. Most of these factors are clearly satisfied by the WIPP site and engender little debate. Some of the factors and their associated aspects are more contentious and have required extensive investigation and study to allow reasoned technical judgments. In the opinion of the Sandia WIPP geotechnical staff, well-supported judgments can now be made on all the relevant issues.

It is important to realize that an attempt to understand complex geological processes may not result in absolute proof of any one hypothesis. A hypothesis may be ruled out if observed data clearly refute it, but more often a hypothesis is adopted because it best explains the observations and presents fewer conflicts with the evidence. Also, it is often virtually impossible to prove a negative hypothesis with respect to some of these geologic issues. For example, it is not practicably possible to *prove* that a large area in the basin does not contain an incipient breccia pipe or a brine reservoir; the argument is always that they may be just too small for geophysics to detect; or they may have been missed by the latest exploratory hole. The best, most meaningful approach to ruling out negative features is to establish a preferred hypothesis for their origin and then to show that the area in question does not possess the requisite characteristics to satisfy the hypothesis. Likewise, hypotheses may sometimes be ruled out if they require conditions that can be shown not to exist. Occasionally one may be left with two or more hypotheses, and a professional judgment is the only way of arriving at a preferred position. For this reason, opinions may sometimes differ among technically competent scientists. For the same reason, the various state and federal technical review groups have been important in providing an independent, unbiased judgment on the various hypotheses that are offered to explain the observations.

It is the judgment of Sandia National Laboratories that the WIPP site fulfills the intent of all the site qualification factors. Sandia recommends, without reservation, the use of the Los Medaños site for the WIPP."

Westinghouse Electric Corporation. 1991A. Waste Isolation Pilot Plant Groundwater Monitoring Program Plan and Procedures Manual. WP02-1. Westinghouse Electric Corporation, Waste Isolation Division, Carlsbad, NM.

FOREWORD, p xi;

" This document is the controlling document for the Waste Isolation Pilot Plant (WIPP) Groundwater Monitoring Program (GMP). The GMP is being conducted as part of the WIPP Operational Environmental Monitoring Program (OEMP), by the Environmental Monitoring (EM) section of the Regulatory and Environmental Programs (REP) department.

This document is a quality assurance project plan (QAPjP) applying to WID environmental data operations (EDOs). As such, its purpose is to define the applicability of the WID quality management system, as described in WP 13-1, to the specific technical activities described within the scope of this plan. Implementation of this plan shall be in accordance with, and subject to the requirements of the quality assurance requirements as prescribed in WP 13-1. Independent assessment of the effectiveness of the activities described in this plan shall be scheduled and performed by the WID Q&RA Department."

Westinghouse Electric Corporation. 1991B. Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 1990. DOE/WIPP 91-008. Westinghouse Electric Corporation, Waste Isolation Division, Carlsbad, NM.

PREFACE;

" This is the seventh Annual Site Environmental Report for the U.S. department of Energy, Waste Isolation Pilot Plant (WIPP). The most significant addition to the 1990 report is the inclusion of the Annual Water Quality Data Report which addresses groundwater surveillance at the WIPP. The Water Quality Report was previously issued as a separate document. The combination of these two reports allows readers to have all environmental monitoring information consolidated together for an easy reference. . . ."

Westinghouse Electric Corporation. 1992. Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 1991. DOE/WIPP 92-007, Westinghouse Electric Corporation, Waste Isolation Division, Carlsbad, NM.

Section 1.3.1 Airborne Particulate and Effluent Monitoring; p 1-4;

" Sampling airborne aerosol particulates was initiated in 1985 and is an important subprogram of the OEMP. The Final Safety Analysis Report (FSAR) (DOE, 1990) identifies the atmosphere pathway as the only credible release pathway resulting in a potential dose to the public. Continuous particulate aerosol samplers operate at eight locations, three within 1000 meters of the facility boundary, four at local ranches and communities, and one at a sample control site.

The continuous aerosol samplers presently being utilized maintain a regulated flow rate of approximately 950 milliliters per second (two cubic feet per minute) of air through a 47-millimeter 1.9 inch) fiber filter for particulate collection. Particulate filters were collected weekly at all locations in 1991. The collected filters were counted at the Environmental Counting Laboratory at the WIPP, where the gross alpha and gross beta activities of each filter were calculated yielding weekly and quarterly averages for each location. Table 5-1 of Chapter 5 of this document lists the quarterly alpha and beta concentrations for each sampling location."

CHAPTER 6 ENVIRONMENTAL NONRADIOLOGICAL PROGRAM INFORMATION, p 6-1;

" This program is described in the OEMP (DOE/WIPP 88-025) for the WIPP. This plan defines the scope and extent of the WIPP effluent and environmental monitoring programs and quality assurance and quality control programs during the operational life of the facility. Nonradiological Environmental Surveillance (NES) is conducted by the Environmental Monitoring Section of the Environment, Safety, and Health department. This program was preceded by the WIPP Biology Program (1975-1982), which combined scientific and technical expertise from six universities to develop an extensive baseline of information describing the major components of the Los Medanos ecosystem prior to the initiation of WIPP construction activities. The principle functions of the NES are:

- To detect and quantify the impacts of construction and operational activities at the WIPP on the surrounding ecosystem
- To continue the development of the ecological data base for the Los Medanos Area which was initiated by the WIPP Biology Program
- To investigate unusual or unexpected elements in the ecological data bases
- To provide environmental data that are important to the mission of the WIPP project, but which have not or will not be acquired by other programs

This section of the ASER presents and discusses data collected between January 1, 1991, and December 31, 1991, as part of the NES of the OEMP. Ecological monitoring at the WIPP includes five subprograms (1) meteorological monitoring, (2) air quality monitoring, (3) water quality monitoring, (4) wildlife population monitoring, and (5) surface disturbance monitoring through the analysis of aerial photographs. The salt impact studies include three subprograms: soil chemistry, soil microbial activity, and vegetation. The results of the environmental monitoring activities and discussions of significant findings are presented in this report.

Unless otherwise noted, all methods used in data collection are those described in the first Ecological Monitoring Program semiannual report (DOE/WIPP 86-002) with the modifications described in subsequent ASER reports (Fisher et. al., 1985; Fisher, 1987; Fisher, 1988; Jones et al., 1989, 1990). . . ."

Westinghouse Electric Corporation. 1993. Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 1992. DOE/WIPP 93-017, Westinghouse Electric Corporation, Waste Isolation Division, Carlsbad, New Mexico.

Introduction, para 2;
"   This report provides a comprehensive description of environmental activities at the WIPP during CY 92. These activities are described in the Operational Environmental Monitoring Plan for the Waste Isolation Pilot Plant (i.e. DOE/WIPP 88-025). This plan defines the scope and extent of the WIPP effluent and Environmental Monitoring Programs during the pre-operational life of the site."

Westinghouse Electric Corporation. 1994. Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 1993. DOE/WIPP 94-2003. Westinghouse Electric Corporation, Waste Isolation Division, Carlsbad, NM.

INTRODUCTION, 1.1 BACKGROUND, p 1-2, para 2;

" A significant development during the construction phase was the promulgation of environmental standards for the management and disposal of TRU wastes by the U. S. Environmental Protection Agency (EPA) (EPA, 1985). In addition, the EPA ruled that facilities that manage radioactive mixed waste are subject to the regulations implementing the Resource Conservation and Recovery Act (RCRA)(U.S. Congress, 1976).

In October 1992, through the WIPP Land Withdrawal Act (LWA), Public Law 102-579 (U.S. Congress, 1992), Congress transferred jurisdiction of the land from the U.S. Bureau of Land Management to the DOE and reserved the land for the use of the DOE for the WIPP Program. The LWA also provided additional authorization to continue the activities initiated by Public Law 96-164. The LWA requirements (Sec. 6) focus on the test phase and the criteria for certification of compliance with the long-term disposal regulations developed by EPA (Sec. 8). While the Test Phase will not be conducted, many requirements such as the development of certification criteria by the EPA, and other requirements necessary to begin disposal are still applicable. For example, the LWA also requires periodic recertification and verification of continuing compliance with applicable regulations during disposal operations.

The LWA and its provisions are as central to regulatory compliance as are the regulations themselves in that the LWA mandates certain schedules, reviews, approvals and limitations. As a result, an updated flexible regulatory compliance strategy that more fully integrates WIPP Project elements and ensures the sufficiency of information to document compliance is needed. This flexible compliance strategy is also necessary to ensure that the WIPP can accommodate the changing TRU waste inventory resulting from increased decommissioning and decontamination of facilities, environmental restoration activities, the dismantlement of weapons, and newly generated TRU waste that will result from treatment of low level wastes. . . ."

1.2 PURPOSE, p 1-4;

" The primary purpose of this document is to provide a strategy by which the WIPP will demonstrate its ability to perform as a deep geologic repository. To achieve this, the document will: (1) communicate to WIPP Project participants, regulatory agencies, and other stakeholders, the DOE's understanding of the regulations related to long-term repository performance; and (2) provide the most efficient strategy that a) integrates WIPP Project elements, b) ensures the sufficiency of information, and c) provides flexibility for changes in the TRU waste generation system to facilitate disposal of defense-generated TRU wastes.

In addition, this document forms a focal point between the DOE and its various external regulators as well as other stakeholders for the purpose of arriving at compliance decisions that consider all relevant input.

- As a compliance strategy that integrates WIPP Project elements, it will enhance mutual understanding between the DOE, its contractors, and its stakeholders resulting in a cost effective and environmentally sound disposal decision.
- As a flexible strategy to accommodate changes in the TRU waste system, it will assure that WIPP's stakeholder's interest are represented in the decision-making process that affects the future of the TRU waste system.
- As a compliance strategy that ensures sufficiency of information, it will foster discussions between DOE, its contractors, and its stakeholders regarding the data used to support a technically sound disposal decision."

Westinghouse Electric Corporation. 1995 Waste Isolation Pilot Plant Site Environmental Report for Calendar Year 1994. DOE/WIPP 95-Draft-2094. Westinghouse Electric Corporation, Waste Isolation Division, Carlsbad, NM.

PREFACE, p. xvi;

" This is the eleventh Annual Site Environmental Report (ASER), documenting the progress of environmental programs at the U.S. Department of Energy (DOE) Waste Isolation Pilot Plant (WIPP).

Although the cancellation of the Test Phase, during 1993, was a significant change in work scope for the WIPP< there are still numerous environmental monitoring and reporting activities that must be performed as a routing part of daily operations. These activities, and the WIPP's ability to demonstrate compliance with both state and federal environmental compliance requirements, are documented in this report.

This report is a compilation and summarization of environmental data collected at the WIPP site during the calendar year 1994. Should a reader of this report desire to obtain copies of the raw data used to generate this document, please write the U.S. Department of Energy, Manager of the Environment, Safety and Health Department, at P.O. Box 3090, Carlsbad, NM, 88221."

Wolfe, H.G. et al., eds. 1977. An Environmental Baseline Study of the Los Medanos Waste Isolation Pilot Plant (WIPP) Project Area of New Mexico: A Progress Report. SAND77-7017. Sandia National Laboratories, Albuquerque, NM.

INTRODUCTION, p 11;

" Sandia Laboratories, Albuquerque, New Mexico, has been conducting exploratory drilling operations for a Waste Isolation Pilot Program (WIPP) in southeastern New Mexico for a year. (See Fig. 1-1 and 1-2.)

Prior to the establishment of such a program, Sandia Laboratories initiated an environmental study to serve as a baseline for evaluation of the impact of their future activities in the Los Medaños area. Much of this area has been influenced by human activities over a long period; consequently, the baseline data does not reflect pristine conditions but rather the present, relatively disturbed condition of the environment. This study thus presents a description of the present level of human impact.

Sandia contracted for this study with the New Mexico Environmental Institute (NMEI). This progress report presents the preliminary results of the study conducted from August 1975 to April 1976 by NMEI."

Wood, B.J., Snow, R.E., Cosler, D.J., and Haji-Djafari, S. 1982. Delaware Mountain Group (DMG) Hydrology -- Salt Removal Potential, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico. TME 3166. U.S. Department of Energy, Albuquerque, NM.

INTRODUCTION AND SUMMARY, p. 1;

" This report provides an account of studies performed to evaluate the potential for salt dissolution in the Castile Formation, removal of dissolved salt by fluids in the Bell Canyon aquifer within the Delaware Mountain Group (DMG), and the potential impact of this process on the long-term integrity of the Waste Isolation Pilot Plant (WIPP) facility.

The results of this study provide responses to the stipulated agreement of July 1, 1981 with the U.S. Department of Energy (DOE) and the state of New Mexico regarding the DMG hydrologic investigation. This study was performed and this report prepared by D'Appolonia Consulting Engineers, Inc. (D'Appolonia), under Subcontract S9-CJR-45451 with Westinghouse Electric Corporation, Advanced Energy Systems Division, under Contract DE-AC04-78-ET05346 with the DOE. The Westinghouse team is serving as the Technical Support Contractors (TSC) to the DOE for the WIPP project. ..."

Section 5.3 Implication of Dissolution on the Underground WIPP Facility, p 100, para 2, line 11;

" As indicated above and discussed in detail in Section 5.1, the average dissolution rate may be anticipated to result in a cavity at the Halite I horizon throughout the Delaware Basin of less than 10 centimeters in 10,000 years, provided mechanisms such as creep do eliminate or retard development. The underground WIPP facility is more than 400 meters above the Halite I horizon. Based on the physical phenomena associated with development, support, and stabilization of a solution cavity, a dissolution zone of 10 centimeters cannot be anticipated to have an effect on the site integrity."

Zoback, M.L., and Zoback, M.D. 1980. "State of Stress in the Conterminous United States." Journal of Geophysical Research, Vol. 85, No. B11, pp. 6113-6156.

Southern Great Plains, p. 6134, col. 2, para. 3;

" The southern Great Plains area is characterized by a very uniform state of stress in which the least principal horizontal stress direction to NNE-SSW. The data come from two primary sources: (1) alinement of post-5 m.y. volcanic feeders in the Raton-Clayton volcanic field of northern New Mexico and (2) fracture orientations obtained from hydraulically fractured wells in the Permian basin of western Texas [*Zemanek et al.,* 1970]. An earthquake focal mechanism and in situ stress measurements in eastern Colorado show consistent orientations. Despite the similar least principal horizontal stress orientations in the southern Great Plains and in the plateau interior, the probable extensional regime (as inferred from earthquake focal mechanisms and basaltic volcanism) distinguishes the southern Great Plains from the Colorado Plateau interior and Midcontinent provinces which are dominated by compressional stress regimes. The least principal horizontal stress directions to the southern Great Plains province are generally oblique to those in the Midcontinent stress province; however, in west-central Texas the data suggest a counter-clockwise rotation of the stress field from west to east to directions more consonant with midcontinent stress orientations (Plates 1 and 2). The easternmost site of this group of data (TX-15) is a normal fault focal mechanism, suggesting that the boundary with the compression-dominated Midcontinent stress province must lie further to the east.

Two important characteristics of the stress field in the southern Great Plains province are (1) its uniformity ($\sim \pm 15°$, which is within the range of estimated accuracy of the different stress indicators) over a region with a north-south extent of at least 1100 km and (2) an abrupt transition in stress orientation in relation to the Rio Grande rift that occurs locally over a lateral distance of <50 km. this $\sim 90°$ change in least principal horizontal stress orientation along the Rio Grande rift-Great Plains boundary corresponds to a decrease in heat flow and a crustal and lithospheric thickening under the Great Plains in relation to the Rio Grande rift [*Thompson and Zoback,* 1979]. IN addition, seismic reflection profiling across the Rio Grande rift's eastern boundary [*Brown et al.*, 1979] has revealed a high-angle, narrow, linear zone defined by a lack of coherent reflections which extends from near the surface to the base of the crust. Physically, this sharp boundary may mark a zone of lateral 'decoupling' within the crust facilitating the abrupt change in stress orientation."

Zoback, M.L., Zoback, M.D., Adams, J., Bell, S., Suter, M., Suarez, G., Estabrook, C., and Magee, M. 1991. Stress Map of North America. Continent Scale Map CSM-5, Scale 1:5,000,000. Geological Society of America, Boulder, CO.

EXPLANATION, sheet 1 of 4;

" This map plots modern maximum horizontal stress (SHmax) orientations for North America inferred from a variety of geophysical and geologic data. These data are described and discussed in the companion DNAG Neotectonics of North America volume (Slemmons, D. B., and others, 1990). A brief description of the various stress indicators is given in the Legend to the right and further details can be found in Zoback and Zoback (1990) and Zoback and others (1990). The center symbol of the oriented lines on the map indicates the type of stress indicator and the length of the lines is scaled proportional to quality as described in the table below. Only A-C quality data are shown on the map, D quality data are retained in the database but are not generally considered to be reliable stress indicators (Zoback and Zoback, 1990; Zoback and others, 1990). Color is used to describe stress regime or style of faulting in terms of relative stress magnitudes (see Legend); SHmax=maximum horizontal stress direction, Sv=vertical stress, and SHmin=minimum horizontal stress direction.

The data are plotted on the DNAG base prepared by the U. S. Geological Survey (Transverse Mercator projection, 1:5,000,000, central meridian 100 deg. W). Continental topography is represented by contours of average topography (250 m contour interval) and was computed using the global digital topography data set (Report MGG-2, National Geophysical Data Center, NOAA, Boulder, CO 80303-3328. The 1° topography data were interpolated and resampled on a 50 km x 50 km grid and were then smoothed using an upward continuation filter (to 15 km) commonly used for potential field data. Bathymetric contours are in corrected meters (Carter's Echo-sounding correction, 3rd ed., 1980). and were derived from U.S. Navy gridded bathymetric data base 'DBDB-5' (5' X 5' grid, 1984) by Peter W. Sloss, National Geophysical Data Center.

All data shown on this map have been released as part of the Geophysics of North America data set available on CD-ROM from the National Geophysical Data Center (NGDC), Boulder, CO 80303-3328. An updated and more detailed release of the data is scheduled in early 1991 by NGDC (World Stress Map Dataset).

The data on the map come from a variety of sources. Individuals responsible for data compilation are listed by region together with references to publications describing the data of the region: . . ."

Zoback, M.D., and Zoback, M.L. 1991. "Tectonic Stress Field of North America and Relative Plate Motions." In Neotectonics of North America, D.B. Slemmons, E.R. Engdahl, M.D. Zoback, and D.D. Blackwell, eds., pp. 339-366. Geological Society of America, Boulder, CO.

STRESS PROVINCES OF NORTH AMERICA, p. 349, col. 1, para. 2;
" In this section we discuss the individual stress provinces shown in Figure 4 and summarized in Table 2.

p. 350;

"

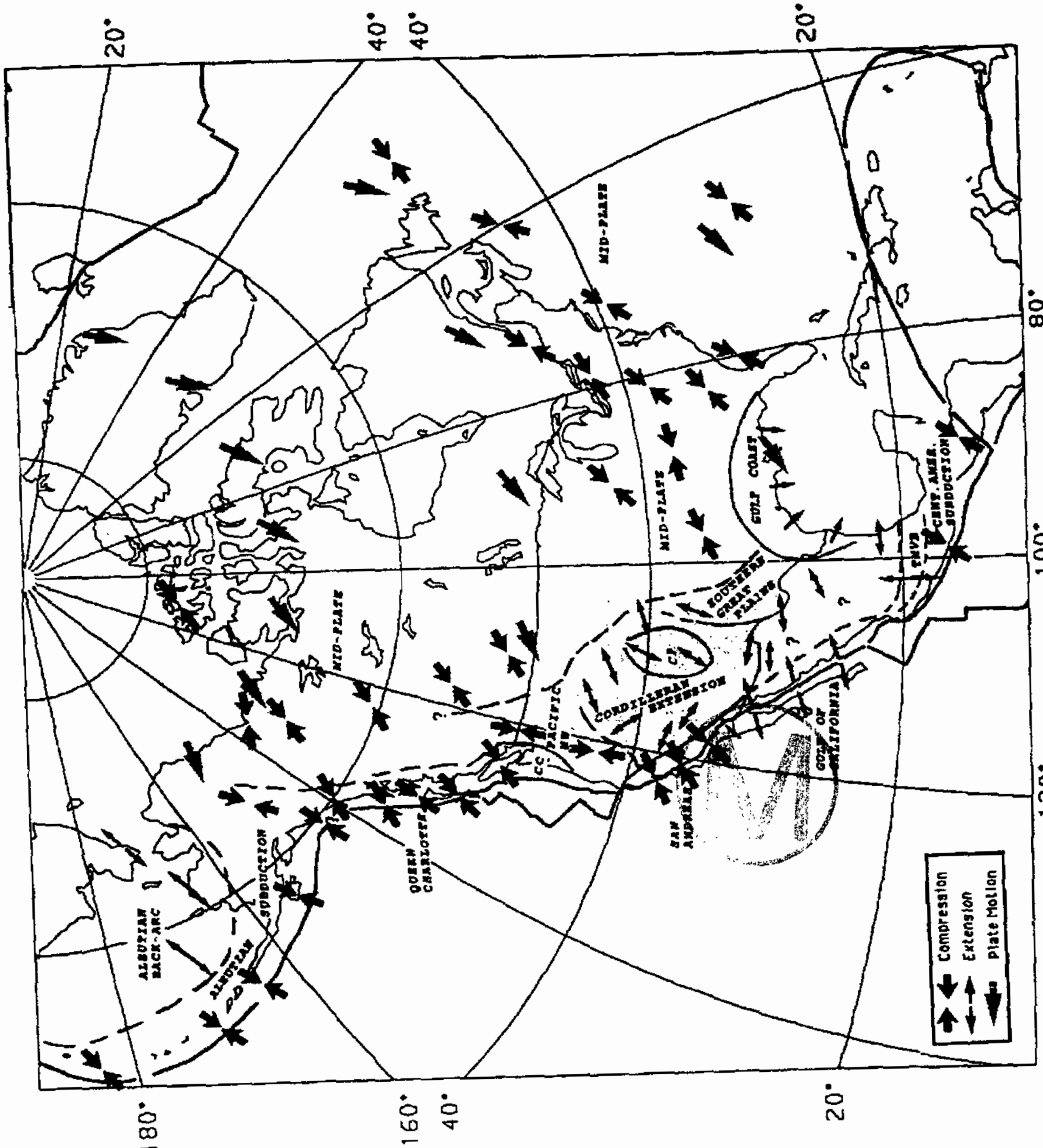
TABLE 2. STRESS PROVINCES OF NORTH AMERICA

	Stress Regime	Principal Stress Direction Maximum	Minimum	Remarks
PLATE-INTERIOR PROVINCES				
Midplate	SS/TF*	ENE	NNW/Vertical	Encompasses most of intraplate North America east of the U.S. Cordillera including the western Atlantic basin. Earthquake focal plane mechanisms in southeastern Canada are predominantly thrust and those in the United States are predominantly strike-slip. Excellent correlation between direction of maximum horizontal stress with absolute plate-motion direction as well as the direction of ridge push from the Mid-Atlantic ridge.
Gulf Coast	NF	Vertical	SSE	Extensive gulfward extension and growth faulting within Coastal Plain sediments. State of stress in the underlaying basement is not known.
Cordilleran Extension	NF/SS	Vertical	WNW (*WSW-WNW*)+	Broad region of variable magnitude extension including the Basin and Range, Rio Grande rift, Northern Rocky Mountain, and Snake River Plain regions of western United States. Extent into Canada and Mexico is uncertain. Correlative with zone of high heat flow, elevation, and thin crust. Pronounced strike-slip deformation (with constant S_{hmin} direction) along western boundary of province (Walker Lane). Predominant S_{hmin} direction within the province is WNW but direction varies between WSW and WNW.
Colorado Plateau/ Southern Great Plains	NF	Vertical	NNE	Unique extension direction, thicker thicker crust, and very low rate of crustal deformation distinguishes the Colorado plateau and Southern Great Plains from the surrounding Cordilleran extension province.

* NF = normal faulting; SS = strike-slip faulting; TF = thrust faulting
+ Directions in italics refer to range of stress directions observed throughout a province."
NOTE: This is not a complete representation of TABLE 2.

p. 349, col. 1, Caption for Figure 4;

" Figure 4. Generalized stress map of North America. Interpretive stress provinces shown in the figure are summarized in Table 2 and discussed in detail in the text. As explained in legend, inward-pointed arrows indicate directions of maximum horizontal compression in areas of reverse and strike-slip faulting and thinner, outward-pointed arrows indicate the direction of least horizontal compression in areas of normal faulting and strike-slip faulting. Single, large shaded arrows indicate direction of absolute plate motion."


20°
40°
40°
20°
80°
100°
120°
180°
160°
40°
20°
MID-PLATE
MID-PLATE
MID-PLATE
MID-PLATE
GULF COAST
SOUTHERN GREAT PLAINS
CORDILLERAN EXTENSION
PACIFIC NW
CC
SAN ANDREAS
GULF OF CALIFORNIA
QUEEN CHARLOTTE
SUBDUCTION
ALEUTIAN
ALEUTIAN BACK-ARC
CENT. AMER. SUBDUCTION
Compression
Extension
Plate Motion

p. 353, col. 1, para. 3;

" **Cordilleran extension province.** This stress province coincides generally with the broad thermally elevated region of the western United States (e.g., Eaton, 1979) and extends southward into northern Mexico. It incorporates the classic Basin and Range subprovince of extensive north-south-trending range-bounding normal faults, as well as the regions surrounding the Colorado Plateau : the Rio Grande Rift, and the middle Rocky Mountains and Denver Basin regions (Fig. 4). All these areas are characterized by extensional tectonics with a S_{hmin} orientation varying between west-northwest to east-northeast. Although seismicity occurs throughout the region (Engdahl and Rinehart, this volume), the rate of tectonic activity in southern parts of this province (northern Mexico, Arizona, New Mexico) and northeastern parts (middle Rocky Mountains and Denver Basin) it is considerably less than the part of the province coincident with the'Great Basin' of Nevada and Utah. As the state of stress, deformation and tectonics of much of the Cordilleran extension province have been recently discussed in detail (Zoback, 1989; Zoback and Zoback, 1989), we only briefly summarize key points in here.

Distinct subprovinces of uniform S_{hmin} orientation can be defined within the Cordilleran Extension province: (1) the northern Basin and Range and Rio Grande rift regions are characterized by a west-northwest S_{hmin}, (2) in southern Arizona, New Mexico, and northern Mexico, Quaternary faulting patterns indicate that the S_{hmin} direction is approximately east-west (Muehlberger and others, 1978), and (3) north of the Snake River Plain and in the Denver Basin and middle Rocky Mountain region (Colorado and Wyoming) the S_{hmin} orientation averages about east-northeast."

p. 353, col. 2, para. 3;

" **Colorado Plateau and Southern Great Plains Provinces.** As illustrated in Figures 2 and 4, these two regions are unique within the western United States Cordillera in showing generally north-northeast, rather than approximately east-west extension. The Colorado Plateau, a relatively stable tectonic block throughout much of Phanerozoic time, is surrounded by active west-northwest extension on both its western and eastern border. Deformation within the Colorado Plateau interior is dominated by small-magnitude normal faulting earthquakes (Wong and Humphrey, 1989). Similarly, the southern Great Plains stress province, which is defined largely on the basis of trends of Quaternary basaltic volcanic vent alignments, is bordered on its western side by the west-northwest extension in the Rio Grande rift. It is difficult to define the northeastern boundary of the Southern Great Plains Province using currently available data. However, the extensional state of stress in this province is markedly different than the compression observed in the Mid-plate province. Southeast of this province a change in extension direction occurs as southeastward (gulfward) extension is observed in the Gulf Coast province."

BIBLIOGRAPHY DOCUMENTS

AIM (Agricultural and Industrial Minerals, Inc.). 1979. Resource Study for the [WIPP], Eddy County, NM. AIM, Inc., San Carlos, CA.

INTRODUCTION, p 1;

" A. Purpose of Study

This study has been prepared under terms of Contract No. EW-78-C-04-4233 dated March 8, 1978 and is submitted in fulfillment of that contract. The purpose is to define and evaluate the potash resources and reserves of the Waste Isolation Pilot Plant (WIPP) site area located in Eddy County, New Mexico, Township 22 South Range 30 and 31 East. Said site comprises approximately 18,960 acres. An additional purpose of the study is to determine the impact on the industry and the market supply if the WIPP area is withdrawn from mining. A third purpose is valuation of leaseholders' interests and the State of New Mexico interest as lessor of certain tracts.

B. Site Division and Ownerships

The Department of Energy has divided the site into four generally concentric zones numbered I, II, III and IV. Within the site are four tracts of Federal and State leased lands numbered 301, 302, 303 and 304, the outlines of which are not related to the zones. Map No. 254-8, Page 67, shows the outline of each leased tract and each zone. Table I-1, Page 4, lists Lessees, Lessors, acreage by tract, acreage by zone and percentage relationships of Federal and State lands to the total WIPP site acreage.

C. Division of Resources and Reserves

These have been divided as follows:

1. By ore zones.
2. By WIPP Zones I, II, III and IV.
3. By leaseholder interest.
4. By State of New Mexico interests.

D. Acknowledgements

AIM, Inc. expresses its sincere appreciation to personnel of the following government agencies and companies for their cooperation, supplying data and for judgements which were most helpful in the development of this report. . . .

E. Assumptions and Conclusions

The conclusions reached herein are based on available data from both government and company core hole information. No new drilling was undertaken. Since the core holes are generally on one mile spacing, (a wide spacing) geologic interpretations have been made to arrive at such factors as grades, mineralogy, thickness, tonnage, etc., contained in given areas.

Since no samples exist that represent the true average of any given ore zone or area, selected samples of various cores were used to perform the metallurgical tests. These cores represent a broad range of grades and containments. The data from metallurgical tests were applied to the calculated grades and containments of a given area to determine if marketable products can be produced. Recoveries were also made on the basis of experience in the potash industry. Cut-off grades and thicknesses were established from experience combined with discussions held with the Carlsbad mining companies. 4.5 feet minimum mining thickness was established as the lower limit even though difficult to sustain.".

Anderson, R.Y., 1982. "Deformation-Dissolution Potential of Bedded Salt, Waste Isolation Pilot Plant Site, Delaware Basin, New Mexico." In Scientific Basis for Nuclear Waste Management, Materials Research Society Proceedings, V. W. Lutze, ed., Vol. 11. Elsevier Science Publishing Co., New York.

INTRODUCTION, p. 449;

" Deep-seated collapse and brecciation is a feature common to bedded salt in a number of evaporite basins. The origin of these features is poorly understood. The relatively young geologic age of uplift and exposure of evaporites in the Delaware Basin, and a still-active hydrologic system, provides a unique opportunity to examine the pathways of water movement related to collapse features and salt dissolution. In addition, salt deformation structures are closely associated with brine, dissolution, and collapse. This report briefly discusses evidence for deep-seated dissolution, considers the relationship between deformation, dissolution, and brine, and examines the potential for dissolution at the WIPP (Waste Isolation Pilot Plant) site with respect to stages in the deformation-dissolution process.

The Delaware Basin, which contains the Upper Permian Castile and Salado evaporites, was uplifted, faulted on the western margin (Fig. 1A), and tilted 19m/km to the east-northeast during the latter part of the Cenozoic, probably 4-6 my ago. This event exposed the tilted limestone (reef) and sandstone aquifers beneath the overlying anhydrite and salt beds (Table 1). Meteoric waters entered the exposed aquifers in the uplifted western and southern margins of the basin. The aquifers became charged and pressurized, with the pressure surface high within the evaporites; almost at the surface. Salt has been removed from beneath and within the evaporite body, apparently by means not related to ordinary near-surface groundwater flow. This report considers how this may have happened."

Anderson, R.Y. 1993. "The Castile as a 'Nonmarine' Evaporite." In Geology of the Carlsbad Region, New Mexico and Texas, D.W. Love et al., Forty-Fourth Annual Field Conference Guidebook. New Mexico Geological Society, Socorro, NM.

p 12, col 2;

" After King (1947) showed that the low proportion of halite to anhydrite in the Castile evaporite could be explained by the reflux of brine from the Delaware Basin, the Castile became the classical example of a marine, 'deep water' evaporite. Anderson and Dean (in press) have reexamined the distribution of evaporites units, as well as geochemical evidence and they suggest that reflux is not the only way to explain the compositional and stratigraphic relationships of the Castile. According to the alternate explanation, the brine was not a residual of sea water flowing directly into the basin. Rather, it is suggested that chloride recharge was from ground water seeping into the basin from the south, especially during lowstands (Fig. 1.12a), with the brine derived from a partly marine source or from previously deposited evaporites. In this model, the Delaware Basin was a hydrologically closed basin with water level subject to extreme highstands (Fig. 1.12b) and lowstands, a type of response similar to that observed in existing closed basins in western North America.

Support for a closed-basin model can be found in the record of climatic variability that is preserved in the Castile. For example, millennial oscillations in climate and lake level are strongly expressed in the closed hydrologic basins in western North America during the late Pleistocene. Millennial cycles also are dominant in the Castile and determine the incidence and duration of halite accumulation (lowstands). Cycles of precession and eccentricity also are well defined in the Castile and in the record of the ocean and cryosphere over the past million years. The occurrence of climate cycles recognized in the Pleistocene and Holocene does not address the question of marine recharge for the Castile. However, strong expression of the same climatic periodicities within the Castile is consistent with a closed-basin hydrologic setting and meteoric recharge.

More direct evidence for meteoric recharge can be seen in the depletion of ^{18}O in limestone beds along the western margin of the basin (Magaritz et al., 1983) and in rapid, synchronous changes in the seasonal rate of accumulation of calcium sulfate (freshening events) that resulted in beds of laminated limestone. Such events can be traced from the western margin to the center of the basin, suggesting that a significant volume of meteoric recharge entered the basin from the west during those times when water level was at or near a highstand (Fig. 1.12b). Other evidence for meteoric contributions can be found in the low bromine concentrations in halite, which give the Castile an affinity with other nonmarine evaporites. Ground-water recharge of ions derived from preexisting evaporites provides an alternate mechanism to account for the low ratio of halite to sulfate.

. . ."

Anderson, R.Y., Dean, W.E., Kirkland, Jr., D.W., and Snider, H. I. 1972. Permian Castile Varved Evaporite Sequence, West Texas and New Mexico. Geological Society of America Bulletin, Vol. 83, No. 1, pp. 59-85.

ABSTRACT; p 59, col 1;

"　Laminations in the Upper Permian evaporite sequence in the Delaware Basin appear in the preevaporite phase of the uppermost Bell Canyon Formation as alternation of siltstone and organic layers. The laminations then change character and composition upward to organically laminated claystone, organically laminated calcite, the calcite-laminated anhydrite typical of the Castile Formation, and finally to the anhydrite-laminated halite of the Castile and Salado.

Laminae are correlative for distances up to 111 km (70.2 mi) and probably throughout most of the basin. Each laminae is synchronous, and each couplet of two laminated components is interpreted as representing an annual layer of sedimentation--a varve.

The thickness of each couplet in the 260,000-varve sequence (a total thickness of 447.2 m, (1465 ft) has been measured individually and recorded and provides the basis for subdividing and correlating major stratigraphic units within the basin. The uppermost 9.2 m (30.3 ft) of the Bell Canyon Formation contains about 50,850 varve couplets; the Basal Limestone Member of the Castile about 600; the lowermost anhydrite member of the Castile (Anhydrite I) contains 38,397; Halite I, 1,063;Anhydrite II, ??,414; Halite II, 1,758; Anhydrite III, 46,592; Halite III, 17,879; and Anhydrite IV, 54,187. The part of the Salado collected (126.6 m) contains 35,422 varve couplets. The Bell Canyon-Castile sequence in the cores studies is apparently continuous, with no recognizable unconformities.

The dominant petrologic oscillation in the Castile and Salado, other than the laminations, is a change from thinner undisturbed anhydrite laminae to thicker anhydrite laminae that generally show a secondary or penecontemporaneous nodular character, with about 1,000 to 3,000 units between major oscillations or nodular beds. These nodular zones are correlative throughout the area of study and underly halite when it is present. The halite layers alternate with anhydrite laminae, are generally recrystallized, and have an average thickness of about 3 cm. The halite beds were once west of their present occurrence in the basin but were dissolved, leaving beds of anhydrite breccia. The onset and cessation of halite deposition in the basin was nearly synchronous.

The Anhydrite I and II Members thicken gradually across the basin from west to east, whereas the Halite I, II, and III Members are thickest in the eastern and northeastern part of the basin and thicken from southeast to northwest. This distribution and the synchroneity indicate a departure from the classical model of evaporite zonation."

Anderson, R.Y., and Kirkland, D.W. 1980. Dissolution of Salt Deposits by Brine Density Flow. Geology, Vol. 8, No. 2, pp. 66-69.

ABSTRACT, P 66;

" The origin of collapse structures and breccias that vertically penetrate or occur within impermeable evaporites has never really been understood. The density of the brine that develops as salt deposits are dissolved can generate continuous gravitational brine movement. If the source of the dissolving water is artesian, or continuous, a flow cycle is developed in which the salt itself supplies the density gradient that becomes the vehicle of its own dissolution. The Delaware Basin in western Texas and southeastern New Mexico provides a particularly good example of how brine density flow can produce dissolution chambers that collapse to form breccias. The potential for dissolution by brine flow is an inherent property of partly exhumed evaporites and may constitute a risk factor in the storage of radioactive waste in evaporite deposits."

Anderson, R.Y., and Powers, D.W. 1978. "Salt Anticlines in the Castile-Salado Evaporite Sequence, Northern Delaware Basin, New Mexico." In Geology and Mineral Deposits of Ochoan Rocks in Delaware Basin and Adjacent Areas, G.S. Austin, ed., Circular 159, New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.

ABSTRACT, p 79, col 1, para 1;

" A number of structures have been encountered within the body of the Castile-Salado evaporites that can reasonably be interpreted as salt anticlines. One such structure, associated with brine, H_2S, and dissolution effects, was found during exploratory coring for the proposed nuclear waste disposal site near Carlsbad, New Mexico. Correlation of stratigraphic units in the recovered core with cores and logs from nearby boreholes shows that the middle anhydrite unit (A-II) of the Castile Formation, which attains dips of as much as 70°, has been displaced vertically by as much as 950 ft (290 m). Extension fractures in the A-II unit suggest that it has been stretched over a pod of exceptionally thick salt of the lower halite unit (H-I) of the Castile Formation that moved into the axis of the anticlinal structure. Exceptionally thick and thin units of lower salt (H-I) occur in other nearby boreholes in a zone of deformation marginal to the reef. Suspected salt anticlines also occur at scattered localities in the northern part of the Delaware Basin. The association of extension fracturing to microfolding in the middle anhydrite unit (A-II) suggests that salt deformation accompanied or followed Cenozoic uplift and tilting of the basin."

Bachman, G.O. 1973. Surficial Features and Late Cenozoic History in Southeastern New Mexico. Open-File Report 4339-8. U.S. Geological Survey, Reston, VA.

ABSTRACT, p. 1;
"   Since deposition of the Ogallala Formation during Pliocene time, southeastern New Mexico has been subjected to erosion, solution, subsidence, and widespread eolian activity. These processes have combined to influence the formation and morphology of major drainage systems. Aligned drainage patterns resulted from solution of caliche localized by longitudinal sand dunes. San Simon Swale appears to have formed by processes of erosion and solution-subsidence of Permian evaporites, and was formerly an important tributary to the Pecos River. The combination of processes that formed San Simon Swale was similar to the combination of erosion and coalescing sinks that formed the lower Pecos Valley in southern New Mexico.

Bachman, G.O., 1985. Assessment of Near-Surface Dissolution at and near the Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico. SAND84-7178. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p. 3;

" The area at and near the WIPP site was examined for evidence of karst development on the geomorphic surface encompassing the site. Certain surficial depressions of initial concern were identified as blowouts in sand dune fields (shallow features unrelated to karstification). An ancient stream system active more than 500,000 years ago contained more water than any system since. During that time (Gatuña, Middle Pleistocene), many karst features such as Clayton Basin and Nash Draw began to form in the region. Halite was probably dissolved from parts of the Rustler Formation at that time. Dissolution of halite and gypsum from intervals encountered in Borehole WIPP-33 west of the WIPP site occurred during later Pleistocene time (i.e., <450,000 yr ago). However, there is no evidence of active near-surface dissolution within a belt to the east of WIPP-33 in the vicinity of the WIPP shaft."

Bachman, G.O., and Johnson, R.B. 1973. Stability of Salt in the Permian Salt Basin of Kansas, Oklahoma, Texas, and New Mexico. Open File Report 4339-4. U.S. Geological Survey, Denver, CO.

ABSTRACT, p 1;

" The Permian salt basin in the Western Interior of the United States is defined as that region comprising a series of sedimentary basins in which halite and associated salts accumulated during Permian time. The region includes the western part of Kansas, Oklahoma, and Texas, and eastern parts of Colorado and New Mexico.

Following a long period of general tectonic stability throughout the region during most of early Paleozoic time, there was much tectonic activity in the area of the Permian salt basin during Late Pennsylvanian and early Permian time just before bedded salt was deposited. The Early Permian tectonism was followed by stabilization of the basins in which the salt was deposited. These salt basins were neither contemporaneous nor continuous throughout the region so that many salt beds are also discontinuous. In general, beds in the northern part of the basin (Kansas and northern Oklahoma) are older, and the salt is progressively younger towards the south.

Since Permian time, the Permian salt basin has been relatively stable tectonically. Regionally, the area of the salt basin has been tilted and warped, has undergone periods of erosion, and has been subject to a major incursion of the sea; but deep-seated faults or igneous intrusions that postdate Permian salt are rare. In areas of the salt basin where salt is near the surface, such as southern New Mexico and central Kansas, there are no indications of younger deep-seated faulting and only a few isolated igneous intrusives of post-Permian age.

On the other hand, subsidence or collapse of the land surface resulting from dissolution has been commonplace in the Permian salt basin. Some dissolution of salt deposits has probably been taking place ever since deposition of the salt more than 230 million years ago. Nevertheless, the subsurface dissolution fronts of the thick bedded-salt deposits of the Permian basin have retreated at a very slow average rate during that 230 million years.

The preservation of bedded salt from subsurface dissolution depends chiefly on the isolation of the salt from moving groundwater that is not completely saturated with salt. Karst topography is a major criterion for recognizing areas where subsurface dissolution has been active in the past; therefore, the age of the karst development is needed to provide the most accurate estimate of the dissolution rate. The Ogallala Formation of Pliocene age is probably the most widespread deposit in the Permian salt basin that can be used as a point of reference for dating the development of recent topography. It is estimated that salt has been dissolved laterally in the vicinity of Carlsbad, New Mexico, at an average rate of about 6-8 miles per million years.

Estimates of future rates of salt dissolution and the resulting lateral retreat of the underground dissolution front can be projected with reasonable confidence for southeastern

New Mexico of the assumption that the climatic changes there in the past 4 million years are representative of climatic changes that may be expected in the near future of geologic time.

Large amounts of salt are carried by present-day rivers in the Permian salt basin; some of the salt is derived from subsurface salt beds, but dissolution is relatively slow. Ground-water movement through the Permian salt basin is also relatively slow."

Bachman, G.O., and Machette, M.N. 1977. Calcic Soils and Calcretes in the Southwestern United States. Open-File Report 77-794. U.S. Geological Survey.

ABSTRACT, p 1:

" Secondary calcium carbonate of diverse origins, 'caliche' of many authors, is widespread in the southwestern United States. 'Caliche' includes various carbonates such as calcic soils and products of ground-water cementation. The term 'caliche' is generally avoided in this report in favor of such terms as calcrete, calcic soils, and pervasively cemented deposits.

Criteria for the recognition of various types of calcrete of diverse origins include field relations and laboratory data. Calcic soils provide a comprehensive set of characteristics that aid in their recognition in the field. These characteristics include a distinctive morphology that is zoned horizontally and can frequently be traced over tens of hundreds of square kilometers.

The major process in the formation of pedogenic calcrete and calic soils is the leaching of calcium carbonate from upper soil horizons by downward percolating soil solutions and reprecipitation of the carbonate in illuvial horizons near the base of the soil profile. The formation of pedogenic calcrete involves many factors including climate, source of carbonate, and tectonic stability of the geomorphic surface on which the calcrete is deposited. Most of the carbonate in pedogenic calcrete is probably derived from windblown sand, dust, and rain.

Calcic soils and pedogenic calcretes follow a six-stage sequence of morphologic development and is based on a classification devised by Gile, Peterson, and Grossman in 1966. The six morphologic stages of carbonate deposition in soils are related to the relative age of the soil and are as follows:

I. The first or youngest stage includes filamentous or fault coatings of carbonate on detrital grains.

II. The second stage includes pebble coatings which are continuous; firm carbonate nodules are few to common.

III. The third stage includes coalesced nodules which occur in a friable or disseminated carbonate matrix.

IV. The fourth stage includes platy, firmly cemented matrix which engulfs nodules; horizon is plugged to downward moving solutions.

V. The fifth stage includes soils which are platy to tabular, dense, strongly cemented. A well-developed laminar layer occurs on the upper surface.

VI. The sixth and most advanced stage is massive, multilaminar, and strongly cemented calcrete with abundant pisoliths, the upper surface of which may be brecciated. Pisoliths may indicate many generations of brecciation and reformation.

In general calcic soils include stages I through III and are friable to moderately indurated; whereas pedogenic calcretes include stages IV through VI and are dense and strongly indurated. In a single pedon the morphologic stage of carbonate deposition

decreases downward in the profile. The stage of development may be used in local regions for correlation and determination of relative ages of soils and geomorphic surfaces.

Some structures observed in pedogenic calcretes may be present in other types of calcrete but the horizontal zonation typical of deposits of soil processes is absent. Laminar structure in particular is not restricted to pedogenic deposits and is common in many varieties of calcrete.

Very little chemical change occurs in the noncalcareous nonclayey fractions of calcretes with age; but clay minerals within calcretes undergo a complex history of authigenesis. There is a depletion of magnesium in the calcareous portion and an enrichment of magnesium in the clayey portion of a calcrete with age. In keeping with this relationship, montmorillonite, or mixed layer montmorillinite-illite, is common in younger calcretes; whereas the high magnesium-silicate clays, sepiolite and palygorskite, are common in older calcretes. This indicates that the magnesium depleted from the carbonate is redistributed authigenically in clay minerals.

The mobility of carbonate introduces many problems in attempts to date calcretes directly. Although the relative ages of soils within a province may be determined by quantitative studies, the absolute age can at present be made only by cross reference to other datable deposits such as lava flows, pumice, ash falls, and fossil-bearing beds. Rates of calcium carbonate accumulation vary from 0.22 to 0.51 g/cm^2/kyr for New Mexico. These rates exceed those of many other areas in the southwestern United States. The amount of pedogenic carbonate in a soil as well as its morphology can be used to correlate both Quaternary alluvial deposits and geomorphic surfaces. Additionally, calcic soils and pedogenic calcrete are useful in analyzing recurrent fault histories.

In many areas where climatic conditions and carbonate sources are amenable to the formation of calcic soils, relict pedogenic calcretes are not preserved. In these regions examined during this study, the absence of such calcretes is the result of tectonic instability and rates of erosion and deposition too rapid for the time required to deposit the calcrete."

Balazs, E.I., 1978 [undated]. Report on First-Order Leveling Survey for Sandia Laboratories Waste Isolation Pilot Plant (WIPP) Project.Report to Sandia National Laboratories, Albuquerque, NM. National Geodetic Survey, Rockville, MD.

ABSTRACT

"   The National Geodetic Survey (NGS) of the National Ocean Survey (NOS) completed 516 km of first-order, class I leveling in New Mexico and Texas in the fall of 1977.

The survey was accomplished in two parts: Part one was the releveling of a 202 km segment of the existing first-order line, from Carlsbad, New Mexico, to 43 miles N. of Sierra Blanca, Texas (L-24244). The purpose of this releveling was to study vertical movement of the bench marks along the line. In part two, three new level lines were established in the San Simon area (L-24247) with a total length of 314 km. The purpose of the new levelings was to establish elevations for bench marks set in the area designated as a waste disposal site. Periodic releveling of these lines will provide information about vertical movement in the area associated with waste disposal. For location of the level lines, see Figure 1.

In addition to the list of adjusted elevations and bench mark descriptions for the above mentioned lines, corresponding lists of the observed elevations (Phase 1) are included. Those elevations can be used for crustal movement studies. Tabulations of differences of observed elevations for different epochs are enclosed. IN order to be consistent, we always subtracted the elevation of the common bench mark of the base line from the corresponding elevation of the other epoch. The computer generated profiles are also enclosed. These profiles show the apparent movement of the bench marks for each time period relative to a bench mark at the beginning of the profile, which was assumed to be stable.

The profile for the entire project which is the combined, smoothed result of the individual profiles, indicates an apparent regional subsidence of approximately 1 dm at Carlsbad relative to BM L 181 at 41 miles SW of Pine Springs, Texas. Alternatively, it might be concluded, based on the available information of the profiles, that the Carlsbad area is stable and there is uplift at the area 41 miles SW of Pine Springs, Texas. The extent of the . . ."

Balazs, E.I., 1982. Vertical Movement in the Los Medaños and Nash Draw Areas, New Mexico, as Indicated by 1977 and 1981 Leveling Surveys. NOAA Technical Memorandum NOS NGS 37, National Geodetic Survey, Rockville, MD.

ABSTRACT, p 1;

" Free-adjusted heights of two survey epochs were compared for the Los Medanos and Nash Draw areas. The changes in heights of common bench marks were tabulated and plotted. The apparent movement for the area documented in this report is relative to bench mark 1 BOR, set in a bridge in Carlsbad, N. Mex. A total of 122 of the 147 common bench marks indicates consistent subsidence averaging approximately 18 mm between 1977 and 1981 (4.6 mm/yr). At two bench marks, located over potash mines in the area, the subsidence is much larger."

Barker, J.M., and Austin, G.S. 1993. "Economic Geology of the Carlsbad Potash District, New Mexico, in Carlsbad Region, New Mexico and West Texas." In Geology of the Carlsbad Region, New Mexico and Texas, D.W. Love et al., eds., Forty-Fourth Annual Field Conference Guidebook, pp. 283-291. New Mexico Geological Society, Socorro, NM.

ABSTRACT, p 283;

" New Mexico produced 83% of domestic potash and 27% of domestic consumption in 1992. Fertilizer was used 95% of U. S. production; 5% was used in chemicals. The potash industry of New Mexico produces sylvite (KCl), langbeinite ($K_2SO_4 \bullet 2Mg(SO_4)_2$) and artificial K_2SO_4. Sylvite grade in New Mexico decreased from 20-25% K_2O in the 1950s to about 14% today. The average grade of langbeinite (first produced in 1940) remains 8-10% K_2O. Reserves in the Known Potash Leasing Area (KPLA) will sustain production for 25 to 35 years and represent 57% of domestic reserves. Potash horizons extend far outside the KPLA, but none are economic. Commercial potash occurs in the middle or McNutt Member of the Salado Formation (Upper Permian Ochoan Stage). The potash distribution in the Salado is asymmetrical, suggesting a reflux model related to a bar-restricted marine embayment with dense brine underflow toward the bar. The dominantly seawater brine was magnesium-rich, producing primary carnallite or polyhalite, later recycled into the modern complex salt assemblage. The 400-ft-thick McNutt Member dips about 1° east and contains 11 of 12 potential ore zones in the Salado. Potash zones are 3-10 ft thick and contain minable sylvite and/or langbeinite, together with halite and accessory minerals. The zones are consistent laterally, but are locally interrupted by barren halite (salt horses) formed later by undersaturated migrating fluids. Room-and-pillar mining, with pulled pillars, recovers >90% of the potash from depths ranging from 885 to 1400 ft by continuous-mining coal equipment or drilling and blasting. Beneficiation is by various separation, flotation, crystallization, leaching and heavy-media circuits optimized for each ore. The mineralogy and proportion of clay minerals, up to 7% of the ore, influence optimum milling procedures and ore grade cutoff. Agriculture, petroleum and nuclear waste disposal affect production of potash from southeastern New Mexico. Agricultural demand for fertilizer is a complex interaction between weather and climate, advances in crop genetics, soil science, farming practices, GNP of importing nations, farm income, population growth, efficient distribution systems, freight rates and backhauls, substitutes, taxes and tariffs. Petroleum companies compete for petroleum under potash and the Waste Isolation Pilot Plant (WIPP) led to withdrawal of potash reserves."

Barrows, L.J. and Fett, J.D. 1985. A High-Precision Gravity Survey in the Delaware Basin of Southeastern New Mexico. Geophysics, Vol. 50, No. 5, pp. 825-833.

ABSTRACT, p 825;

" Since 1974, the Department of Energy has been studying bedded salt deposits in southeastern New Mexico as a possible location for disposing of defense-generated transuranic and low-level radioactive wastes. The program known as the Waste Isolation Pilot Plant , includes intensive geologic characterization of about 40 km^2 and construction of an underground test facility. The gravity survey reported is part of the site geologic characterization.

The gravity survey was conducted to delineate structural features near and at the proposed site. However, during the survey the gravity field was found to be dominated by effects of lateral density variations within relatively flat-lying strata. Particularly distinctive is a pattern of elongate negative anomalies about one-half mGal in amplitude. Boreholes in the anomalies encountered normal stratigraphy and no unusual geologic structures. However, borehole densilogs showed lower acoustic velocities that are measured outside of the anomalies. The low densities adequately account for the observed gravity anomalies.

The regional stratigraphy contains water-soluble minerals (halite, polyhalite, anhydrite-gypsum, carbonates). Much of this material has dissolved and the region has been identified as a karstland. At the site, dissolution is slowly affecting the Rustler formation overlying the main salt-bearing units. The low rock densities, associated with the negative gravity anomalies, are interpreted as due to alteration in the vicinity of solution conduits within the Rustler formation. This interpretation is supported by (1) partial coincidence between the negative gravity anomalies and closed topographic depressions (alluvial dolines); (2) greater anhydrite-to-gypsum conversion detected in boreholes within the anomalies; and (3) solution conduits encountered in one of the boreholes."

Beauheim, R.L., 1986. Hydraulic-Test Interpretations for Well DOE-2 at the Waste Isolation Pilot Plant (WIPP) Site. SAND86-1364. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p 3;

" Eleven different zones were tested in Well DOE-2 in five phases of testing between 1984 and 1986. Testing techniques included a constant-head, borehole-infiltration test, drill-stem tests, slug tests, pressure-pulse tests, and multiwell pumping tests. Four of the zones tested--the lower Dewey Lake Red Beds, the Tamarisk Member of the Rustler Formation, the lower unnamed member of the Rustler Formation and the Rustler/Salado contact, and the entire Salado Formation--had permeabilities too low to measure with the equipment and test techniques used. The other zones had permeabilities ranging over six orders of magnitude. No saturated strata were encountered above the Rustler Formation, although parts of the middle Dewey Lake Red Beds appear to have appreciable permeability.

In the Rustler Formation, the Culebra Dolomite Member is the most permeable unit, having a transmissivity of ~90 ft^2/day. The Culebra behaves hydraulically as a double-porosity system, with the major permeability provided by fractures and the major storage provided by matrix porosity. The Culebra at DOE-2 is well connected hydraulically to the Culebra at Wells H-6b and WIPP-13 to the west, probably by interconnected fractures. Response times between these wells are very short (<1 day/10,000 ft). The Culebra does not appear to be as fractured to the south at Wells WIPP-12 and 18, or to the east at Well H-5b, as indicated by delayed, low-magnitude (or nonexistent) responses to DOE-2 pumping, and by low permeabilities interpreted from other tests conducted at those wells. The other Rustler members at DOE-2, which are not known to be fractured and do not display hydraulic responses typical . . ."

Beauheim, R.L., and Holt, R.M. 1990. "Hydrogeology of the WIPP Site." In Geological and Hydrological Studies of Evaporites in the Northern Delaware Basin for the Waste Isolation Pilot Plant (WIPP), New Mexico, Geological Society of America 1990 Annual Meeting Field Trip #14 Guidebook, pp. 131-179. Dallas Geological Society, Dallas, TX.

Introduction, p 2, col. 1;

" The field trip provides an on site introduction to the geology and hydrology of the Waste Isolation Pilot Plant (WIPP) site in southeastern New Mexico. The mission of the WIPP is to dispose of transuranic (TRU) waste generated since 1970 by the U. S. defense programs. After 18 years of study and the publication of hundreds of documents, these studies remain unknown to many geologists. Although many of the studies are unique, they lack recognition. This field trip and guidebook begin to redress this imbalance."

Beauheim, R.L., Roberts, R.M., Dale, T.F., Fort, M.D., and Stensrud, W.A. 1993. Hydraulic Testing of Salado Formation Evaporites at the Waste Isolation Pilot Plant Site: Second Interpretive Report. SAND92-0533. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT;

" Pressure-pulse, constant-pressure flow, and pressure-buildup tests have been performed in bedded evaporites of the Salado Formation at the Waste Isolation Pilot Plant (WIPP) site to evaluate the hydraulic properties controlling brine flow through the Salado. Transmissivities ranging from about 7 x 10^{-15} to 5 x 10^{-13} m^2/s have been interpreted from six sequences of tests conducted on five stratigraphic intervals within 15 m of the WIPP underground excavations. The corresponding vertically averaged hydraulic conductivities of the intervals range from about 1.1 x 10^{-14} to 2 x 10^{-12} m/s (permeabilities of 2 x 10^{-21} to 3 x 10^{-19} m^2). Storativities of the tested intervals range from about 1 x 10^{-8} to 2 x 10^{-6}, and values of specific storage range from 9 x 10^{-8} to 1 x 10^{-5} m^{-1}. Pore pressures in eight stratigraphic intervals range from about 2.5 to 12.5 MPa, and appear to be affected by stress relief around the excavations. Anhydrite interbeds appear to be one or more orders of magnitude more permeable than the surrounding halite, primarily because of subhorizontal bedding-plane fractures present in the anhydrites. Interpretations of the tests revealed no apparent hydrologic boundaries within the radii of influence of the tests, which were calculated to range from about 2 to 20 m from the test holes. An assumption of Darcy flow through the evaporites is thought to be a reasonable interpretive approach because Darcy-flow models are able to replicate the flow and pressure behavior observed during entire testing sequences involving different types of tests performed with different hydraulic gradients."

Bertram-Howery, S.G., and Hunter, R.L. 1989. Plans for Evaluation of the Waste Isolation Pilot Plant Compliance with EPA Standards for Radioactive Waste Management and Disposal. SAND88-2871. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p. i;

" The Department of Energy (DOE) is actively pursuing the disposal of transuranic (TRU) waste in a geologic environment at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico. The WIPP Project will assess compliance with the Environmental Protection Agency's Environmental Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes (40 CFR Part 191). The Standard is divided into two subparts. Subpart A limits annual radiation doses to members of the public from waste management and storage operations at disposal facilities, and Subpart B limits cumulative releases of radioactive materials for 10,000 years, radiation doses to members of the public for 1000 years, and radioactive contamination of certain sources of ground water for 1000 years, as a result of disposal of wastes. The WIPP Project will assess compliance with Subpart A primarily by means of an extensive monitoring program. The Project will assess compliance with Subpart B primarily using performance-assessment techniques developed for the evaluation of the performance of high-level-waste repositories. Compliance with the Assurance Requirements and the Ground Water Protection Requirements will be assessed using other techniques. The WIPP Project will be the first to evaluate the compliance of a mined geologic repository with the EPA Standard. Although Subpart B of the Standard was remanded to EPA by the United States Court of Appeals for the First Circuit, this paper discusses the Standard as first promulgated. Compliance plans for the WIPP will be revised as necessary in response to any changes in the Standard."

Blaney, H.F., and Hanson, E.G. 1965. Consumptive Use and Water Requirements in New Mexico. Technical Report 32. New Mexico State Engineer's Office.

ABSTRACT, p 1;

" Many factors influence the amount of water that is consumed by plants. The more important natural influences are climate, water supply, soil, and topography. The climatic factors believed to have the greatest influence on consumptive use are precipitation, temperature, solar radiation, humidity, wind movement, and growing season. Irrigation practices also influence the amount of water consumed as do the kinds of crops grown, their stage of growth, plant species, and many other factors.

This report includes results of experimental studies in New Mexico, Arizona, and other western states. An empirical formula has been developed from these results and from data compiled in the Pecos River Joint Investigation of 1939-41 (9)* which show the relationship between temperature, length of growing season, monthly percent of annual daytime hours, and consumptive use of water. From this relationship, consumptive use of water by crops and natural vegetation can be readily estimated for any area where the basic climatological data are available. Irrigation requirements may be estimated from consumptive use.

Briefly, the procedure was developed by correlating measured consumptive-use data with monthly temperature, monthly percentages of annual daytime hours, quantity and occurrence of precipitation, and length of growing or irrigation season. The coefficients thus developed allow for the computation of consumptive use of each crop if only monthly temperature, latitude, and growing period of the crop are known, since monthly percentages of annual daytime hours are available for latitudes in New Mexico. Seasonal consumptive use can be computed from the Blaney-Criddle (B-C) formula $U = KF$; where U = consumptive use of water in inches, K = empirical seasonal use coefficient, and F = sum of monthly use factors (f) for the season. The monthly use factor (f) is the product of mean monthly temperature (t) and monthly (p) percent of annual daytime hours (4). The equation for monthly or short-period use is $u = kf$.

The seasonal coefficient for each crop appears to be approximately constant for most areas where irrigation is in practice. However, the coefficients do not appear to be constant for consecutive short periods of time throughout the growing season. For short periods, the higher the temperature, the larger the coefficient (k) appears to be. However, temperature is not the only factor affecting consumptive-use relationships. Each crop has its own particular growth and water-use pattern. Thus, for short periods of time, use coefficients vary, largely depending upon temperature and stage of growth.

The net amount of irrigation water required to satisfy consumptive use during any period of time is determined by subtracting the effective precipitation and other available water from the total requirement for the period. This net requirement of irrigation water, divided by the irrigation efficiency, is the overall water requirement to satisfy the needs of the crop. If efficiency measurements are not available they can be estimated by taking into account irrigation practices, soil characteristics, topography, skill of the irrigator, degree of land preparation, and availability and cost of water supplies. Irrigation efficiency may be measured in the field, but such measurements are expensive to make and -- as an alternative approach -- they are often estimated by making allowances for certain wastes such as ditch seepage, deep percolation, and surface runoff. The diversion requirement is the net consumptive irrigation requirement corrected for conveyance and application losses."

Blackwell, D.D., Steele, J.L., and Carter, L.S. 1991. "Heat-Flow Patterns of the North American Continent; A Discussion of the Geothermal Map of North America." In Neotectonics of North America, D.B. Slemmons, E.R. Engdahl, M.D. Zoback, and D.D. Blackwell, eds., pp. 423-436. Geological Society of America, Boulder, CO.

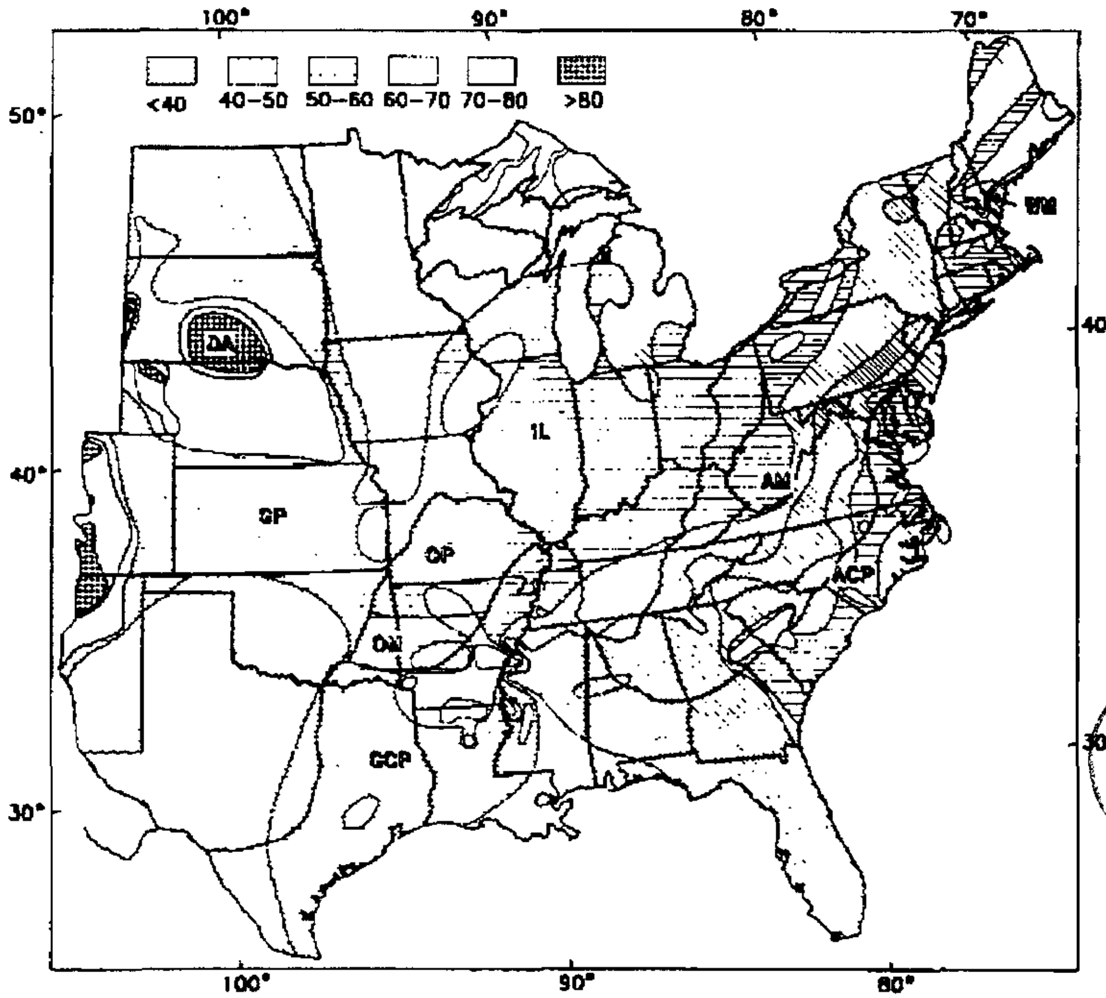


Figure 2. Heat-flow map for the eastern United States. The contours are from the DNAG *Geothermal Map of North America* and are shown at 10-mWm^{-2} intervals. Each band of heat flow is shown by a different pattern. Abbreviations are explained in the text.

Bodine, M.W., Jr., 1978. "Clay-Mineral Assemblages from Drill Core of Ochoan Evaporites, Eddy County, New Mexico," Geology and Mineral Deposits of Ochoan Rocks in Delaware Basin and Adjacent Areas, Circular 159, New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.

ABSTRACT, p. 21;

" The ERDA-9 drill hole, Eddy County, New Mexico, was cored for 1,987 ft, from 230 ft below the top of the Salado Formation through the upper 41 ft of the Castile Formation. Clay minerals in 47 insoluble residues include corrensite, random to partially ordered clinochlore-saponite mixed-layer clays, illite, clinochlore, saponite, a tentatively identified talc-saponite mixed-layer clay, serpentine, and talc. Serpentine is restricted to the Castile and lowermost Salado Formations; (?)talc-saponite is confined to some polyhalite beds in and overlying the McNutt potash zone. The salztons (thin argillaceous seams) consist of corrensite, illite, and clinochlore, while the adjacent evaporite strata often contain abundant to random mixed-layer clinochlore-saponite, mixed-layer (?)talc-saponite, or saponite. Chemical compositions of the residues have high Mg-Al atom ratios reflecting abundance of the trioctahedral clays. Mineralogy and chemistry of the assemblages strongly indicate that severe alteration and Mg-enrichment of normal clay detritus occurred in the evaporite environment through brine-sediment interaction. It is further suggested that the relatively immature clays--saponite, mixed-layer (?)talc-saponite, and randomly interstratified clinochlore-saponite--formed later through recrystallization of preexisting trioctahedral clays in response to transient pore fluids; the salztons, impermeable to such fluids, developed a more mature clay assemblage in a static pore fluid environment. The serpentine-saponite residues with their high Mg-Al and Si-Al atom ratios in Castile and lowermost Salado evaporites are indicative of a silica-rich detrital source; the more aluminous clay assemblages with decreased Mg-Al and Si-Al atom ratios in the overlying evaporite strata suggest a substantially more argillaceous detrital source."

Borns, D.J. and Shaffer, S.E. 1985. Regional Well-Log Correlation in the New Mexico Portion of the Delaware Basin. SAND83-1798. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p 3;

"	Although well logs provide the most complete record of stratigraphy and structure in the northern Delaware Basin, regional interpretations of these logs generate problems of ambiguous lithologic signatures and one-hole anomalies. Interpretation must therefore be based on log-to-log correlation rather than on inferrences from single logs. In this report, logs from 276 wells were used to make stratigraphic picks of Ochoan horizons (the Rustler, Salado, and Castile Formations) in the New Mexico portion of the Delaware Basin. Current log correlation suggests that: (1) the Castile is characterized by lateral thickening and thinning; (2) some Castile thinnings are of Permian age; (3) irregular topography in the Guadalupian Bell Canyon Formation may produce apparent structures in the overlying Ochoan units; and (4) extensive dissolution of the Salado is not apparent in the area of the Waste Isolation Pilot Plant (WIPP) site."

Borns, D.J., and Stormont, J.C. 1987. Delineation of the Disturbed Rock Zone around Excavations in Salt, Waste Isolation Pilot Plant (WIPP), SE New Mexico; Abstracts with Programs. 1987 Annual Meeting and Exposition of the Geological Society of America, Vol. 19, No. 7. Geological Society of America, Phoenix, AZ.

ABSTRACT, p 353;

" At the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico, the Disturbed Rock Zone (DRZ, the zone of rock in which the mechanical and hydrologic properties have changed in response to excavation) has been characterized with visual observations, geophysical methods, and gas-flow measurements. The visual observations, geophysics, and gas-flow tests have defined a DRZ at the WIPP extending laterally throughout the excavation and varying in depth from 1 to 5 m. Desaturation and microfracturing has occurred to some degree within the zone. The dilation that results from the microfracturing in the DRZ provides a component of the observed closure."

Brinster, K.F., 1991. Preliminary Geohydrologic Conceptual Model of the Los Medaños Region Near the Waste Isolation Pilot Plant for the Purpose of Performance Assessment. SAND89-7147 and addendum. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT;

" This report describes a geohydrologic conceptual model of the northern Delaware Basin to be used in modeling three dimensional, regional ground-water flow for assessing the performance of the Waste Isolation Pilot Plant (WIPP) in the Los Medaños region near Carlsbad, New Mexico. Geochemical and hydrological evidence indicates that flow is transient in the Rustler Formation and the Capitan aquifer in response to changing geologic, hydrologic, and climatic conditions. Before the Pleistocene, ground-water flow in the Rustler Formation was generally eastward, but uneven tilting of the Delaware Basin lowered the regional base level and formed fractures in the evaporitic sequence of rocks approximately parallel to the basin axis. Dissolution along the fractures, coupled with erosion, formed Nash Draw. Also, the drop in base level resulted in an increase in the carrying power of the Pecos River, which began incising the capitan aquifer near Carlsbad, New Mexico. Erosion and downcutting released hydraulic pressure that caused a reversal in Rustler ground-water flow direction near the WIPP. Flow in the Rustler west of the WIPP is toward Nash Draw and eventually toward Malaga Bend; flow south of the WIPP is toward Malaga bend."

Brokaw, A.L., Jones, C.L., Cooley, M.E., and Hays, W.H. 1972. Geology and Hydrology of the Carlsbad Potash Area, Eddy and Lea Counties, New Mexico, Open File Report 4339-1, U.S. Geological Survey, Denver, CO.

ABSTRACT;

" The potash mines of southeastern New Mexico are in a sparsely populated area 15-30 miles east of Carlsbad. Topographic relief is low, surface drainage poor, and collapse features common. The climate is semiarid.

Sedimentary rocks attain thicknesses of more than 20,000 feet and range in age from Ordovician to Quaternary. The area includes the northern end of the Delaware basin and the largely buried Capitan Reef. The basin contains as much as 13,000 feet of Permian strata. The oldest exposed rocks are of Late Permian age, but drilling has provided much data on the buried older rocks. The principle structures are broad gentle features related to late Paleozoic sedimentation: the northern Delaware basin, a shelf north and west of the basin, and a central basin platform to the east. These structures were tilted eastward before Pliocene time, have been inactive since, and now show a general eastward dip of less than 2°.

The salt deposits are in the Late Permian Ochoan Series composed of a thick salt-bearing evaporite lower part (Castile, Salado, and Rustler Formations) and a thin non-salt-bearing upper part (Dewey Redbeds).

The Castile Formation consists largely of interlaminated gray anhydrite and brownish-gray limestone, but includes much rock salt. It is about 1,500-1,600 feet thick along the southern edge of the potash area; it thins northward to about 1,000 feet near the margin of the Delaware basin and tongues out in the southernmost parts of the northwest shelf. All the salt is concentrated in a thick middle member which lies 200-300 ft above the base of the formation.

The Salado Formation, the main salt-bearing unit of the potash area, ranges in thickness from about 1,900 feet in the south to about 1,000 feet in the north. The formation is characterized by thick persistent units of rock salt alternating with thinner units of anhydrite and polyhalite. Thin seams of claystone underlie the anhydrite and polyhalite unit, and there are a few beds of sandstone and siltstone at large intervals. The Salado Formation is divided into three informal units: a lower and an upper salt member, generally free of sylvite and other potassium and magnesium evaporite minerals, and the McNutt potash zone, generally rich in these minerals.

The Rustler Formation mostly anhydrite and rock salt, thins from 300 to 400 feet in the southern part of the area to about 200-250 feet in the northern part. Some dolomite is present in the upper and lower parts of the formation, and thin to thick units of sandstone and shale are interbedded at long to short intervals.

The Dewey Lake Redbeds at the top of the Ochoan Series consist of reddish-brown siltstone and fine-grained sandstone. The formation is 250-550 feet thick in the potash area.

Three main hydrologic units control the ground-water hydrology of the Carlsbad potash mining area: the Pecos River, the water-bearing strata overlying the Salado

Formation, and the Capitan Limestone and other water-bearing strata underlying the Salado. The distribution and development of large dissolution features, particularly in the Nash Draw and Clayton Basin areas, exert a major effect on the occurrence and movement of the ground water. The Pecos River receives nearly all of the ground-water outflow from the area. Most of that outflow reaches the Pecos near Malaga Bend.

The main water-yielding units overlying the Salado Formation are the basal solution breccia zone and the Culebra Dolomite Member of the Rustler Formation, the Santa Rosa Sandstone, and the alluvium. The basal solution breccia zone is the hydrologic unit most significant in the solution of halite from the upper part of the Salado Formation. The easternmost extent of evaporite solution in the potash mining area is roughly at the common boundary between Ranges 30 and 31 E. The formations above the Salado Formation seem to be connected hydrologically and can be considered a single multiple aquifer system. Solution activity and associated collapse, subsidence, and fracturing have increased the overall permeability of the rocks and the interformational movement of water in the aquifer system.

Ground water in the formations above the Salado moves generally southward and southwestward across the potash mining area toward the Pecos River. Although the total amount of ground water discharging to the Pecos River is not known, it has been estimated that 200 gals per minute enter the river from the basal solution breccia zone.

The potentiometric and water-table contours outline a series of ground-water ridges and troughs imposed on the regional southward to southwestward pattern of ground-water movement. A large southwestward-plunging ground-water trough extends from Malaga Bend northeastward roughly through Nash Draw to beyond the mining area in the vicinity of Laguna Plata. Another much smaller trough is east and southeast of the Project Gnome site.

The Salado Formation has an intergranular porosity and permeability that ranges from low to virtually none. Locally, fractures and solution openings impart a spotty formational permeability. In the potash mining area, the Salado Formation is dry except for water in the leached zone at the top of the formation and small pockets of water or water and gas encountered ocassionally during mining.

The Cambrian to Permian sedimentary rocks underlying the Salado Formation contain water of brine composition and are under high artesian pressure. These rocks are not exposed in the potash mining area but lie deeply buried throughout much of southeastern New Mexico and western Texas. In the potash mining area the elevations of the potentiometric surfaces of different zones of these rocks range from a few feet to a few hundred feet above or below the land surface."

Brookins, D.G. 1980. Polyhalite K-Ar Radiometric Ages from Aoutheastern New Mexico. In Isochron/West pp. 29-31.

p. 29, col. 1;

" This paper lists four new radiometric K-Ar age determinations for polyhalites from southeastern New Mexico. These data are compared with seven published ages by Brookins and others (1980). The new (nos. 1-4) samples were chosen because they were mixed with halite and sylvite, although the exact halide content could not be determined from x-ray diffratometry. Nor can it be stated with certainty that other halides and-or other evaporite minerals are present or not. The detailed geology, mineralogy, chemistry and precise sample locations are given in SAND (1978). Earlier studies of langbeinite and langbeinite-sylvite mixtures have been reported in this journal by Schilling (1973), and will not be repeated here except to note that a distinct lowering of K-Ar ages with increasing sylvite content was noted. The purpose of this note is to see if similar effects are noted for polyhalites. The K-Ar analyses and age calculations were carried out by Geochron Laboratories, Inc., Cambridge, Mass."

Brookins, D.G. and Lambert, S.J. 1987. Radiometric Dating of Ochoan (Permian) Evaporites, WIPP site, Delaware Basin, New Mexico, USA. Materials Research Society, ed., Vol. 84, pp. 771-780.

ABSTRACT, p. 771;

" We have attempted radiometric dating of halide-sulfate salts and clay minerals from the Delaware Basin, New Mexico, USA, as part of geochemical study of the stability of the evaporite sequence at the WIPP (Waste Isolation Pilot Plant--a US DOE facility) site. We undertook this dating to determine: (1) primary age of evaporite genesis or time(s) of recrystallization, (2) if previously undated evaporite minerals (leonite, polyhalite, kieserite) give useful data, and (3) if the detrital clay minerals have been radiometrically reset at any time following their incorporation into the evaporite medium. We have shown earlier that polyhalites can indeed be successfully dated by the K-Ar method, and once corrections are applied for admixed halide minerals, dates of 210-230 Ma for the Delaware Basin are obtained. Rb-Sr isochrons from early stage sylvites-polyhalites-anhydrites yield 220 $\pm$ 10 Ma, even when some sylvites yield lower K-Ar dates due to loss of $^{40}Ar^*$. K-Ar dates on leonites and kieserites are also low due to $^{40}Ar^*$ loss, but their Rb-Sr dates are higher. Detrital clay minerals from the Delaware Basin collectively yield a highly scattered isochron (390 $\pm$ 77 Ma), but samples from a local area, such as the WIPP Site, give a much better age of 428 $\pm$ 7 Ma. These dates show that the interaction between the clay minerals and the evaporitic brines was insufficient to reset the clay minerals Rb-Sr systematics. In a related study, we note that a dike emplaced in the evaporite at 34 Ma had only very limited effect on the intruded rocks; contact phenomena were all within 2 m of the dike. All of our geochemical (radio-metric and trace element) studies of the WIPP site argue for preservation of the isotopic and chemical integrity of the major minerals for the past 200 Ma."

Brookins, D.G., Lambert, S.J., and Ward, D.B. 1990. Authigenic Clay Minerals in the Rustler Formation, WIPP Site Area, New Mexico. SAND89-1405. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p i, para 2;

" We have investigated the Rb-Sr systematics of clay minerals from the Culebra Member and elsewhere in the Rustler Formation. By separating the less than 0.125 μm size material we are able to deal with presumed true authigenic clay minerals. The authigenic fraction is especially sensitive to chemical and isotopic exchange with waters, and an episodic exposure to a large amount of water will reset the clay minerals to such a time. Our data yield 259 $\pm$ 22 Ma Rb-Sr isochron, which is consistent with the Late Permian age of the Rustler Formation. This age demonstrates that age-determining cations in these clay minerals have preserved their isotopic and chemical integrity since the Late Permian."

Brookins, D.G., Register, J.K., and Krueger, H. 1980. Potassium-Argon Dating of Polyhalite in Southeast New Mexico. Geochimica et Cosmoshimica Acta, Vol. 44, pp. 635-637.

ABSTRACT, p 635;

"   Polyhalite $K_2Ca_2Mg(SO_4)_4{\bullet}2H_2O$, is an important mineral in many evaporites. Although its use for K-Ar dating has never been investigated, our results indicate that it is a very useful mineral for dating events ranging from the time of potash mineralization to any younger events which may have affected the evaporite. Five K-Ar dates on pure polyhalite, including two from included material and from beds distorted by the formation of a rubble chimney, yield dates between 198 and 216 Myp, in good agreement with Rb-Sr dates and the diagenetic age of the potash deposits from the same rocks. Two polyhalites mixed with sylvite gave lower dates (154 and 174 Myr) which is to be expected because of radiogenic ^{40}K loss from the sylvite phase. One polyhalite, formed after the intrusion of a 31 Myr lamphrophyre dike, yielded 21 Myr. Collectively our results indicate that pure polyhalite is satisfactory for K-Ar dating and may provide critical age information in studies of the geologic history of the evaporite sequences."

Cauffman, T.L., LaVenue, A.M., and McCord, J.P. 1990. Ground-Water Flow Modeling of the Culebra Dolomite. Volume II: Data Base. SAND89-7068/2. Sandia National Laboratories, Albuquerque, NM.

PREFACE, p ii;

" The objective of this report is to present and discuss the hydrogeologic data base for the Culebra dolomite at the WIPP site. The data base includes:

- coordinates of the WIPP-area boreholes,
- Culebra elevations,
- Culebra transmissivities.
- Culebra storativities,
- Culebra formation-fluid densities,
- borehole fluid-density histories for the WIPP-site boreholes,
- estimates of the uncertainty in the borehole-fluid densities and the uncertainty in the related equivalent-freshwater heads,
- transient freshwater heads,
- estimates of an undisturbed freshwater head, and the uncertainty in this value for the WIPP-site boreholes, and
- shaft construction, grouting, and inflow histories.

This report documents the hydrogeologic data base subsequently used in a study which modeled ground-water flow in the Culebra dolomite. The modeling study is given in a companion report 'Ground-Water Flow Modeling of the culebra Dolomite: Volume I - Model Calibration', SAND89-7068/1, by A.M. LaVenue, T.L. Cauffman, and J.F. Pickens."

Chapman, J.B., 1986. Stable Isotopes in Southeastern New Mexico Groundwater: Implications for Dating Recharge in the WIPP Area. EEG-35. DOE/AL/10752-35. Environmental Evaluation Group, Santa Fe, NM.

EXECUTIVE SUMMARY, p iv;

" The first geologic repository for nuclear waste in the United States, the Waste Isolation Pilot Plant (WIPP), is being excavated at a depth of 2150 ft below ground surface in the Salado Formation in southeastern New Mexico. If a breach of the repository occurs, the water-bearing zones of the Rustler Formation, overlying the Salado, are considered to be the most likely pathways for the transport of radionuclides to the biosphere. A thorough characterization of the hydrology of the Rustler Formation is crucial to the evaluation of the consequences of a breach of the WIPP repository.

The Department of Energy is currently conducting studies of the Rustler Formation (many at the request of the State of New Mexico) that should significantly improve knowledge about the radionuclide contaminant transport ability of the Rustler. One recently completed study examined stable isotope data from Rustler groundwater and concluded that Rustler groundwater in the vicinity of the WIPP Site is not receiving significant modern meteoric recharge (Lambert, 1986). In addition, Lambert (1986) concludes that the stable isotope data reveal an hydraulic isolation of two possible discharge areas (well WIPP-29 and Surprise Spring) from the Rustler Formation elsewhere in Nash Draw and near the site. The conclusion of Lambert's (1986) stable isotope study allow longer residence time of water in the Rustler Formation and reduce the calculated consequences of a breach of the WIPP repository.

The present study compiles stable isotope data from throughout southeastern New Mexico and compares them to data from the WIPP area. The stable isotopic compositions of most samples of groundwater from the Rustler Formation are similar to the composition of other, verifiable young, groundwater in the area. Though the stable-isotope data cannot indicate ages for water in the various aquifers, neither do the data show any distinction between most Rustler groundwater and verifiable young groundwater.

A small number of samples, primarily from the Rustler/Salado contact east of Nash Draw, have isotopic compositions that are not characteristic of recently recharged meteoric water. These waters' enrichment in heavy isotopes may be due to mixing with deeper groundwater (supported by the stable isotopic composition of Salado fluid inclusions and Castile brine) or to exchange between the groundwater and hydrous minerals.

A comparison of the heavy isotope enrichment observed in evaporating waters and the composition of the water at WIPP-29 and Surprise Spring shows that the isotopic composition of these Nash Draw waters could be derived by evaporating Rustler groundwater. Based on stable isotopes, both WIPP-29 and Surprise Spring could be discharge areas for Rustler groundwater moving from elsewhere in Nash Draw and the east.

The enrichment in heavy isotopes found in water from pools in Carlsbad Caverns was used by Lambert (1986) as evidence that the relatively depleted Rustler water was recharged during a past, more pluvial, time. However, the uniqueness of the isotopic composition of water in the Caverns' pools suggest that rather than representing the composition of recent recharge, the heavy isotopes are enriched by evaporation and equilibrium isotope exchange in the humid cave environment. Recharge in the extreme karst environment near the cavern may also favor isotopically heavy precipitation."

Chapman, J.B., 1988. Chemical and Radiochemical Characteristics of Groundwater in the Culebra Dolomite, Southeastern NM. EEG-39. Environmental Evaluation Group, Santa Fe, NM.

EXECUTIVE SUMMARY, p. iii;

" The nation's first geologic repository for radioactive waste is being excavated in southeastern New Mexico at the Waste Isolation Pilot Plant (WIPP). It is located in the northern part of the Delaware Basin, within the bedded halite of the Salado Formation. Post-closure radioactive release scenarios from WIPP often involve hydrologic transport of radionuclides through the overlying Rustler Formation, in the Culebra Dolomite Member. The Environmental Evaluation Group (EEG) has conducted an investigation of the chemistry of Culebra groundwater with several objectives. Major ion analyses provide geochemical data that can be used to help determine groundwater flow paths and reactions that occur along those flow paths. Radiochemical data establish a baseline of existing radionuclides in area groundwater prior to the arrival of waste at WIPP. Both stable and radioactive constituents provide information that can be used to help predict the behavior of the Culebra as a radionuclide transport pathway.

Salinities in Culebra groundwater generally increase from west to east, with a large decrease in the area south of NM Highway 128. The linear correlation between total dissolved solids and Cl, and the almost one-to-one molar correlation between Cl and Na, are strong evidence that the salinity increase is due to halite dissolution. The increase in K and Mg concentrations eastward across the WIPP site corresponds to an increase in Cl, probably due to the dissolution of evaporite minerals coexisting with the halite. There is no obvious reason to relate the high K and Mg concentrations to low aquifer transmissivity and long residence times (as concluded by Mercer, 1983).

Two chemical facies exist in Culebra groundwater, and one of these can be further subdivided. A Na-Cl type water dominates over most of the sampled area with a Ca-SO_4 type occurring in the southern to southwestern area. The Na-Cl water can be subdivided into a low Ca area to the east and a higher Ca area to the west.

As groundwater moves from north to south across the area, the Total Dissolved Solids (TDS) decrease by an order of magnitude and the major hydrochemical facies change from Na-Cl to Ca-SO_4. The only plausible mechanism to effect this change is the influx of a large quantity of low TDS water. The possibility of recharge in the southern area is enhanced by the presence of solution and fill features such as the gypsum caves in the Forty-Niner Member of the Rustler near the Gnome site. These features could behave as conduits supplying fresher water to deeper Rustler units.

Exclusive of the low-salinity southern area, most wells located on the same general flow path have similar ion ratios. A few anomalies, especially in the area around wells H-1, H-2, and H-3 could be due to leakage of more saline water into the Culebra from underlying units. Abnormally high pressures in the Salado could provide a driving force for fluid movement upward. The possibility of such leakage is also indicated by the oxygen and hydrogen isotopic compositions that indicate mixing through the Rustler, Salado, and Castile formations."

Chaturvedi, L., ed. 1987. The Rustler Formation at the WIPP Site, Report of a Workshop on the Geology and Hydrology of the Rustler Formation as it Relates to the WIPP Project. EEG-34, DOE/AL/10752-34. Environmental Evaluation Group, Santa Fe, NM.

INTRODUCTION, p. 1;

" A workshop on 'The Rustler Formation at the WIPP Site' was organized by the Environmental Evaluation Group on March 7, 1985. The workshop was held at a time when a new series of studies on the Rustler Formation was starting. It provided the scientists from Sandia National Laboratories, the U.S. Geological Survey, IT Corporation, the Department of Energy and the Environmental Evaluation Group, an opportunity to exchange and discuss the up-to-date information on the geological and hydrological characteristics of the Rustler Formation. The papers and the summaries that follow reflect the status of knowledge at the time of the workshop (March, 1985). The decision to publish the proceedings was not made until after all the papers were received by the end of 1986.

Eight papers were presented at the workshop and much of the time was spent in discussing the relevance and significance of results obtained thus far and the need for further work. Following is a brief description of each of the papers presented and a summary of the discussions."

Chugg, J.C., Anderson, G.W., Kink, D.L., and Jones, L.H. 1952. Soil Survey of Eddy Area, New Mexico. U.S. Department of Agriculture.

" Major fieldwork for this soil survey was done in the period 1960-]965. Soil names and descriptions were approved in 1966. Unless otherwise indicated, statements in this publication refer to conditions in the Area in 1965. This survey was made cooperatively by the Soil Conservation Service and the New Mexico Agricultural Experiment Station. It is part of the technical assistance furnished to the Carlsbad, Central Valley, and Penasco Soil and Water Conservation Districts.

Either enlarged or reduced copies of the soil map in this publication can be made by commercial photographers, or they can be purchased on individual order from the Cartographic Division, Soil Conservation Service, USDA, Washington, D.C. 20250.

HOW TO USE THIS SOIL SURVEY

THIS SOIL SURVEY contains information that can be applied in managing farms and ranches; in selecting sites for roads, ponds, buildings, and other structures; and in judging the suitability of tracts of land for agriculture, industry, and recreation.

Locating Soils

All the soils of the Eddy Area are shown on the detailed map at the back of this publication. This map consists of many sheets made from aerial photographs. Each sheet is numbered to correspond with a number on the Index to Map Sheets.

On each sheet of the detailed map, soil areas are outlined and are identified by symbols. All areas marked with the same symbol are the same kind of soil. The soil symbol is inside the area if there is enough room; otherwise, it is outside and a pointer shows where the symbol belongs.

Finding and Using Information

The "Guide to Mapping Units,, can be used to find information. This guide lists all the soils of the Area in alphabetic order by map symbol and gives the capability classification of each. It also shows the page where each soil is described and the page for the capability unit and range site in which the soil has been placed. The first part of the guide lists the soils mapped at low intensity; the second part lists the soils mapped at high intensity.

Individual colored maps showing the relative suitability or degree of limitation of soils for many specific purposes can be developed by using the soil map and the information in the text. Translucent material can be used as an overlay over the soil map and colored to show soils that have the same limitation or suitability. For example, soils that have a slight limitation for a given use can be colored green, those with a moderate limitation can be colored yellow, and those with a severe limitation can be colored red.

. . ."

Cornell, C.A. 1968. Engineering Seismic Risk Analysis. Seismological Society of America Bulletin. Vol. 58, pp. 1583-1606.

ABSTRACT, p 1583;

" This paper introduces a method for the evaluation of the seismic risk at the site of an engineering project. The results are in terms of a ground motion parameter (such as peak acceleration) versus average return period. The method incorporates the influence of all potential sources of earthquakes and the average activity rates assigned to them. Arbitrary geographical relationships between the site and potential point, line, or areal sources can be modeled with computational ease. In the range of interest, the derived distributions of maximum annual ground motions are in the form of Type I or Type II extreme value distributions, if the more commonly assumed magnitude distribution and attenuation laws are used."

Cornell, C.A. 1971. "Probabilistic Analysis of Damage to Structures Under Seismic Load." In Dynamic Waves in Civil Engineering, D.A. Howell, I.P. Haigh, and C. Taylor, eds., pp. 473-488.

p. 473;

" Balanced engineering design in the face of uncertain loadings requires an assessment of the risks of various levels of damage associated with alternative designs. The appropriate analysis involves stochastic models of the occurrences in time, the sizes, and the induced damages of loading events. This paper is a compilation of recent work in such risk analysis. The emphasis will be on aseismic structural design, although the application of certain of the methodology to such problems as wind, storm, hurricane, tornado, and sea waves will be evident.

Much of the work to be reported has been done by the author or under his supervision at M.I.T., but several other investigators have also been interested in this and related topics recently. With the limited space available in this summary paper thorough referencing will be left to the reports mentioned in the body of the paper [1,2,3,4,5,6]. Nonetheless, the work of Luis Esteva of the University of Mexico[7,8,9] (whom the author visited in 1966 and who visited M.I.T. in 1969), and the efforts of the author's coworker Erik H. Vanmarcke should be given special mention. Many of the pieces of this paper are due in large part to them. The author would like, too, to acknowledge the support of the M.I.T. Interamerican Program and the National Science Foundation (Grant GK-5141).

To assess the seismic risk at a building site one must anticipate the number, locations, and magnitudes of future earthquakes in a region surrounding his site. This study must be coupled with some means of predicting the motions at the site of a given event at a given location, and some means of predicting the damage to the structure when such motions are experienced. The first portion of this paper will focus on seismicity, that is, on the ground motions themselves; the latter portion will discuss structural analysis, that is, measures of damage for given ground motion parameters, plus the coupling of the probabilistic analysis of the seismicity and the structural analyses."

Cornell, C.A., and Merz, H.A. 1975. Seismic Risk Analysis of Boston. Journal of the Structural Engineering American Society of Civil Engineering, Vol. 10, pp. 2027-2043.

ABSTRACT, p. iii;

" The paper presents an analysis of the annual risk that a firm-ground Boston building site might experience any particular level of seismic ground motion intensity, as expressed in Modified Mercalli Intensity, peak ground acceleration, or design response spectrum. The emphasis is upon providing the input for such an analysis in a real case and upon studying the sensitivity of the results to various important parameters."

Cornell, C.A., and Vanmarke, E.H., 1969. "The Major Influences on Seismic Risk." In Fourth World Conference on Earthquake Engineering, Vol. I, pp. 69-83. Santiago, Chile.

SYNOPSIS, p. A-1;

" A new, analytical method of seismic risk analysis is used to study the sensitivity of the peak ground acceleration values associated with prescribed design return periods to the assumptions which must be made when analyzing a site. The predominant influences on risk are thereby demonstrated quantitatively. It is shown that typically the more frequent, but smaller earthquakes contribute more to the risk than larger, more broadly destructive earthquakes. The importance of collecting instrumental data to provide more accurate attenuation laws for near-focus conditions (even for smaller earthquakes) is emphasized when the major influences on seismic risk are appreciated."

Crandall, K.H. 1929. Permian Stratigraphy of Southeastern New Mexico and Adjacent Parts of Western Texas. American Association of Petroleum Geologists Bulletin, Vol. 13.

ABSTRACT, p 927;

" The relationships of the Permian formations exposed in the Guadalupe, Delaware, and Apache mountains and immediately east have for some time been the subject of much dispute. These are greatly clarified by the classification of the Capitan and Apache limestones as reef formations built of the flanks of a large, subsiding basin. This basin was formed principally after the deposition of the lower Delaware limestone and then was partly filled with Delaware sand. The reefs were built during the deposition of the upper part of the Delaware sandstones. The Carlsbad limestones are considered the lagoonal facies of the reef series.

After being restricted from open marine conditions, the basin was filled with the products of an evaporating sea, the Castile gypsum and a distinct salt series.

No attempt is made to subdivide Darton's Chupadera in other parts of New Mexico."

Crawford, J.E., and Wallace, C.S. 1993. "Geology and Mineralization of the Culberson Sulfur Deposit." In Geology of the Carlsbad Region, New Mexico and West Texas, D.W. Love et al., eds., Forty-Fourth Annual Field Conference Guidebook, pp. 301–316. New Mexico Geological Society, Socorro, NM.

ABSTRACT, p 301;

" The Culberson sulfur deposit occurs as a replacement of Upper Permian evaporites (Salado and Castile Formations) by sulfur-bearing carbonates in the west-central Delaware basin. Structures from two major periods of tectonic activity control the location of sulfur mineralization. Pre-mineralization faults developed in response to Laramide compressional tectonics in the Late Cretaceous to early Tertiary, as indicated by breccia clast assemblages filling paleokarst features along the faults. Basin and Range extensional tectonics uplifted the western Delaware basin beginning in the middle to latest Miocene, resulting in a change in basin hydrodynamics conducive to bioepigenesis. Age of mineralization may be less than 5 Ma, based on mineralization cross-cutting karst-related deposits thought to be of Ogallala (middle-late Miocene) age. Crude oil analysis and correlation of anionic ground water constituents indicate the Guadalupian Cherry Canyon Formation is a probable source for hydrocarbons and oxygenated waters necessary for bioepigenetic sulfur deposition at Culberson. Sulfur occurs as microcrystalline dissemination in replacement limestone and as crystalline vug fillings associated with epigenetic barite, celestite and isotopically light carbonate minerals."

Crawley, M.E. 1988. Hydrostatic Pressure and Fluid-Density Distribution of the Culebra Dolomite Member of the Rustler Formation Near the Waste Isolation Pilot Plant, Southeastern New Mexico. DOE/WIPP 88-030. U.S. Department of Energy, Carlsbad, NM.

INTRODUCTION, p. 1-1;

" This report presents data collected during the three field periods of Pressure - Density Survey program for the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico. The location of the WIPP Site is shown in Figure 1. The WIPP project is operated by the United States Department of Energy (DOE) for the purpose of providing a research and development facility to demonstrate the safe disposal of radioactive wastes generated by the defense activities of the United States Government. This report presents data collected from 33 individual wells (Table 1A) located in the vicinity of the WIPP Site (Figure 2). Specific information concerning well completions, surveyed elevations, and other data is given in Table 1B.

The Pressure - Density Survey program (Crawley, 1987[a]) was developed to provide ground-water density and pressure information needed to analyze the ground-water hydrology of the Culebra Member of the Rustler Formation. Because the Culebra is a dipping geologic unit containing highly variable density water, formation pressures and accurately defined formation water densities must be used to determine ground-water flow directions (Jorgensen et al., 1982). Past investigations have calculated or estimated formation pressures using measured water levels from wells and single water-density values derived from the literature or estimated for various points across the project area. Estimated formation pressures are often in considerable error relative to actual measured pressures. The Pressure - Density Survey program has attempted to measure directly the pressures at the formation level, and to define the density profile of the fluids in the well bores standing above the depth of the formation in each well."

Dalrymple, G.B., and Lanphere, M.A. 1969. Potassium-Argon Dating. W.H. Freeman and Company.

NOTE: The above listed document was not available for inclusion in the Reference Expansion as of the printing date. Page changes will be provided as the above document becomes available for inclusion.

Davies, P.B. 1984. Deep-Seated Dissolution and Subsidence in Bedded Salt Deposits [Ph.D. Thesis]. Stanford University, Palo Alto, CA.

Section 2.3.5 Summary, p 175;

" A suite of structure contour maps constructed from available borehole logs confirms the existence of an anomalous, closed, structural depression in the northern portion of the WIPP site. This depression persists through several hundred feet of the middle and upper Salado Formation. The depression is broad and shallow in the upper portion of the section and becomes narrower and deeper in successively lower strata. Isopach maps show that the strongest local variations in bed thickness occur in the lowermost unit and are spatially associated with the structural depression. The salt appears to be anomalously thin in the margin areas.

Physical analyses of salt deformation processes suggest that this structural depression formed as the result of ductile subsidence in response to the localized removal of salt at some lower horizon. Processes capable of removing salt include dissolution of lower Castile salt, dissolution of lower Salado salt, and depletion of Castile salt by gravity driven flow. Deep boreholes in the northern WIPP area and elsewhere in the basin reveal geologic features that are characteristic of each of these processes. Consideration of complex structures in these areas leads to the conclusion that there are potentially significant interrelationships between individual processes and that more than one process may be active in a given area. For example, lower Castile salt dissolution may play a critical role in triggering the gravity foundering process by creating local increase in the deviatoric stress at the quasi-stable Anhydrite II and III density inversions and by causing the influx of a small amount of intergranular saturated brine, thereby decreasing the strength of the salt. Another example of process interrelationships is the potentially important role of lower Castile salt dissolution and gravity foundering in creating vertical and horizontal hydrologic pathways, thereby facilitating lower Salado dissolution.

At the Salado depression in the northern WIPP site, there is insufficient data in the Castile and lower Salado to delineate which processes have been active and what process interrelationships exist. Therefore, either additional subsurface data should be gathered in the lower Salado and Castile, or safety analyses of the WIPP facility should explicitly encompass all possible processes, or both."

DOE (U.S. Department of Energy). 1989. Draft Supplement Environmental Impact Statement Waste Isolation Pilot Plant. DOE/EIS-0026-DS. U.S. Department of Energy, Washington, D.C.

ABSTRACT, p iii;

" IN 1980, the DOE published the Final Environmental Impact Statement (FEIS) for the WIPP. This FEIS analyzed and compared the environmental impacts of various alternatives for demonstrating the safe disposal of transuranic (TRU) radioactive wastes resulting from DOE national defense related activities. Based on the environmental analyses in the FEIS, the DOE published a Record of decision in 1981 to proceed with the phased development of the WIPP in southeastern New Mexico as authorized by the Congress in Public Law 96-164.

Since publication of the FEIS, new geological and hydrological information has led to changes in the understanding of the hydrogeological characteristics of the WIPP site as they relate to the long-term performance of the underground waste repository. In addition, there have been changes in the information and assumptions used to analyze the environmental impacts in the FEIS. These changes include: 1) analyses of certain additional DOE generator and/or storage sites as potential contributors to the WIPP waste inventory, 2) changes in the composition of the TRU waste inventory, 3) consideration of the hazardous chemical constituents in TRU wastes, 4) modification and refinement of the system for the transportation of TRU wastes to the WIPP, and 5) addition of the Test Phase.

The purpose of this SEIS is to update the environmental record established in 1980 by evaluating the environmental impacts associated with new information, new circumstances, and proposal modifications. This SEIS evaluates and compares the proposed action and two alternatives for demonstrating the safe disposal of TRU wastes:

The proposed action is to operate the WIPP under a 'Test Phase' for approximately five years during which time certain tests and operational demonstration would be carried out. The tests would be conducted to reduce uncertainties associated with the prediction of natural processes that might affect long-term performance of the underground waste repository. Results of these tests would be used to assess the ability of the WIPP to meet applicable federal standards for the long-term protection of the public and the environment. The operational demonstrations would be conducted to show the ability of the TRU waste management system to certify, package, transport, and emplace TRU wastes in the WIPP safely and efficiently. Upon completion of the Test Phase, the DOE would determine, based on a performance assessment, whether the WIPP would comply with U.S. Environmental Protection Agency (EPA) standards for the long-term disposal of TRU wastes (i.e., 40 CFR Part 191, Subpart B). If there is a determination of compliance, the WIPP would enter a permanent disposal phase of approximately 20 years to demonstrate the safe disposal of TRU wastes. After completion of waste emplacement, the surface facilities would be decommissioned, and the WIPP underground facilities would serve as a permanent radioactive waste repository.

The first alternative, no action, is similar to the no action alternative discussed in the 1980 FEIS. Under this alternative, TRU wastes would continue to be stored at the various generator and storage sites, while the WIPP facility would be decommissioned and potentially put to other uses.

The second alternative to the proposed action is to delay emplacement of TRU wastes in the WIPP underground until a determination has been made of compliance with EPA standards for TRU waste disposal (i.e., 40 CFR Part 191, Subpart B). The DOE has determined that bin-scale tests could be conducted outside the WIPP underground facilities in a specially designed aboveground facility. This alternative has many implications including delays in both the operational demonstrations and room-scale tests, and the lack of room-scale test data for the compliance demonstration, a temporary mothballing of the WIPP facilities. This is true in any case. The specialized facility for aboveground bin-scale tests could be constructed at any one of several DOE sites. In order to analyze the environmental impacts of this alternative in the SEIS, the DOE has evaluated the Idaho National Engineering Laboratory in Idaho as a representative site for the aboveground bin-scale tests."

DOE (U.S. Department of Energy). 1983. Basic Data Report for Borehole Cabin Baby-1 Deepening and Hydrologic Testing. WTSD-TME-020. United States Department of Energy, Albuquerque, NM.

Section 1.0 ABSTRACT, p 1-1;

" Borehole Cabin Baby-1 was originally drilled to a depth of 4159.0 feet below kelly bushing (8.0 feet above ground surface) in 1974 and 1975 as a 'wildcat' hydrocarbon exploratory well. Control of the borehole was given to the U. S. Department of Energy (DOE) after it was found to be a 'dry hole'. Cabin Baby-1 was reentered, deepened, and hydrologically tested in August and September, 1983. The well is located in Section 5, T23S, R31E, just outside the limit of WIPP Zone III, approximately 2.5 miles south of the WIPP exploratory shaft.

The deepening and testing of Cabin Baby-1 was undertaken for several reasons:

- To provide data on the hydrologic properties, including hydrostatic head potential of selected permeable zones in the Bell Canyon Formation.
- To provide representative fluid samples from selected permeable zones in the Bell Canyon Formation for determination of fluid composition and density.
- To define further the stratigraphy of the upper Bell Canyon Formation at the Cabin Baby-1 location.

The borehole was deepened from the previous total depth to a new depth of 4298.6 feet below kelly bushing by continuous coring. Field operations related to deepening and logging of the borehole began August 12, 1983 and were completed August 30, 1983. Hydrologic testing activities began August 30, 1983 and were completed September 29, 1983. Drill-stem tests were conducted in four zones in the Bell Canyon Formation, and one test of the Salado Formation was performed. Fluid samples were collected from the Hays and Olds sandstones of the Bell Canyon Formation."

DOE (U.S. Department of Energy), 1990. Final Supplement, Environmental Impact Statement, Waste Isolation Pilot Plant. DOE/EIS-0026-FS. Office of Environmental Restoration and Waste Management, Washington, D.C.

Volume 1, Section 1.3 PURPOSE AND NEED FOR SUPPLEMENT TO FEIS, p 1-4;

" Since the publication of the FEIS in October 1980 and the subsequent Record of Decision to proceed with the phased construction and operation of the WIPP, new geologic and hydrologic information has led to changes in the understanding of the hydrogeologic characteristics of the area as they relate to the long-term performance of the WIPP. In addition, several changes have occurred in the Proposed Action and in the information and assumptions used to calculated the impacts reported in the FEIS. These include changes in the composition of the waste inventory, the transportation of waste to the WIPP, modification of the Test Phase, and the management of TRU mixed waste with hazardous chemical constituents.

This SEIS evaluates the environmental consequences of the Proposed Action as modified since 1980 in light of new information and assumptions. Modifications to the Proposed Action since 1980 that are examined in this SEIS are as follows: . . .

The new data and information and the resulting interpretations principally address the geologic and hydrologic systems at the WIPP site. They include:

- Determination of a locally lower permeability in the Salado Formation, the geologic formation in which the WIPP underground facilities are located (Subsection 4.3.2).
- Determination of a potentially higher moisture content in the Salado Formation and consequent brine inflow (Subsection 4.3.2).
- Discovery of a higher transmissivity zone in the Rustler Formation in the southeastern portion of the WIPP site (Subsection 4.3.3).
- New data leading to a conclusion that 'salt creep' (convergence) in the repository occurs faster than previously believed (Subsection 4.3.2).
- Pressurized brines within the Castile Formation which are assumed to be present beneath a portion of the WIPP waste emplacement panels (Subsection 4.3.4.2).
- Discovery of fractures in SPDV rooms (Subsection 4.3.2.4)."

DOE (U.S. Department of Energy), 1993. Waste Isolation Pilot Plant Land Management Plan. DOE/WIPP 93-004. U.S. Department of Energy, Carlsbad Area Office Carlsbad, NM.

Section 1.2 Management Goal, p 1-5;

" The goal of this land management plan is to manage the surface of the withdrawal area under the traditional public land use concept of multiple use and to minimize, to the extent possible, land use restrictions. It is not the intent of the DOE to manage the surface of the withdrawal area as a WIPP exclusive-use area. The subsurface of the withdrawal area is restricted to exclusive use by the WIPP, except for two 320-acre tracts of land within the withdrawal area that are leased for oil and gas development below 6000 feet (Federal Oil and Gas Leases No. NMNM 02953 and No. NMNM 02953C). This restriction is needed to protect the long-term integrity of the WIPP repository. In addition, it is clearly the intent of DOE that during repository operations, facility safety and security shall be maintained."

M

DOE (U.S. Department of Energy), 1994. Format and Content Guide for Title 40 CFR 191 and Title 40 CFR 268.6 Compliance Reports. DOE/CAO-94-2004. Carlsbad, NM.

INTRODUCTION, p 1;

" This Format and Content Guide was followed in preparing the WIPP Compliance Status Report submitted in March 1994 and will be used for the compliance documents scheduled for submittal in the Spring of 1995. The Compliance Status Report was issued to stakeholders in March 1994 and describes the status of associated activities on compliance with the requirements in Title 40 CFR 268.6 and Title 40 CFR 191. The Compliance Status Report focuses on 1) the information required for a demonstration of compliance, 2) preliminary results, 3) the areas of the WIPP program that are either not currently mature enough, or do not provide adequate margin for a demonstration of compliance, and 4) the areas of the WIPP program that will be focused upon to provide the remaining necessary information for use in the 1995 compliance demonstration reports. The Compliance Status report is not intended to constitute a statement of compliance or a demonstration of compliance. It is intended to report the status of progress made to date in project efforts to achieve the required level of data/information necessary for the required compliance demonstrations. Comments on the Compliance Status Report from stakeholders will likely result in a modified Format and Content Guide, as will the promulgation of the EPA's Compliance Criteria for WIPP (40 CFR 194)."

DOE (U.S. Department of Energy), 1994. Waste Isolation Pilot Plant 1994 Environmental Monitoring Plan. DOE/WIPP 94-024. U.S. department of Energy, Carlsbad, NM.

Section 1.0 INTRODUCTION, p 1-1;

" U.S. Department of Energy (DOE) Order 5400.1, General Environmental Protection Program Requirements (DOE, 1990a), requires each DOE facility to prepare an Environmental Monitoring Plan (EMP). This document is prepared for the Waste Isolation Pilot Plant (WIPP) in accordance with the guidance contained in DOE Order 5400.1 (DOE, 1990a); DOE Order 5400.5, Radiation Protection of the Public and Environment (DOE, 1990b); and the Environmental Regulatory Guide for Radiological Effluent Monitoring and Environmental Surveillance (DOE/EH-0173T, 1991). The WIPP project is operated by Westinghouse Electric Corporation, Waste Isolation Division (WID), for the DOE.

This plan defines the extent and scope of the WIPP effluent and environmental monitoring programs during the facility's preoperational and operational life. This document also discusses the WIPP's quality assurance/quality control programs.

This plan provides a comprehensive description of environmental activities at WIPP including:

- A summary of environmental programs including the status of environmental permits and monitoring activities (Section 1.0);
- A description of the WIPP project and its mission (Section 2.0);
- A description of the local environment including demographics (Section 3.0);
- An overview of the methodology used to assess radiological consequences to the public including brief discussions of potential exposure pathways, routine and accidental releases, and their consequences (Section 4.0);
- A summary of preoperational environmental monitoring and assessment activities (Section 5.0); and
- Responses to the requirements described in the Environmental Regulatory Guide for Radiological Effluent Monitoring and Environmental Surveillance (DOE/EH-0173T).

This document extensively references DOE Orders and other federal and state regulations affecting effluent and environmental monitoring programs at the site. WIPP procedure manuals, which implement the requirements of this program plan, are also referenced.

. . ."

DOE (U.S. Department of Energy) and state of New Mexico. 1981. Consultation and Cooperation Agreement. Appendix A to the Stipulated Agreement Resolving Civil Action, 81-0363JB, state of New Mexico vs. United States Department of Energy, United States District Court, Albuquerque, NM.

STIPULATED AGREEMENT, p. 1;

" Whereas, the plaintiff, State of New Mexico, ex rel. Jeff Bingaman, Attorney General, has brought this action to address four major concerns of the State of New Mexico; and,

Whereas, these concerns include: (1) that the final decision point for commencing construction of a permanent WIPP repository and its operation should not be reached until all interested parties including the State of New Mexico know the results of actual site and design validation tests and the SPDV program in general; and (2) that the State of New Mexico be given the opportunity to have a final resolution of all essential and integral off-site state government concerns involving health, safety, and public welfare issues prior to a final decision to commence construction of permanent WIPP facilities; and (3) that the State of New mexico be entitled to a binding and enforceable consultation and cooperation agreement that does not waive any right by the State to judicial review of any federal agency action with respect to the WIPP project; and (4) the concern that the withdrawal provisions of the Federal Land Policy and Management Act be complied with, including public hearings to be held before a decision is made to withdraw federal lands from the public domain for the WIPP project; and . . ."

Doser, D.I., Baker, M.R., Luo, M., Marroquin, P., Ballesteros, L., Kingwell, J., Diaz, H.L., and Kaip, G. Undated. The Not So Simple Relationship between Seismicity and Oil Production in the Permian Basin, West Texas. Department of Geological Sciences, University of Texas at El Paso, El Paso, Texas.

ABSTRACT, p 481;

" We have relocated seismicity occurring in the Permian Basin of west Texas between 1975 and 1979 using three-dimensional velocity models constructed from well log information and compared the locations to detailed geological and geophysical models of specific oil fields. The seismicity appears to be related to a variety of causes including migration of naturally occurring overpressured fluids, tectonic activity, reservoir production, and enhanced recovery operations. Many earthquakes may represent a combination of these effects. Although the Permian Basin is the site of numerous oil and gas fields, only a limited number of fields appears to be associated with seismicity. We find that there are similarities in the structural setting in the fields associated with seismicity. Furthermore, fields within the Delaware Basin that are associated with seismicity are located in regions of high vertical and lateral fluid pressure gradients related to an overpressured zone with the Delaware Basin."

Dunham, R.J. 1972. Capitan Reef, New Mexico and Texas: Facts and Questions to Aid Interpretation and Group Discussion. Publication 72-14, pp. 297. Permian Basin Section, Society of Economic Paleontologists and Mineralogists.

PREFACE; p i;

" This book was originally prepared in September, 1962, for geologists working for one particular oil company. In offering it to others at this time I feel the need to explain. The research behind the book and the writing itself were financed by Shell Development Company, with the aim of sharpening the conceptual tools Shell Oil Company used in searching for new hydrocarbons in carbonate reservoir rocks, and in wisely and profitably producing the new reserves and those already found. When Shell's purpose had been served, the book was released to me. The officers of the Permian Basin section of the Society of Economic Paleontologists and Mineralogists at that time, Shell management, and I decided that the book in practically its original edition can still be helpful despite the 1962-vintage words. We see the help going mostly to graduate school and other university groups but also to those geologists who lack contact with the equivalent of Shell's large-scale research effort or are in need of a refresher in carbonates.

The style is out of the ordinary . . ."

EPA (U.S. Environmental Protection Agency), 1990. "Background Document for the U.S. Environmental Protection Agency's Proposed Decision on the No Migration Variance for U.S. Department of Energy's Waste Isolation Pilot Plant," U.S. Environmental Protection Agency, Washington, D.C.

NOTE: The above listed document was not available for inclusion in the Reference Expansion as of the printing date. Page changes will be provided as the above document becomes available for inclusion.

EPA (U.S. Environmental Protection Agency), 1990. Conditional No-Migration Determination for the Department of Energy Waste Isolation Pilot Plant. Federal Register, Volume 55, No. 220, p. 47700, November 14, 1990. Office of Solid Waste and Emergency Response, Washington D.C.

"**Summary**:In response to a petition from the Department of Energy (DOE), the Environmental Protection Agency (EPA) is today making a determination of no migration for placement of hazardous waste at DOE's Waste Isolation Pilot Plant (WIPP), located near Carlsbad, New Mexico. Today's determination imposes several conditions on such placement and is for a maximum of ten years. As a result of this determination, DOE may place a limited amount of untreated hazardous waste subject to the land disposal restrictions of the resource Conservation and Recovery Act (RCRA) in the WIPP for the purposes of testing and experimentation."

"**I. Background**

A. RCRA Land Disposal Restrictions

The Hazardous and Solid Waste Amendments (HSWA) of 1984, which amend the Resource Conservation and Recovery Act (RCRA), imposed substantial new requirements on the land disposal of hazardous waste. In particular, the amendments prohibit the continued land disposal of hazardous wastes, unless either (1) the wastes meet treatment standards specified by the EPA, or (2) the Administrator determines that the prohibition is not required in order to protect human health and the environment. This latter determination must be based on a demonstration by the owner/operator of the facility receiving the waste 'that there will be no migration of hazardous constituents from the disposal unit or injection zone as long as the wastes remain hazardous.' (RCRA sections 3004(d)(1), (e)(1), and (g)(5).) The Department of Energy (DOE) has chosen to comply with the land disposal restrictions for certain transuranic (TRU) wastes to be shipped for testing and experimentation at its Waste Isolation Pilot Plant (WIPP) by pursuing the second option. Today's notice approves, with conditions, DOE's petition for the WIPP site."

EPA (U.S. Environmental Protection Agency), 1992. "No-Migration" Variances to the Hazardous Waste Land Disposal Prohibitions: A Guidance Manual for Petitioners [Draft], EPA530-R-92-023, Office of Solid Waste, Washington, D.C.

Introduction, p ii;

" This draft guidance manual is intended to assist hazardous waste management facility owners and operators who may be considering petitioning the U. S. Environmental Protection Agency (EPA) for a variance from land disposal prohibitions at specific sites for specific wastes. The guidance manual also provides the EPA interpretation and suggested procedures to implement the regulatory standards and procedures set out in 40 CFR 268.6. Readers should note that this guidance document is only a draft, and will be updated consistent with the final 'No Migration' rule, scheduled for publication in January 1993. Thus, this draft guidance manual is not itself binding on the Agency, the regulated community, or the public. EPA will fully consider alternative approaches raised by the applicant or other interested parties to the extent consistent with existing regulations at 40 CFR 268.6, the Resource Conservation and Recovery Act, and other EPA regulations. This manual also contains descriptions of additional requirements for 'no migration' petitions in the Land Disposal Restrictions First Third Rule promulgated on August 17, 1988 (53 FR 31138). The manual specifically does not address the requirements for 'no migration' petitions for waste disposal in deep injection wells. Requirements for deep well injection specifically pertain to the unique technological and hydrological conditions associated with injection. The reader should refer to the Underground Injection Control Rule promulgated on July 26, 1988 (53 FR 28118) for a complete discussion of how the Agency applies the 'no migration' standards in deep injection wells.

This manual is not a comprehensive review of 'no migration' variances, and will not provide the answers to all petitioners' questions; however, it does address the required scope of credible petitions. The EPA is strongly encouraging petitioners to meet with the Agency before preparing petitions to determine the scope and level of detail that will be required in individual petitions."

Esteva, L. and Rosenblueth, E. 1964. Espectros de Temblores a Distancias Moderas y Grandes. Bol. Soc. Mex. Ing. Sism, Vol. 2, pp. 1-18.

NOTE: The above listed document was not available for inclusion in the Reference Expansion as of the printing date. Page changes will be provided as the above document becomes available for inclusion.

Evernden, J.F. 1967. Magnitude Determination at Regional and Near-Regional Distances in the United States. Seismological Society of America Bulletin, Vol. 57, pp. 591-639.

ABSTRACT, p 591;

"   This report deals with the problems of variation P_n amplitudes in the regional and near-regional distance ranges (200-2100 kilometers). The data used were recorded by Long Range Seismic Measurement vans of the VELA Seismological Center as a result of earthquakes throughout the United States and numerous nuclear and chemical explosions in the same region.

It is shown that the pattern of P_n amplitudes versus Δ in Western United States and Eastern United States are markedly different and that these differences are related to different velocity structures in the two regions. These differences extend to at least 150 kilometers depth.

Neither the Western United States nor Eastern United States amplitude patterns conform even approximately to that predicted or suggested by Gutenberg and Richter in the 1000-2000 kilometer range. The predicted zone of low-amplitude signals in that distance range does not exist and overestimation of magnitude by as much as 1.5 magnitude units is frequently done because of failure to properly understand the patterns of radiation.

By proper calibration of the Western United States by use of numerous events, it is now possible to make consistent estimates of magnitude at all distance ranges for most explosions and earthquakes. Obtaining consistent estimates of amplitude as a function of distance for a particular event requires a knowledge of the energy distribution between the several refracted phases used between 200 and 2500 kilometers distance. Data on hand show that the energy portion function is reasonably uniform throughout the regions investigated but that locally it may vary radically, resulting in a ten-fold change in relative excitation of two refracted phases.

Patterns of energy radiation and decay are probably approximately determinable from knowledge of velocity structure and vice versa. Both are best determinable from explosion data where origin time and focus are accurately known."

Ewing, T.E. 1993. "Erosional Margins and Patterns of Subsidence in the Late Paleozoic West Texas Basin and Adjoining Basins of West Texas and New Mexico," New Mexico Geological Society Guidebook, 44th Field Conference, Carlsbad Region New Mexico and West Texas, D.W. Love et al., eds., pp. 155-166.

ABSTRACT, p. 155;

" The West Texas Basin is a complex late Paleozoic basin on the unstable craton. It is a composite of Early Pennsylvanian and Early Permian deformation and Early Pennsylvanian through late Permian subsidence. The postdeformational bowl of subsidence of the West Texas Basin is broadly similar to the subsidence of true intracratonic basins, such as the Michigan and Williston Basins. Unlike these basins, however, the present boundaries of the West Texas Basin do not follow or preserve the original limits of subsidence. The southern, western and to a lesser degree the eastern margins have been altered by pre-Albian uplift and erosion, assisted by Laramide and Tertiary uplift on the western margin. Only the northern margin is preserved, although it is complicated by the neighboring Anadarko Basin. The Pennsylvanian and Permian subsidence continued to the south and west of the preserved basin and probably connected with the Orogrande and Pedregosa Basins. This larger 'Permian Basin' contains both the Central Basin axis and the Diablo-Pedernal axis as intrabasin tectonic belts. The post-Permian erosion was probably due to a combination of uplift on the flanks of the Triassic-Jurassic rift complex, which resulted in the opening of the Gulf of Mexico, and uplift on the flanks of the Early Cretaceous Bisbee-Chihuahua Trough. Reconnaissance subsidence analysis of the West Texas Basin discloses a complex pattern of subsidence rates through the Permian. The most rapid tectonic subsidence took place in the Wolfcampian of the southern Delaware Basin, between the Marathon thrust sheets and the Fort Stockton uplift. Flexural subsidence is probably responsible. Post-Wolfcampian (postdeformational) subsidence of unknown origin continued to be centered in the north-south Delaware Basin trough, but extended north and east over a broad area of the Central Basin axis, the MIdland Basin and the Northwest shelf to form the 'Permian Basin.'"

Ferrall, C.C., and Gibbons, J.F. 1980. Core Study of Rustler Formation over the WIPP Site. SAND79-7110. Sandia National Laboratories, Albuquerque, NM.

INTRODUCTION, p. 1;

" This core study deals with the nature of the Rustler Formation at the Waste Isolation Pilot Project (WIPP) site in support of evaluating the influence that the Rustler will have on the effective isolation of wastes potentially disposed in the underlying formation.

The Rustler Formation is the uppermost evaporite formation of the Ochoan age rocks of the Permian Basin in southeastern New Mexico and western Texas. In the region of the WIPP site, the Rustler rocks make up a laterally continuous formation that occurs between the Salado Formation and the existing topographic surface. It is the Salado Formation into which the proposed waste repository is to be placed.

The core study described in this report was conducted in order to provide parameters for the thermomechanical modeling of the behavior of the Rustler Formation in response to heating. The aim of the core study has been to characterize the various members and units of the Rustler Formation in terms of physical properties, distribution, internal discontinuities, and boundary effects. The principle features treated here are results of the original deposition, diagenetic changes which the rocks have undergone, and the strain history of the rocks since deposition. Special attention has been paid to the extent to which the formation is fractured and the nature of fractures so that some estimate can be made of the potential for these discontinuities to be the locus of further strain.

The emphasis of this core study has been a megascopic observation of the rocks. For this purpose . . ."

Foster, R.W. 1974. Oil and Gas Potential of a Proposed Site for the Disposal of High-Level Radioactive Waste. Open-File Report, Contract No. AF(40-1)-4423. Oak Ridge National Laboratory, Oak Ridge, TN.

INTRODUCTION, p. 1;

" This study was in part funded by the Atomic Energy Commission under Contract No. AT-(40-1)-4423. Terms of this contract as they involve this particular study, are restated here so that reviewers may be aware of the basic aims of the project.

Project I - Evaluate the Petroleum Potential of the Proposed Radioactive Waste Disposal Site: Initial studies to be completed by February 15, 1973, will involve the development of pertinent information related to the location of a favorable site for coring of the Salado Formation and underlying rocks somewhere within Ts. 22-23 S., [Ts. 21-22 S.] , Rs. 31-32 E.

Evaluation of petroleum potential of the above-mentioned townships will include all rocks from the surface to the Pre-Cambrian [Precambrian] basement with emphasis on the deeper horizons. This study will include all wells in the area, and pertinent structural, lithologic and isopach data for the proposed disposal site. Necessary regional interpretation of these strata will be conducted and will include existing fields, wells, secondary recovery operations, areas of salt water disposal, production data, and pressures. In addition, the 1961 report by Foster and Stipp showing basement configuration in southeastern New Mexico will be revised. . . ."

Freeze, R.A., and Witherspoon, P.A. 1967. "Theoretical Analyses of Regional Groundwater Flow: 2. Effect of Water-Table Configuration and Subsurface Permeability Variation," Water Resources Research. Vol. 3, No. 2, pp. 623-634.

ABSTRACT, p 623;

" Details of steady-state flow in regional groundwater basins can be investigated using digital computer solutions of appropriately designed mathematical models. The factors that must be considered are: (1) ratio of depth to lateral extent of the basin; (2) water-table configuration; and (3) stratigraphy and resulting subsurface variations in permeability. The results of this study provide a theoretical basis for the following properties of regional flow systems: (10 groundwater discharge will tend to be concentrated in major valleys; (2) recharge areas are invariably larger than discharge areas; (3) in hummocky terrain, numerous sub-basins are superposed on the regional system; (4) buried aquifers tend to concentrate flow toward the principle discharge area, have a limiting effect on sub-basins, and need not outcrop to produce artesian flow conditions; (5) stratigraphic discontinuities can lead to distributions of recharge and discharge areas that are difficult to anticipate and that are largely independent of the water-table configuration."

FWS (U.S. Fish and Wildlife Services). 1989. Letter from John C. Peterson, Field Supervisor, Albuquerque, NM, to Jack B. Tillman, Project Manager, U.S. DOE-Carlsbad, May 25, 1989.

Cover Letter;
"Dear Mr. Tillman:

This responds to your letter dated May 19, 1989 requesting an update of the 1979 consultation regarding the affects of the Waste Isolation Pilot Plant (WIPP) on species Federally listed or proposed to be listed as threatened or endangered. Your geographic area is T22S, R31E, Sections 15-22 and 27-34 of eastern Eddy County, New Mexico.

We have reviewed the 1979 list of species occurring in the project area and find there are none that should be added at this time. However, the black-footed ferret should be removed. The current list should then include the American peregrine falcon, bald eagle, Pecos gambusia and Lee's pincussion cactus.

We suggest you contact the New Mexico Department of Game and Fish and the New Mexico Energy, Minerals and Natural Resources Department for information concerning fish, wildlife and plants of State concern.

If we can be of further assistance, please call Jerry Burton at (505) 883-7877 or FTS 474-7877.

Sincerely yours,
John C. Peterson
Field Supervisor"

Galley, J.E. 1958. "Oil and Geology in the Permian Basin of Texas and New Mexico." In Habitat of Oil—A Symposium, L. G. Weeks, ed.

ABSTRACT, p 395;

" Pre-Mississippian strata in the Permian Basin area consist chiefly of carbonate deposits of Ordovician, Silurian, and Devonian age which were produced in a marine environment probably characterized by clear, shallow seas covering a broad southward-sloping shelf. Oil accumulated in reservoirs in the carbonates, and in sandstone units of Cambrian and middle Ordovician age, the possible external sources being marine shale associated with the sandstone, a shale formation overlying the highest carbonate, and Pennsylvanian and Permian strata which lie unconformably on the older beds, as well as lower Paleozoic strata in a clastic basin south of the carbonate shelf. Mississippian strata are chiefly shale and limestone, containing probable source beds but generally poor reservoir strata.

Near the end of Mississippian time the tectonic environment changed from one of broad structures of gentle relief on a flat cratonic platform to an almost closed basin surrounded by mountain areas of high relief, the greatest of which was the Ouachita-Marathon complex.

Pennsylvanian strata, consisting of interbedded and intergrading marine shale, sandstone and limestone, reflect the changed environment. Oil, which the author believes to be indigenous to the system, accumulated in structural, stratigraphic, and porosity traps in Pennsylvanian reservoirs.

The Permian Period was characterized by deep but areally restricted marine basins of clastic deposition, stagnant at depth and surrounded by shoal platforms on which thick masses of carbonates accumulated and shallow lagoons extended to the shorelines. Burial of earlier strata by evaporites and red beds brought the period to a close. The principle sites of oil generation probably were in the basins; reservoirs include basinal sandstone and platform carbonate and sandstone rocks. The Guadalupe Series, which is stratigraphically the youngest and highest important producing unit and was therefore among the first to be exploited, contained more than half of all the oil which to date has been found in the Permian Basin."

M

Garber, R.A., Grover, G.A., and Harris, P.M. 1989. "Geology of the Capitan Shelf Margin—Subsurface Data from the Northern Delaware Basin." In Subsurface and Outcrop Examination of the Capitan Shelf Margin, Northern Delaware Basin, P.M. Harris and G.A Grover, eds., Core Workshop No. 13, p. 3-269. Society of Economic Paleontologists and Mineralogists (SEPM).

ABSTRACT, p 3;

" Facies relations determined from outcrop studies have been used in conjunction with subsurface data to better understand the geologic evolution, depositional facies, and diagenesis of the Capitan shelf margin. These studies have centered on a 2400 ft (731 m) portion of the 4800 ft (1463 m) continuous core from the Gulf PDB-04 research well that is located in Eddy County, New Mexico, at the northern end of the Delaware Basin.

The evolution of the Capitan shelf and margin was examined after (a) the establishment of time lines for shelf-to-basin correlations in the Late Guadalupian and (b) the confirmation of the stratigraphic units penetrated in the PDB-04 well. Subsurface and outcrop data revealed that the evolution of the 25 m.y. duration Capitan shelf margin occurred in two major growth phases: a 1.5 m.y. duration phase during Seven Rivers time when over 80% of the total progradation, over half of the aggradation, deposition of thick carbonate debris units on the slope and basin margin, and influx of over 60% of the total siliciclastics of the Bell Canyon Formation occurred. A subsequent, 1.0 m.y. growth phase during Yates and Tansill time is dominated by aggradation, steepening of the margin, and corresponds with abundant clastic deposition on the shelf. Maximum progradation of up to 12 miles (19 km) occurred along the northern rim of the basin, where progradation rates in excess of 7500 μm/year are measured.

Detailed shelf-to-basin correlations have revealed that three major processes were responsible for the profound progradation and differentiation of Capitan growth into two major phases: (a) fluctuations of sea level, (b) maximum emplacement of allochthonous carbonate debris along the basin margin during Seven Rivers time, and (c) that abundant siliciclastics bypassed the actively prograding shelf margin and were an important foundation for the progradation. . . ."

Griswold, G.B., 1977. Site Selection and Evaluation Studies of the Waste Isolation Pilot Plant (WIPP), Los Medaños, Eddy County, New Mexico. SAND77-0946. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p. 3;

" Bedded-salt deposits of the Salado Formation have been selected for evaluation for a proposed Waste Isolation Pilot Plant (WIPP) to be located in Eddy County, NM, ~26 mi east of Carlsbad. Site selection and evaluation studies that included geologic mapping, geophysical surveys, drilling, and resource appraisal were conducted over and under the prospective location. The lower portion of the Salado meets essential criteria for waste isolation. Beds chosen for waste storage lie 2074-2730 ft below the surface. High-purity salt exists at these depths, and the geologic structure revealed by geophysical surveys indicates that these beds are essentially flat. Additional geophysical surveys are now under way. The initial interpretation of the new data indicates that more structure may exist in the salt beds in the northern portion of the site area. Full evaluation of potentially commercial deposits of potash and natural gas within the WIPP site will be reported by separate studies, as will be the hydrologic details of the region."

Guilinger, J.R. 1993. "The Geology and Development of the Phillips Ranch Sulfur Deposit." In Geology of the Carlsbad Region, New Mexico and West Texas, D.W. Love et al., eds., Forty-Fourth Annual Field Conference Guidebook, pp. 21-23. New Mexico Geological Society, Socorro, NM.

p 21;

" IN April 1990, Addwest Minerals acquired the Phillips Ranch sulfur property. The deposit is hosted in the lower portion of the Permian Castile anhydrite at a depth of 1400 to 1800 ft below the surface. In July 1990, Addwest successfully completed a drilling program designed to test the grade and continuity of previous favorable results that Texasgulf, Inc. and Pennzoil Sulphur reported in their drilling programs.

The drilling of a regional gravity low . . ."

Gutenberg, B. and Richter, C.F. 1942. Earthquakes Magnitude, Intensity, Energy and Accelerations. Seismological Society of America Bulletin. Vol. 32. pp. 163-191.

p 163;

" The MAGNITUDE of an earthquake was originally defined by the junior author (Richter, 1935), for shocks in southern California, as the logarithm of the maximum trace amplitude expressed in thousandths of a millimeter with which the standard short-period torsion seismometer (free period 0.8 sec., static magnification 2800, damping nearly critical) would register that earthquake at an epicentral distance of 100 kilometers. Gutenberg and Richter (1936) extended the scale to apply to earthquakes occurring elsewhere and recorded on other types of instruments.

Application of the scale involves tables of the logarithm of the maximum trace amplitude for a shock of magnitude zero as a function of epicentral distance. These tables, given in the papers referred to, conveniently represented by a nomogram (fig. 1) designed by Mr. John M. Nordquist, who has drafted all the figures. The magnitude can then be found for shocks of 'normal' depth (about 20 km.). For slightly different depths a correction can be determined by the methods of the present paper. For shocks deeper than about 40 km. no reliable method for assigning magnitudes has been developed.

The magnitude scale has been applied with success to the local earthquakes of New Zealand, where standard torsion seismometers are in operation (Hayes, 1941); its extended form has been used by Ramanathan and Mukherji (1938) and by Mukherjee and Rangaswami (1941).

The purpose of the present paper is primarily to develop and investigate the relation of the magnitude, thus defined, to the energy released in an earthquake; also the relation of intensity on the Modified Mercalli Scale of 1931 to instrumentally determined acceleration. The connection of both magnitude and intensity with other physical elements of an earthquake is also investigated, largely with the help of the empirical equation (eq. 20, below) connecting magnitude with acceleration at the epicenter. The effect of focal depth on all the quantities is discussed."

Harding, S.T., Carver, D., Henrisey, R.F., Dart, R.L., and Langer, C.J. 1978. The Scurry County, Texas, Earthquake Series of 1977-1978: Induced Seismicity? Earthquake Notes, Vol. 49, No. 3.

p. 14;

" Three recent earthquakes (M_L 4.0 on 7 June 1977, M_L 3.5 on 28 November 1977, and M_L 4.75-5.0 on 16 June 1978) were located by the National Earthquake Information Service near Snyder, Texas, in an area where no previous seismic activity had been reported. Eight aftershocks in the magnitude range M_L 1.0-3.0 and a range of focal depth from 1 to 5 km were recorded by a 10-station portable seismograph net whose installation began within a day following the 16 June 1978 earthquake. The aftershocks occurred at the north end of the Scurry Oil Field in Scurry, Kent, and Borden Counties, about 140 km northeast of Midland. Parts of that oil field were undergoing large-scale water flooding, with well-head pressures between 144.8 and 220.6 bars at the time of the recent earthquakes.

The historical lack of seismic activity for this region, coupled with the epicentral locations falling within the oil field and the presence of high-pressure water flooding, suggest the possibility that the earthquakes and aftershocks were induced by the oil-field activities."

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G., and Smith, D.G. 1989. A Geologic Time Scale 1989. Cambridge Earth Science Series. Cambridge University Press.

"This book (GTS 89) is the planned successor to *A Geologic Time Scale* by W. B. Harland, A.V. Cox, P. G. Llewellyn, C. A. G. Pickton, A. G. Smith and R. Walters published in 1982 (GTS 82). It adopts the same style and employs and develops similar methods, but it has been entirely reworked. The state of the art in 1989 is thus presented, but the data assembled provide a source of reference which will serve for some years.

The work develops and assesses a new calibration of the geologic time scale employing a new database (amended to 1988). The new scale is summarized on the book covers and on a wall chart to be published separately. The work has been coordinated in detail throughout; nevertheless each chapter can stand on its own.

Chapter 1 sets out the principles and summarizes the results.

Chapter 2 treats the chronometric scale which is defined numerically and applies mainly for Precambrian time.

Chapter 3 treats the chronostratic scale which is defined in rock. Both Chapters 2 and 3 summarize progress made towards international agreement concerning definition, nomenclature and classification.

Chapter 4 explains the principles on which the database of isotopic determinations has been refined by tests both stratigraphic and geomechanical. Many of the GTS 82 age determinations have been rejected; the database now includes Cenozoic data; about 700 determinations are listed.

Chapter 5 calibrates the chronostratic scale, applying and developing the chronogram method to the data. This enables a time scale to be generated automatically and so allows comparison of the effects of the inclusion and exclusion of different classes of data.

Chapter 6 updates the magnetostratigraphic scale which in turn enables some refinement of the resulting time scale.

Chapter 7. Natural events are distinguished from the artifactual time scales and some global events are plotted linearly against the new time scale. This material has been adopted to the wall chart.

Appendices: (1) reproduces a list of the origins of stage and other names; (2) gives a system of stratigraphic abbreviations; (3) treats isotopic dating methods; (4) plots 125 chronograms; (5) plots the definitive magnetostratigraphic time scale; and (6) introduces the wall chart.

The list of nearly 100 cited and other references amounts to a selected bibliography. There are both general and stratigraphic indexes.

The whole work results in a time scale for 1989. By showing its mode of construction the reader can assess how the scale may be modified as more critical data become available. The estimated uncertainty in the time scale values adopted is significantly less than in previously published estimates."

Harms, J.C., and Williamson, C.R. 1988. Deep-Water Density Current Deposits of Delaware Mountain Group (Permian), Delaware Basin, Texas and New Mexico. American Association of Petroleum Geologists Bulletin, Vol. 72.

ABSTRACT, p. 299;

" The Guadalpian Delaware Mountain Group is a 1000-1600-m (3281-5250-ft) thick section of siltstone and sandstone deposited in a deep-water density-stratified basin surrounded by carbonate banks or reefs and broad shallow evaporite-clastic shelves. The most prevalent style of basinal deposition was suspension settling of silt. Laminated siltstone beds are laterally extensive and cover basin-floor topographic irregularities and flat-floor channels as much as 30 m (99 ft) deep and 1 km or more wide. Channels can be observed in outcrop at the basin margin and can be inferred from closely spaced wells in the basin. The channels are straight to slightly sinuous, trend at high angles to the basin margin, and extend at least 70 km (43 mi) into the basin. Sandstone beds, confined to channels, form numerous stratigraphic traps. Hydrocarbon sealing beds are provided by laminated organic siltstone, which laterally can form the erosional margin where channels are cut into siltstone beds. Thick beds of very fine-grained sandstones fill the channels. These sandstones contain abundant large and small-scale traction-current-produced stratification. These sandy channel deposits generally lack texturally graded sedimentation units and show no regular vertical sequence of stratification types or bed thickness.

Outcrop and subsurface evidence indicates Delaware Mountain Group sediments were deposited by saline density currents. Dense saline water originated on evaporitic shelves and spilled across the carbonate rim, down steep marginal slopes, and into the basin. Basinal waters were density stratified. Denser flows moved along the basin floor cutting channels or depositing sand in existing channels; less-dense flows moved along density interfaces in the water column and carried silt-size material far into the basin where it settled to the floor as thin alternating layers of detrital silt and organic debris. Little proximal to distal change occurred in the size or nature of the channels. Exploration predictions based on submarine fan models formed by turbidity currents would anticipate very different proximal-distal changes in sandstone geometry and facies."

Haug, A., Kelley, V.A., LaVenue, A.M., and Pickens, J.F. 1987. Modeling of Ground-Water Flow in the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) Site: Interim Report. SAND86-7167. Sandia National Laboratories, Albuquerque, NM.

INTRODUCTION, p. 1-1;

" The modeling studies of ground-water flow in the Culebra Dolomite Member of the Rustler Formation reported here have been performed as part of the regional hydrologic characterization studies for the Waste Isolation Pilot Plant (WIPP) site in southeastern New Mexico (Figure 1.1). The site characterization studies are being conducted in accordance with the Consultation and Cooperation Agreement between the U.S. Department of Energy and the State of New Mexico as part of the evaluation of the suitability of bedded salt of the Salado Formation for isolation of defense transuranic waste. The regional hydrologic characterization studies are being conducted by Sandia National Laboratories on behalf of the Department of Energy.

Hawley, J.W. 1993. "The Ogallala and Gatuña Formations in the Southeastern New Mexico Region, a Progress Report." In Geology of the Carlsbad Region, New Mexico and West Texas, D.W. Love et al., eds., Forty-Fourth Annual Field Conference Guidebook. New Mexico Geological Society, Socorro, NM.

ABSTRACT, p 261;

" The Ogallala Formation in the Southern High Plains section (Great Plains province) of southeastern New Mexico includes alluvial, eolian and playa-lake deposits and pedogenic calcretes of late Miocene and early Pliocene age (about 4-12 Ma). Beneath the Llano Estacado, it forms an almost continuous cover on rocks of Mesozoic age, is locally more than 400 ft (120 m) thick and is a major aquifer. In the Pecos Valley section of the Great Plains and along the Portales Valley through the western Llano Estacado, fine- to coarse-grained clastics of the late Miocene to middle Pleistocene age locally form thick fills (> 1000 ft., 300 m) in large solution-subsidence depressions. These features are aligned along segments of the ancestral Pecos and Brazos Valleys and are underlain by evaporites of Late Permian age. Some of these deposits have always been included in the Ogallala Formation, but in the lower Pecos Valley area (Roswell, NM to Pecos, TX), correlative depression and valley fills have been mapped variously as 'older alluvium, quartzose conglomerate, valley-fill alluvial deposits,' and as the Gatuña Formation. Gatuña-Ogallala chronologic and nomenclature problems have not yet been resolved in that area; however, it is clear that an ancestral 'lower' Pecos fluvial system has existed since late Miocene time near the present valley position between the Roswell (artesian) and Delaware Basins. In the sediment source area west of the Great Plains, Ogallala and Gatuña correlatives are discontinuous, commonly thin and only locally aquifers. The oldest deposits include piedmont fan alluvium, pediment veneers and valley and basin fills. They record semiarid climatic conditions, prior epeirogenic uplift and volcanism and ongoing Basin-and-Range tectonism in a broad area extending southward from the Southern Rocky Mountains through the Sacramento section of the Basin and Range province. Significant uplift of mountain fault blocks occurred along the Rio Grande rift margin in the western part of the (sediment) source region. The facies-distribution patterns of both the Ogallala and Gatuña Formations are quite complex west of the Southern High Plains. The oldest units may form basal fills of structural basins, solution-subsidence depressions, or stream valleys, or they may be preserved as piedmont alluvium capping high divides and tablelands, with younger deposits occurring as inset valley fills. Rising western highlands not only contributed runoff and sediment to prominent zones of secondary-carbonate accumulation in paleosols of the High Plains eolian cover indicates increasingly dry and more continental conditions in late Cenozoic time. Episodic deflation of alluvial plains prograding eastward and southeastward from mountain and piedmont source areas also produced eolian sediments that are a significant component of the Ogallala Formation and overlying Plio-Pleistocene deposits of the Llano Estacado area."

Hendrickson, G.E., and Jones, R.S. 1952. Geology and Ground-Water Resources of Eddy County, New Mexico. Ground-Water Report, Vol. 3, p. 169. New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.

ABSTRACT;

" Eddy County is physiographically diverse. It includes the Guadalupe Mountains in the southwest, the foothills of the Sacramento Mountains in the northwest, two areas of alluvial terraces bordering the Pecos River on the west, the Mescalero pediment east of the Pecos, and a small area of the High Plains in the northeast corner of the county.

Ground water supplies all public and domestic requirements, most of the stock water, and much of the irrigation water in the county. Some ground water is used for potash refining. The greatest use of ground water is for irrigation. The uses for public supply, industrial supply, and stock and domestic supplies follow in that order.

Ground water occurs in limestone, sandstone, siltstone, and gypsum of Permian and Triassic age, and in sand, silt, gravel, and conglomerate of Tertiary and Quaternary age.

In the Guadalupe Mountains water occurs mostly in limestone, but also in sandstone and siltstone, of Permian age, and in sand and gravel of Quaternary age. Ground water is used for stock and domestic supply, and a little for garden and orchard irrigation. The chief ground-water problem in this area is to find water at moderate depth. The quality and quantity of water are generally satisfactory for all uses. Windmills pump water from depths as great as 900 feet, and dry holes have been drilled to depths of more than 1,000 feet. The most favorable locations for wells are in or near arroyos where recharge is concentrated and water may be perched at the base of the arroyo gravels.

In the Carlsbad area, ground water occurs in the Carlsbad limestone, in the gypsiferous Castile and Rustler formations, and in the alluvium. Ground water is used chiefly for public supply, irrigation, and potash refining. Ground water is available in sufficient quantities for all present uses and is generally of fairly good quality in the Carlsbad limestone, although impotable water is found locally. The water in the overlying Castile and Rustler formations and in the alluvium is impotable in most places. The quality of water pumped from the Carlsbad limestone by the Carlsbad city wells had a wide annual range, but the chloride content of the water pumped showed a general increase from 1943 to 1950. If this increase continues the city of Carlsbad may be obliged to obtain its water from some other source. In the irrigation district south of Carlsbad, ground water is pumped from the alluvium primarily to supplement the surface supply of water for irrigation, except west of the main canal where some land having no surface-water rights is irrigated by ground water. Water levels in wells have declined several feet in places west of the main canal in recent years, but east of the canal water levels have declined little or not at all.

In the lower parts of the Roswell basin, the chief use of ground water is for irrigation. Water is obtained from shallow water-table wells in the alluvium, and from deep artesian wells in the San Andres formation and the lower part of the overlying Chalk Bluff formation. As all water rights are fully developed, the chief problem is to prevent wastage or overuse of water. Water levels in the artesian and especially in the water-table aquifers

have, over a period of years, shown a marked decline. West of the irrigated area depths to water increase to more than 800 feet at the county line. The chief use of ground water west of the irrigated area is for stock and domestic supplies, and the problem is to find water at comparatively shallow depths.

In the area between the Guadalupe Mountains and the Pecos River and generally south of latitude 32°15', ground water is used chiefly for stock and domestic supplies. Water from Rattlesnake Springs is used for the public supply at the Carlsbad caverns, and water from Blue and Geyser Springs is used for irrigation. Water is obtained from the alluvium, from the Castile formation, and possibly from the Rustler formation. Water from the alluvium near the mountains is generally of good quality, but farther east, as the water moves through gypsiferous rocks, the sulfate content increases and the water is locally unfit for domestic use. The depth to water in most wells is less than 100 feet, and the quantity of water available is generally sufficient for stock and domestic supplies.

East of the Pecos River ground water is used for stock and domestic supplies and for potash refining. Water is obtained from the limestone, gypsum, and redbeds of the Chalk Bluff formation and the Rustler formation and from the sandstone of the Dockum group. The chief ground-water problem is to find water of good quality, as the quantity available is generally sufficient and depths to water are not great. Water of fair quality is obtained from wells in the Chalk Bluff formation, which extends northward from Lake Avalon to and beyond the county line in a belt 6 to 10 miles wide bordering the Pecos River on the east, and also from some wells in the Dockum group near the east boundary of the county. Water of poor quality is obtained from most of the wells in Clayton Basin and Nash Draw and just east of the Pecos River from Malaga Bend southward to and beyond the county line. In the small area of the High Plains in the northeast corner of the county a few stock wells provide water of good quality."

Hern, J.L., Powers, D.W., and Barrows, L.J. 1979. Seismic Reflection Data Report Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico. SAND79-0264. Vols. 1 and 2. Sandia National Laboratories. Albuquerque, NM.

Section 1.0 ABSTRACT;

" This report describes three seismic reflection (Vibroseis) surveys conducted from 1976 through 1978 by Sandia laboratories to support investigations for the Waste Isolation Pilot Plant (WIPP). Volume I describes the purpose, field parameters, and data processing parameters. Volume II contains uninterrupted processed lines and shotpoint maps. Data interpretations will be the subject of the subsequent reports.

The data collected during these three surveys total 77 line miles; 72 line miles of this are on or very near the WIPP site. The first of the surveys (1976 SAN) covered 25 line miles and was conducted similarly to previous petroleum industry surveys in the area/ 1976 SAN supplemented existing petroleum industry data. The two subsequent surveys (1977 X and 1978 Y) used shorter geophone spacings (110'), higher signal frequencies (up to 100 Hz), and higher data sampling rates (2 ms.) to better define the shallow zone (less than 4000') of primary interest. 1977 X contained 47 line miles on or near the center of the WIPP site. These data show increasing discrimination of shallow reflectors as data collection parameters were modified. Data tables of recording and processing parameters are included.

A fourth Vibroseis survey was conducted at the WIPP site in 1978 by Grant Geophysical Company for Bechtel; the data are not in final form and are not included. Petroleum industry data and an inconclusive weight-drop survey, conducted in 1976, are also not included in this report."

Hicks, P.A. 1981. Mitigative Collection and Testing of Five Archaeological Sites on the Waste Isolation Pilot Project near Carlsbad, New Mexico for Westinghouse, Inc. Agency for Conservation Archaeology, Eastern New Mexico University, Portales, NM.

ABSTRACT, p 1;

" On September 19 & 20, 1981, the Agency for Conservation Archaeology (ACA), Eastern New Mexico University, conducted work at five archaeological sites in order to mitigate the effects of the construction and operation of the Waste Isolation Pilot Project (WIPP) near Carlsbad, New Mexico. The five sites, ENM 10206, ENM 10207, ENM 10209, ENM 10211, and ENM 10212, are all located in close proximity to the southern access road, or ancillary travel routes, placing them in situations of high to moderate impact from increased hydrocarbon pollution from vehicles and illicit collecting and digging activities. Mitigation of these archaeological sites consisted of the point proveniencing of all exposed artifacts and cultural features; the collection of all artifacts, exclusive of burned stone; and the excavation of several test pits to discern if cultural materials extended below the surface. The results of these mitigation procedures are herein reported."

Hicks, P.A. 1981. Mitigation of Four Archaeological Sites on the Waste Isolation Pilot Project near Carlsbad, New Mexico for Westinghouse, Inc. Agency for Conservation Archeology, Eastern New Mexico University, Portales, NM.

ABSTRACT, p 1;

" In January and August of 1981, the Agency for Conservation Archaeology (ACA), Eastern New Mexico University, conducted work at four archaeological sites in order to mitigate the effects of the construction and operation of the Waste Isolation Pilot Project (WIPP) near Carlsbad, New Mexico. The four sites, ENM 10201, ENM 10233, ENM 10237 and ENM 10241, all lie within 40 meters of the proposed location of the SPDV facilities. Mitigation of these archaeological sites consisted of the point proveniencing of all exposed artifacts and cultural features; the collection of all artifacts, exclusive of burned stone; and the excavation of several test pits to discern if cultural materials extended below the surface. The results of these mitigation procedures are herein reported."

Hills, J.M., and Kottlowski, F.E. 1983. Southwest/Southwest Mid-Continent Region. Correlation Chart Series. American Association of Petroleum Geologists.

EDITOR'S NOTE;

" The COSUNA Correlation Charts are intended to show stratigraphic columns which provide fairly complete coverage of the geology of the United States. In most cases, these columns are generalizations of the geology of an area and do not represent single surface or subsurface locations. The locations of the columns on the index map are intended to show the areas in which the stratigraphy is uniform enough to be shown in a single column. Since the columns are generalized they often show a range of thicknesses for each of the units and their dominant lithology within the map area.

Because the COSUNA Charts are correlation charts and not cross-sections their vertical scale is time, not thickness. Due to this difference, a number of features which may be shown on cross-sections cannot be shown on correlation charts.

The positional relationships of units separated by angular unconformities are not necessarily shown properly in each of the columns. Tilted contact lines show a time transgressive relationship the geographic directionality of which is not necessarily implied by the tilt of the line in the column. Units involved in faulting and especially those involved in thrust sheets are shown at a time at which they were deposited, not in the position into which they were thrust.

Igneous intrusives are shown at the time that they were intruded, not necessarily in the strata in which they intrude. Questioned contacts were placed for convenience in the vertical position near where they are most likely to occur. The amount of question in their positioning may vary from contact to contact.

Detailed information regarding the contacts, lithology, paleontology, references, and other significant information on each of the units on this chart is available by accessing the computerized COSU data file on the Petroleum Data System of the University of Oklahoma, Norman, Oklahoma."

Holt, R.M. 1993. Sedimentary Textures, Structures, and Lithofacies in the Salado Formation: A Guide for Recognition, Classification, and Interpretation. DOE/WIPP 93-056. U.S. Department of Energy, Carlsbad, NM.

1.0 INTRODUCTION, p 1-1;

" Evaporite rocks are difficult for most geologists to describe well, because geologists receive very little formal training in the study of evaporites. Although a variety of sedimentary textures and features are present, they are often difficult to recognize and describe. As a result, evaporite descriptions usually contain only mineralogical and crystal size data. Because the geologist's level of experience and background varies, consistent descriptions suitable for multiple uses, such as site characterization, are rarely produced.

At the Waste Isolation Pilot Plant (WIPP) site, the evaporites of the Salado Formation are described from cores and underground exposures as part of general site characterization activities. These activities are performed to document the strata surrounding the underground excavations. The geologic data collected during these activities, however, have potentially many uses besides simple documentation. For example, the data may be used for assessing variability within the formation as relevant to problems of hydrologic, mechanical, geochemical, or gas-flow anisotropy. The data should provide the basis for a second round of more task-specific data collection, if needed. In addition, high-quality detailed data may be essential for the resolution of yet undefined future problems, when data collection may be limited by logistics. The data collected during site characterization activities must be as complete and consistent as possible to meet these various needs, and investigators must be aware of their responsibility to collect those data.

This report is designed to fill the gap left in most geologist's experience by providing the information needed to completely and consistently describe and interpret the rocks of the Salado Formation in the vicinity of the WIPP. The rocks within the Salado Formation display a wide variety of uncommon sedimentary textures and structures. Investigators will become familiar with the types of sedimentary features present within the Salado, the processes which generated those features, the occurrence and distribution of those features in relation to Salado lithofacies, and current depositional models of Salado lithofacies. In addition, methods of describing and classifying evaporite rocks in underground exposures and cores will be presented.

A sedimentological approach to the study of evaporites is being employed by an increasing number of investigators (e.g., Holser, 1966; Kinsman, 1969; Shearman, 1970; Arthurton, 1973; Garrison et al., 1978; Arakel, 1980; Handford, 1981; Kushnir, 1981; Handford, 1982; Lowenstein, 1982, 1987, 1988; Southgate, 1982; Warren, 1982; Hovorka, 1983a, 1983b; Sonnefeld and Hudec, 1985; Lowenstein and Hardie, 1985; Fracasso and Hovorka, 1986; Casas and Lowenstein, 1989; Holt and Powers, 1990) and is emphasized here. Because modern evaporites often provide excellent analogues for depositional and early diagenetic features and textural and mineralogical facies distribution in ancient evaporites, recent studies of the Salado (e.g., Lowenstein, 1982, 1983, 1988; Jarolimek et al., 1983; Borns, 1985; and Holt and Powers, 1990) have relied extensively on modern analogues. In the following discussion, most descriptions and interpretations of Salado textures, sedimentary structures, and lithofacies are supported by descriptions of modern analogues.

This report is subdivided into four parts: first, the general geology of the Salado is presented (Chapter 2.0) to provide background for investigators. Second, typical Salado sedimentary structures and fabrics within sulfate, halite, and mudrocks are described and interpreted (Chapter 3.0). Third, Salado halite, sulfate, and mudrock lithofacies are discussed (Chapter 4.0). Finally, rock classification systems and descriptive procedures for halite, sulfate, and mudrocks are outlined (Chapter 5.0). The information contained within this report is derived largely from the evaporite literature, including work performed by WIPP investigators and unpublished work by the author."

Holt, R.M., and Powers, D.W. 1986. Geotechnical Activities in the Exhaust Shaft. DOE-WIPP-86-008. U.S. Department of Energy, Carlsbad, NM.

INTRODUCTION, p. 1-1;

" The Waste Isolation Pilot Plant (WIPP) project is a Department of Energy (DOE) research-and-development facility constructed to demonstrate the safe disposal of radioactive wastes derived from the defense activities of the United States. The WIPP project's mission consists of two parts. The first is to demonstrate the safe handling and disposal of transuranic (TRU) waste in bedded salt. The second is to create a research facility for in-situ examination of the technical issues related to the emplacement of defense-related radioactive waste in bedded salt.

The WIPP facility is located approximately 26 miles east of Carlsbad, New Mexico in an area known as Los Medanos (Figure 1). The underground portion of the facility is located at a depth of approximately 2,150 feet in the bedded salt deposits of the Salado Formation (Figure 2). An extensive program of site characterization and validation has been conducted for the past nine years (1976-1985). The results of these studies are summarized in the WIPP 'Geological Characterization Report' (Powers et al., 1978), the WIPP 'Safety Analysis Report' (DOE, 1980), the WIPP 'Preliminary Design Validation Report' (Bechtel, 1983), and the WIPP 'Results of Site Validation Experiments' (Black et al., 1983). Additional site investigations are being conducted as part of an ongoing program to further refine the understanding of the site-specific geology. The geotechnical activities conducted in the exhaust shaft are part of this program.

The exhaust shaft will provide a pathway for the release of exhaust air from the facility to the surface. The shaft is an enlargement of a six-foot diameter, upreamed shaft. The finished diameter is 14 feet in the lined portion of the shaft and 15 feet minimum in the unlined portion. Geotechnical activities consisting of reconnaissance geologic mapping, detailed geologic mapping in specific zones of interest, geologic confirmation of instrument locations, and field adjustment and modification of the key and aquifer seal design were performed concurrently with construction from July 16, 1984 to January 18, 1985. This report presents and discusses the findings from the geologic mapping efforts in the exhaust shaft. Also, the construction history of the exhaust shaft is summarized, and several engineering geology characteristics are discussed."

Holt, R.M., and Powers, D.W. 1990. "Halite Sequences within the Late Permian Salado Formation in the Vicinity of the Waste Isolation Pilot Plant." In Geological and Hydrological Studies of Evaporites in the Northern Delaware Basin for the Waste Isolation Pilot Plant (WIPP), New Mexico, D. Powers et al., eds., Field Trip #14. Geological Society of America, Dallas, TX.

INTRODUCTION, p. 45;

" A sedimentological approach has been used increasingly in the study of ancient halite rocks. As studies of ancient halites have been largely limited to data collected from core and, occasionally, limited underground exposures, most modern and experimental halite analogues have been examined for textures and features which may be identifiable from core or thin-section (Shearman, 1970; Arthurton, 1973; Handford, 1982; Southgate, 1982; Sonnenfeld and Hudec, 1983; Lowenstein and Hardie, 1985; Casas and Lowenstein, 1989). Numerous investigators (e.g., Garrison and others, 1978; Handford, 1981; Hovorka, 1983a, 1983b; Fracasso and Hovorka, 1986; Lowenstein, 1982, 1987, 1988) have used this approach to refine our understanding of the depositional systems of ancient halite rocks. Large-scale surface textures from modern halite deposits have been described by several investigators (e.g., Hunt and Washburn, 1960; Christiansen, 1963; Hunt and others, 1966; Cooke and Smalley, 1968). Except for a few studies of large-scale halite textures from underground exposures (e.g., Tucker, 1981; Powers and Hassinger, 1985), these fabrics have not commonly been studied in ancient halite deposits because they are not often recognized in samples of limited size, and their ability to survive beyond the time of deposition is considered questionable.

Exposures of the Late Permian Salado Formation in a shaft at the Waste Isolation Pilot Plant (WIPP) site showed abundant, previously unreported, large and small halite textures. Many of the large textures are similar to features that occur at the devil's Golf Course in Death Valley, California (Holt and Powerrs, in prep.). We were able to recognize, describe, and interpret numerous previously unrecognized halite textures and fabrics and to place these features into their stratigraphic context. To further refine the depositional model of Salado halite, we have constructed an 'idealized' Salado halite sequence of lithofacies based upon shaft mapping data, interpreted the fabrics observed within Salado halite sequences based upon their relationship to paleo-water table position, and interpreted the depositional environments of the lithofacies within our idealized sequence. . . ."

Holt, R.M., and Powers, D.W. 1993. "Summary of Delaware Basin End-Stage Deposits." In Geology of the Carlsbad Region, New Mexico and West Texas, D.W. Love et al., eds., Forty-Fourth Annual Field Conference Guidebook, pp. 90–92. New Mexico Geological Society, Socorro, NM.

p 90;

" The Salado, Rustler and Dewey Lake Formations record the end-stage depositional history of the Delaware Basin. After the Delaware Basin became isolated from marine environments at the beginning of the Ochoan Epoch, a unique series of depositional environments produced one of the thickest, uninterrupted records of deposition in the world. As the deep evaporitic lagoons that deposited the Castile Formation became hydrologically isolated from marine waters, solutes and sediments were derived from terrigenous sources outside the basin and Salado salt pan and related environments developed. Salado sediments completely filled the basin and extended over the Central Basin Platform and the Northwest Shelf. Both minor eustatic fluctuations and intermittent meteoric events inundated the basin, producing shallow saline lagoons, that deposited sulfate and ultimately evaporated to halite saturation. During Salado and Rustler time, a cyclical pattern of flooding by desiccation to evaporitic conditions, subaerial exposure and syndepositional alteration produced a series of characteristic environments and lithofacies. This pattern was broken by Middle Dewey Lake time as low-energy fluvial environments dominated sedimentation.

The following discussion summarizes our understanding of the sedimentology and depositional history of the Salado, Rustler and Dewey Lake Formations. . . ."

Howard, K.A., Aaron, J.M., Brabb, E.E., Brock, M.R., Gower, H.D., Hunt, S.J., Milton, D.J., Muehlberger, W.R., Nakata, J.K., Plafker, G., Prowell, D.C., Wallace, R.E., and Witkind, I.J. 1971 [reprinted 1991]. Preliminary Map of Young Faults in the United States as a Guide to Possible Fault Activity: Miscellaneous Field Studies Map MF-916, 1:5,000,000. 2 sheets. U.S. Geological Survey.

RIO GRANDE BASIN AND RANGE, Sheet 2 of 2;
"Rio Grande.--Abundant high-angle normal faulting in the late Cenozoic has formed the Rio Grande trough and adjacent basins and ranges. Evidence for movements in the Quaternary is common. The Rio Grande fault systems blend northward with similar basin-and-range faults that are somewhat masked by the surrounding topography of high Colorado Rocky Mountains."

Hubbert, M.K, 1940. "The Theory of Ground-Water Motion," The Journal of Geology, Vol. 48, no. 8, pt. 1, pp. 785-944.

ABSTRACT, p. 785, Para. 1;

" The existing analytical treatments of ground-water flow have mostly been founded upon the erroneous conception, borrowed from the theory of the flow of the ideal frictionless fluids of classical hydrodynamics, that ground-water motion is derivable from a velocity potential. This conception is in conformity with the principle of the conservation of matter but not with that of the conservation of energy. In the present paper it is shown that a more exceptionless analytical theory results if a potential whose value at a given point is defined to be equal to the work required to transform a unit mass of fluid from an arbitrary standard state to the state at the point in question is employed. Denoting this function by ϕ, it is shown that the differential equation of fluid flow in an isotropic medium is given by $q = -\sigma$ grad ϕ, where q is the flow vector whose magnitude is equal to the volume of fluid crossing a unit of area normal to the flow direction in unit time, and σ a specific conductivity parameter depending upon both the properties of the fluid and the medium. This is an expression of Darcy's law and is physically, as well as mathematically, analogous to Ohm's law in electricity and leads to the same deductions in analogous situations.

It is shown that $\sigma = kp/\eta$, where k is the permeability parameter depending upon the geometrical properties of the medium only and p and η are the density and viscosity, respectively, of the fluid.

The remainder of the paper is devoted to deducting the consequences of Darcy's law as just expressed, with particular regard for the practical problems of ground-water hydrology."

Jarolimek, L., Timmer, M.J., and McKinney, R.F. 1983. Geotechnical Activities in the Exploratory Shaft -- Selection of the Facility Interval, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico. TME 3178, U.S. Department of Energy, Albuquerque, NM.

Section 1.0 ABSTRACT, p 1-1;

" This report on geotechnical activities in the exploratory shaft was prepared as part of the Site validation Field Program for the U. S. Department of Energy's Waste Isolation Pilot Plant near Carlsbad, New Mexico. The report (1) summarizes basic data on shaft drilling and construction, (2) presents the geologic mapping results which essentially correspond to the conditions predicted from previous investigations, and (3) discusses the optimization process based on the geologic conditions encountered and its results for the (a) adjustment and modification of the shaft key design, (b) selection of the facility interval, and (c) selection of the geotechnical instrument locations."

Jarolimek, L., Timmer, M.J., and Powers, D.W. 1983. Correlation of Drillhole and Shaft Logs, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico. TME 3179. U.S. Department of Energy, Albuquerque, NM.

ABSTRACT, p. 1-1;

" This report on stratigraphic correlations from drillhole and shaft data along a generally north-south section across the potential extent of underground excavations of the Waste Isolation Pilot Plant (WIPP) facility was prepared as part of the *Site Validation Field Program Plan*. The results provide (1) input for the report entitled '*Results of Site validation Experiments*,' (2) input for other WIPP-related investigations, including the Design Validation Program, and (3) a framework for further underground activities at WIPP.

In general, this correlation study confirmed previous findings, including:

- A relatively high consistency of thickness and lateral continuity of all beds within the Salado Formation, especially in the host rock interval strata;
- Gentle, generally south and southeastward dips/slopes of the host rock interval strata;
- Close correspondence between stratigraphic data obtained from the present underground excavations and data derived from the previous investigative drill holes and shafts; and
- Depositional origin of the undulations on the top of Marker Bed (MB) 139 and relatively small variation in its thickness (1.2 to 4.1 ft)."

John, C.B., Cheeseman, R.J., Lorenz, J.C., and Millgate, M.L. 1978. Potash Ore Reserves in The Proposed [WIPP] Plant Area. Open-File Report for Eddy County, Southeastern, NM. U.S. Geological Survey.

ABSTRACTp. i;

" The proposed Waste Isolation Pilot Plant (WIPP) area includes about 18,960 acres in Tps. 22 and 23 S., Rs. 30 and 31., New Mexico Principle Meridian, Eddy County, southeastern New Mexico. It is located within the Carlsbad Mining District about 25 miles east of Carlsbad.

The WIPP area is immediately south of the Capitan Limestone subcrop, which formed the northern margin of the Delaware Basin in Permian time. During Late Permian (Ochoan) time, gypsum, anhydrite, and halite were deposited in the seas of the Delaware Basin to form the Castile Formation. These deposits have a maximum thickness of about 2,000 feet and grade upward into the more argillaceous beds of the Salado Formation. The Salado Formation contains abundant sulfate minerals, notably anhydrite and polyhalite. The potash ore minerals, langbeinite and sylvite, occur in the upper part of the Salado Formation in the McNutt potash zone, a local name applied to a potassium-rich zone.

Structurally, the WIPP area is situated within a broad syncline (mapped on top of the Salado) plunging gently to the southeast. Drill holes and surface geology analyses indicate no faulting in the area; and the only structural anomalies found are a local high and a small depression located in the southwest corner and north-central part of the WIPP area, respectively.

The minimum US Geological Survey standards for leasable potash ore are 4 feet of 10 percent K_2O as sylvite, 4 feet of 4 percent K_2O as langbeinite, or 4 feet of equivalent mixed ore as defined by a minimum of three data points in any one ore zone. Seven ore zones -- the 10th, 9th, 8th, 5th, 4th, 3d, and 2d -- maintain at least this thickness and grade in parts of the WIPP area. The WIPP area overlies an estimated 353.3 million tons (U.S. Geological Survey lease grade) of measured and indicated sylvite and langbeinite potash ore reserves. Approximately two-thirds of this ore occurs in intervals in the 10th and 4th ore zones; the rest is distributed among the five other ore zones."

Johnson, K.S. 1978. "Stratigraphy and Mineral Resources of Guadalupian and Ochoan Rocks in the Texas Panhandle and Western Oklahoma." In Geology and Mineral Deposits of Ochoan Rocks in Delaware Basin and Adjacent Areas, G.S. Austin, ed., Circular 159, pp. 57-62. New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.

ABSTRACT, p 57;

" Permian strata of Guadalupian and Ochoan age in the Texas Panhandle and western Oklahoma comprise a thick sequence of evaporites and red-bed shales and sandstones deposited north and northeast of the platform bounding the Midland Basin. These strata are 400 to 600 ft thick in much of the area, but they reach 2,000 to 3,000 ft in the major depositional basins. The study area embraces the Palo Duro, Anadarko, and Dalhart Basins and the Matador, Wichita-Amarillo, Cimarron, and Bravo uplifts. Lithostratigraphic studies enable correlation of the fossiliferous sequence of west Texas and southeast New Mexico with the sparingly fossiliferous red beds and evaporites of the Texas Panhandle and western Oklahoma. The early Guadalupian San Andres Formation of the Palo Duro Basin is correlative with the San Angelo (Duncan), Flowerpot, Blaine, and Dog Creek Formations of the El Reno Group farther north and east. The late Guadalupian Artesia Group of the Palo Duro Basin is equivalent to the Whitehorse Group and part of the overlying Cloud Chief Formation of the Anadarko Basin. Ochoan strata in the western and central parts of the Palo Duro Basin include the Salado, Rustler, and Dewey Lake Formations. The Salado salts pinch out northward within the basin, whereas the upper part of the Rustler extends northward and is correlative with the Alibates Bed. The Dewey Lake is believed equivalent to the Doxey Shale of western Oklahoma. The youngest Ochoan unit is the Elk City Sandstone, which apparently is limited to the axis of the Anadarko Basin. Mineral resources that have been developed include salt, gypsum, copper, uranium, petroleum, dolomite, sandstone, shale, and flint. Other minerals present in small quantities include potash and celestite."

Jones, C.L. 1954. The Occurrence and Distribution of Potassium Minerals in Southeastern New Mexico. Guidebook to Southeastern New Mexico. New Mexico Geographical Society, Albuquerque, NM.

p 107;

" The closing epoch in Permian time is especially known for the extensive evaporite deposits that fill the Delaware basin and extend across the Capitan reef zone for considerable distances over the shelf area. This epoch is represented by the strata of the Ochoa series, which includes the following formations:

Dewey Lake redbeds
Rustler formation
Salado formation
Castile formation

Extensive deposits of halite and anhydrite occur in each of the formations except the Dewey Lake, which does not contain evaporite deposits and which is composed entirely of red sandstone, siltstone, and minor amounts of shale. The Dewey Lake red beds form the protective cover that serves to retard the dissolution and removal of the soluble salts comprising the evaporite deposits of earlier formations of the Ochoa series.

Extensive evaporite deposits are found . . ."

Jones, C.L., 1978. Test Drilling for Potash Resources: Waste Isolation Pilot Plant Site, Eddy County, New Mexico. Open-File Report 78-592. Vols. 1 and 2. U.S. Geological Survey, Denver, CO.

ABSTRACT, p 1;

" Twenty-one borings to augment existing information on potash resources at the proposed site for a waste isolation pilot plant in eastern Eddy County, N. Mex., were drilled and logged in an 11-week period, mid-August to November 1976. The basic data developed from the borings are tabulated in the present report. The tabulation includes lithologic and geophysical logs of all the borings, as well as the results of chemical analyses, X-ray determinations, and calculations to establish a modal mineralogical composition of core samples from potash ore zones and mineralized salt beds."

Jones, C.L. 1981. Geologic Data for Borehole ERDA-9, Eddy County, New Mexico. Open-File Report 81-469. U.S. Geological Survey, Denver, CO.

ABSTRACT, p. 1;

" Borehole ERDA-9 is an exploratory well drilled in eastern Eddy County, New Mexico to evaluate and test salt beds for disposal of nuclear wastes. The drilling was done between April 28 and June 4, 1976.

Lithologic and stratigraphic details of the geologic section in ERDA-9 are described herein. The section includes: (1) the Mescalero caliche and the Gatuna Formation of Pleistocene age, (2) the Santa Rosa Sandstone of Triassic age, and (3) the Dewey Lake Red Beds, the Rustler Formation, the Salado Formation, and part of the Castile Formation, all of Permian age."

Keesey, J.J. 1976. Hydrocarbon Evaluation, Proposed Southeastern New Mexico Radioactive Material Storage Site, Eddy County, New Mexico. Vols. I and II. Sipes, Williamson, and Aycock, Midland, TX.

Introduction, Vol 1, p 1, para 2;

" The purpose of this evaluation was to determine the future remaining economically recoverable oil and gas reserves underlying the proposed radioactive waste material storage site, commonly known as the Los Medanos Site. This evaluation is to serve as a guideline to Sandia Laboratories in determining the acceptability of the "site area" and the potential value to the owners of the hydrocarbon rights. It is not, however, intended to be the basis for condemnation proceedings.

Keesey, J.J., 1977. Hydrocarbon Evaluation, Waste Isolation Pilot Plant Site Area To State and Federal Royalty Interests. Eddy County, NM.

"Gentlemen:

Subject: Hydrocarbon Evaluation, Waste Isolation Pilot Plant Site Area To State and Federal Royalty Interest, Eddy County, New Mexico

In accordance with Mr. George Griswold's request, we have prepared an evaluation to determine the future net revenue and fair market value to the royalty interests held by the State of New Mexico and the United States of America (Federal Government) in the Waste Isolation Pilot Plant (WIPP) site area. The potential values to the State of New Mexico and the Federal Government are from oil and gas production projected to be recovered from twenty potential locations within the boundaries of the WIPP site area. The results of our evaluation can be summarized as follows:

Effective Date: April 1, 1977

	State of New Mexico	Federal Government	Total
Net Reserves Remaining to Evaluated Interest			
BBL	65,470	112,753	178,223
MCF	7,608,000	36,529,000	44,137,000
Future Net Revenue to Evaluated Interest, $			
Undiscounted	1,763,091	7,633,865	9,416,956
Discounted at six percent	1,182,691	5,804,989	6,987,682
Hydrocarbon Fair Market Value, $	751,861	2,949,329	3,701,190
Acreage Value, $	135,000	91,200	226,200
Total Fair Market Value, $	886,861	3,040,529	3,927,390

The bases for the subject evaluation are two earlier reports prepared by Sipes, Williamson & Aycock, Inc. for Sandia Laboratories and the United States Energy Research and Development Administration (ERDA). The first of these reports was entitled, 'Hydrocarbon Evaluation, Proposed Southeastern New Mexico Radioactive Material Storage Site, Eddy County, New Mexico,' dated September 1, 1976. This report was prepared for Sandia Laboratories and was the basis for establishing the potential hydrocarbon reserves underlying the WIPP site area. The second report was entitled, 'Appraisal Report, Waste Isolation Pilot Plant Site, Eddy County, New Mexico' dated June 17, 1977, and was prepared for ERDA. The second report included the same ultimate forecasts as the first report, but contained updated cash flow projections to account for (1) changes in gas prices; (2) reimbursement for severance taxes; (3) forecasted changes in drilling times due to Bass

Enterprises Production Company's announced plans for drilling; (4) changes in discounting effects due to the later effective date; and (5) drilling costs to allow for directionally drilling under the known potash area. These two reports should be referred to for detailed information regarding reserve determination, pricing, drilling times, etc.

The subject report contains the same production and cash flow projections as were contained in the June 17, 1977 appraisal report for ERDA. This report, however, depicts only the income from royalty interests owned by the State of New Mexico and the Federal Government. For purposes of this report, it was assumed that the State of New Mexico and the Federal Government owned twelve and one-half percent (12.5%) royalty interest in their respective tracts. All capital costs and operating expenses were deleted as the State or Federal Government would not be responsible for such items. In addition, production taxes and ad valorem taxes were set at zero. Another change that was made for these runs was that the primary discount factor employed was six percent per annum whereas a ten percent primary discount factor was used for the referenced June 17, 1977 report. The six percent discount factor was used in accordance with Mr. George Griswold's instructions and was based on the premise that the State of New Mexico and the Federal Government could borrow money at a lower interest rate than the leasehold operators. For comparative purposes, secondary discount factors of eight, ten, twelve and fifteen percent per annum were calculated and are shown as a total figure in the lower right-hand corner of each printout.

Table No. 1 is a summary table depicting the wells forecasted, reserve category, assigned reserves and future net revenue to the State and Federal Government from their royalty interest holdings. ..."

Kelley, V.A., and Pickens, J.F. 1986. Interpretation of the Convergent-Flow Tracer Tests Conducted in the Culebra Dolomite at the H-3 and H-4 Hydropads at the Waste Isolation Pilot Plant (WIPP) Site. SAND86-7161. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p. ii;

" Tracer tests utilizing conservative organic tracers have been conducted in the Culebra Dolomite Member of the Rustler Formation at the locations of the H-2, H-3, H-4, and H-6 hydropads. The objective of this report is to present a quantitative evaluation of the physical solute-transport parameters of the Culebra dolomite at the H-3 and H-4 hydropad locations from interpretation of the tracer-test data. The tracer-test configurations consisted of a pumping well and two tracer-addition wells arranged in approximate equilateral triangles with 30-m sides. The transport of organic tracers from the tracer-addition wells to the pumping wells was analyzed using the finite-difference model SWIFT II, which is capable of simulating single- and double-porosity flow and transport.

The interpretive approach for analyzing the tracer-breakthrough curves at the pumping well first consisted of estimating the appropriate governing processes using the information base for each specific hydropad. For the H-3 hydropad, the test data indicated that a double-porosity interpretation approach was the most appropriate. In this conceptualization, the fractures represented the principle transport medium and the matrix provided the bulk of the solute-storage capability. The simulation model accounted for advective-dispersive transport in the fractures and diffusive transport in the matrix. Calibration of the tracer-breakthrough curves included conducting a parameter sensitivity analysis on longitudinal dispersivity, tortuosity, matrix porosity, fracture porosity, effective matrix block size, pumping rate, initial tracer-input distribution, and distance between pumping and tracer-addition wells. Calibration of the tracer-breakthrough curves for the H-3 tracer test resulted in longitudinal dispersivities from 5 to 10% of the flow path (well-separation distance), a fracture porosity of 1.9×10^{-3}, and effective matrix block sizes of 0.25 to 2.1 m.

There is uncertainty in the assumed or calibrated values for tortuosity, fracture porosity, matrix porosity, and matrix block size which were used to describe solute transport in the Culebra at the H-3 hydropad. Reduction in this uncertainty would require additional laboratory and field testing (e.g., additional drilling and coring, additional matrix porosity determinations on core, diffusion experiments, and additional on-site tracer testing). The results obtained from the conservative-tracer test suggest that fracture flow and matrix diffusion dominate solute transport in the Culebra at the H-3 hydropad. Further, the parameters derived to fit the tracer-breakthrough curves are thought to be consistent with the physical conceptualization of the Culebra at the H-3 hydropad.

The interpretation of the H-4 hydropad tracer test has not provided quantitative estimates of the physical solute-transport parameters for the Culebra. Qualitatively, the observed tracer-breakthrough curves could be simulated by representing the Culebra with a layered system of higher- and lower-permeability units. In this system, transport would be dominated by the higher-permeability zones with diffusive interaction with the lower-permeability zones. No evidence was obtained to indicate that transport of the tracers had

occurred through fractures; however, considering the fractured nature of the Culebra at the H-3 and H-6 hydropads and other locations at the WIPP site, the existence of fractures in the Culebra at the H-4 hydropad should still be considered a possibility. However, if present, these fractures do not appear to have had a significant effect on solute transport on paths examined in the H-4 tracer test."

Kenney, J.W., Downes, P.S., Gray, D.H., and Ballard, S.C. 1995. Radionuclide Baseline in Soil Near Project Gnome and the Waste Isolation Pilot Plant. EEG-58. Environmental Evaluation Group, Albuquerque, NM.

EXECUTIVE SUMMARY, p. x;

" The Gnome site is the location of a 1961 underground nuclear detonation in the Atomic Energy Commission (AEC) Plowshare program that vented radioactive contamination to the atmosphere. The resulting ground contamination was cleaned up in 1968-1969 and again in 1977 as weathering affected some shallow burial. Subsequent environmental surveys revealed slightly elevated ^{137}Cs levels, but no transuranic contamination.

The Waste Isolation Pilot Plant (WIPP) is approximately 8.8 km (5.5 mi) northeast of the Gnome site, and the Gnome site is within the preoperational radiological surveillance area for the WIPP. The Environmental Evaluation Group (EEG) conducts a WIPP preoperational radiological surveillance program, and the EEG initiated field surveys at Gnome in 1994.

The EEG used a combination of traditional and state-of-the-art radiological survey techniques. In addition, soil samples were collected for analysis in the newly established EEG radiochemistry laboratory, and the EEG results were compared to commercial laboratory analyses. New methods for contamination surveys, sample screening and telemetry were evaluated and found to be more sensitive and efficient than historical methods.

Localized and surface contamination was identified, and soil samples were taken from selected areas and control locations outside the Gnome site. Radiochemical analyses by EEG and a commercial laboratory indicated elevated levels of ^{238}Pu, $^{239+240}$Pu, and ^{241}Am at Gnome. The radioactivity was heterogeneously distributed within the samples which is consistent with contamination from atmospheric nuclear weapons testing. Samples outside the Gnome area did not indicate transuranic contamination.

The EEG radiochemical analyses, limited to surface soil samples, show the presence of transuranic contamination at the Gnome site. Although there is measurable transuranic contamination at Gnome, the levels do not appear to present any immediate health and safety concerns. Additional work is needed to determine if contamination is ta greater soil depths, and if further remedial action is needed."

King, P.B. 1948. Geology of the Southern Guadalupe Mountains, Texas. Professional Paper 215. U.S. Geological Survey, Washington, D.C.

ABSTRACT, P 1;

" This report deals with an area of 425 square miles in the western part of Texas, immediately south of the New Mexico line. The area comprises the south end of the Guadalupe Mountains and the adjacent part of the Delaware Mountains; it includes the highest peaks in the State of Texas. The area is a segment of a large mountain mass that extends 50 miles or more northward and southward. The report describes the geology of the area, that is, the nature of its rocks, tectonics, and surface features, and the evidence that they give as to the evolution of the area through geologic time. Incidental reference is made to the geology of surrounding regions in order to place the area in its environment.

Stratigraphy of Permian Rocks-- . . ."

M

King, R.H. 1947. Sedimentation in Permian Castile Sea. American Association of Petroleum Geologists Bulletin, Vol. 31, pp. 470–477.

ABSTRACT, p 470:

" The Permian Castile formation is a favorable starting point for a study of precipitated marine sediments because of its relatively simple stratigraphy. It is 1,300 to 2,000 feet thick and consists principally of 'banded' or laminated anhydrite, but it contains some salt and other materials. It was deposited within the deep steep-walled Delaware Basin of western Texas and southeastern New Mexico. Throughout Castile time communication with the open sea was maintained through a restricted channel near the southwest corner of the basin. Paucity of detrital material indicates that the deposit consists almost exclusively of marine evaporites.

It is suggested that the water within the basin consisted of a body of brine lying below average wave base and a less dense surface layer lying above average wave base. Some of the dense brine continuously returned to the open sea; otherwise the volume of halite deposited would have been about 30 times as great as the volume of anhydrite instead of somewhat less than the volume of anhydrite. The barrier must therefore have been incomplete. Either the top lay partly below wave base or the barrier was permeable. This theory of reflux is presented as a modification of Ochsenius' bar theory.

The calcium sulphate presumably was deposited as anhydrite rather than as gypsum because of the salinity of the brine. The banding is ascribed to seasonal variation in temperature. The average net rate of evaporation in Castile time is calculated as 114 inches a year."

Klemmick, G.F. 1993. "Geology of the Pokorny Sulfur Deposit, Culberson County, Texas." In Geology of the Carlsbad Region, New Mexico and West Texas, D.W. Love et al., eds., Forty-Fourth Annual Field Conference Guidebook, pp. 18–19. New Mexico Geological Society, Socorro, NM.

p 18;

" The Pokorny sulfur deposit is located in the northwest corner of the Delaware Basin, in the Rustler Springs sulfur district of west Texas (Fig. 1.20), approximately 35 mi south of Carlsbad, New Mexico, in northeast Culberson County, Texas (Fig. 1.21). To date, 57 sulfur test wells have been drilled by Addwest Minerals delineating a resource of greater than one million long tons (lt) of native sulfur.

The Pokorny sulfur deposit was inadvertently discovered . . ."

Kunkler, J.L. 1980. Evaluation of the Malaga Bend Salinity Alleviation Project. Open-File Report 80-1111. U.S. Geological Survey, Denver, CO.

ABSTRACT, p 1;

" In an effort to reduce the flow of brine springs in the Malaga Bend reach of the Pecos River in southeastern New Mexico, brine was pumped from an aquifer underlying the Malaga Bend reach to a local depression known as Anderson Lake. The attempt to improve the quality of river water with this experiment was not successful because brine leakage from Anderson Lake to the nearby Pecos River through permeable subsurface rocks was greater than the previous natural spring inflow.

Brine leakage from Anderson Lake from July 22, 1963, through September 30, 1968, was estimated by evaporation-pan, salt-accumulation, and dissolved-constituent methods. The leakage values given by these three methods are in good agreement with each other and indicate that between the dates given, leakage from the lake was about 2,300 acre-feet, compared with a brine inflow to the lake of about 3,690 acre-feet. Other data indicate that pumping from the brine aquifer greatly reduced the natural inflow from brine springs to the Malaga Bend reach.

The rate of brine leakage from Anderson Lake is probably greater than might be expected from other brine lakes in the area because the cavities in the bottom of the lake are in hydrologic connection with the Pecos River. This connection is shown by a relation between the salinity of the Pecos River and the reservoir stage of Anderson Lake."

Lambert, S.J., and Carter, J.A. 1984. "Uranium-Isotope Disequilibrium in Brine Reservoirs of the Castile Formation." In Principles and Methods, Northern Delaware Basin, Southeastern New Mexico. SAND83-0144. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p 3;

" We evaluated uranium isotope activity ratios with respect to models for the origin of the brines in two brine reservoirs in the Castile Formation (ERDA No. 6 and WIPP No. 12). In Castile anhydrite, a completely closed water system that was continuously leaching Th-recoil-produced ^{234}U from freshly exposed surfaces of fractured host rock would give rise to uranium 234/238 isotope activity ratio (α) values significantly higher than observed values. Therefore, the brine occurrences are not the result of continuous deformation. Similarly, a model assuming movement of intergranular Permian seawater into fractures was found inconsistent with observed uranium isotope systematics. The observed α-values (95% confidence limits) of ERDA No. 6 (1.34 to 1.58) and WIPP No. 12 (1.74 to 2.54), used in conjunction with an inferred initial α_0 higher than observed values, allows calculation of reasonable finite minimum ages, involving no preferential leaching of ^{234}U in the host rock. If the brine occurrences are inferred to have been connected at one time with a more extensive nearby hydrologic system, the Capitan limestone ($\alpha_0 = 5.1$), calculated minimum ages of isolation from that system are 700 000 to 880 000 yr for ERDA No. 6 and 360 000 to 610 000 yr for WIPP No. 12. These ranges in ages are the 95% confidence limits based on experimental determination of α-values. The ages thus derived may reflect an episode of structural deformation in the Pleistocene that allowed water to enter the resulting fractures."

Lang, W.B. 1935. Upper Permian Formation of Delaware Basin of Texas and New Mexico. American Association of Petroleum Geologists Bulletin, Vol. 19, pp. 262–276.

ABSTRACT, p 262;
" The purpose of this paper is to define and name the formations of the Delaware basin of Texas and New Mexico above the Delaware Mountain formation, that future discussions of the stratigraphy of the area may be facilitated. Something of the relationships and characteristics of these formations are given. The question of the age of the Bissett formation is also discussed."

Lang, W.B. 1947. "Occurrence of Comanche Rocks in Black River Valley, New Mexico." American Association of Petroleum Geologists Bulletin, Vol. 31, pp. 1472-1478.

ABSTRACT, p. 1472;

" The discovery of Comanche fossils in Black River Valley provides a means for more accurately defining the position of the Comanche shoreline in southeastern New Mexico. An explanation is offered for the anomalous occurrence of these fossils and one which may help to clarify previous misconceptions of the geology of the area. A brief reference is made to related early geologic explorations in the region.

In the valley of Black River, near the center of the east side of the NW. ¼ of Sec. 31, T. 25 S., R. 25 E., Eddy County, New Mexico, and about 200 feet southeast of the highway (U.S. 62, State 180) is a patch of loose gravel and rock débris resting on a top soil of gypsite. This débris, which is likely to be overlooked by anyone not purposely in search of it, was turned up by the Army in 1943 when grading a new road, and it was found by a party of Superior Oil Company geologists on a field trip in 1944.[3] This material is of interest because it is geologically anomalous to the area. Here and for miles around, the Castile formation of Permian age, where not covered by a remnant of Rustler dolomite, the Quaternary Gatuña formation, or more recent valley deposits, is exposed at the surface.

Scattered about within a circle approximately 200 feet in diameter are fragments of sandstone and limestone. Many of the fragments are fossiliferous. Though the fossils are abundant they are limited in variety, as becomes apparent when the ground is carefully combed for every variant form. R. W. Imlay examined a collection made here and listed the following forms.

Anorthopygus s. sp
Gryphaea corrugata (Say)
Neithea texana (Roemer)
Opis? sp.
Protocardia texana (Conrad)

Imlay states

Gryphaea corrugata Say ranges through the Duck Creek and Kiamichi. The new species of the echinoid genus *Anorthopygus* has been identified by C. W. Cooke, who notes that it has been found in the Duck Creek and Fort Worth. Furthermore, the rock matrix resembles the Duck Creek limestone.

These identifications place the horizon of the strata from which the fragments were derived at the base of the Washita group of the Comanche series. The Kiamichi formation, which was formerly placed at the base of the Washita group, is now placed by the United States Geological Survey at the top of the underlying Fredericksburg group of the Comanche series."

Lappin, A.R., Hunter, R.L., Garber, D.P., Davies, P.B., Beauheim, R.L., Borns, D.J., Brush, L.H., Butcher, B.M., Cauffman, T., Chu, M.S.Y., Gomez, L.S., Guzowski, R.V., Iuzzolino, H.J., Kelley, V., Lambert, S.J., Marietta, M.G., Mercer, J.W., Nowak, E.J., Pickens, J., Rechard, R.P., Reeves, M., Robinson, K.L., and Siegel, M.D., eds., 1989. Systems Analysis, Long-Term Radionuclide Transport, and Dose Assessments, Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico: March 1989. SAND89-0462. Sandia National Laboratories, Albuquerque, NM.

EXECUTIVE SUMMARY, p iii;

" This report summarizes the current understanding of the expected long-term behavior of the Waste Isolation Pilot Plant (WIPP) repository and estimates long-term radionuclide doses in a series of six analyses investigating both undisturbed repository performance (Case I) and performance in response to a relatively high-consequence human Intrusion (Case II). It is the result of an intensive effort over a short time. The U. S. Department of Energy (DOE) decided to have Sandia National Laboratories prepare this report as a result of a meeting held January 5, 1989. The conceptual model of the expected long-term behavior of the WIPP repository used in this report was formulated in early to mid January 1989, drawing on information and understanding developed over the past decade. Numerical modeling of ground-water flow, radionuclide transport, and doses to humans began January 20, 1989 and was completed March 20, 1989.

The report has several objectives:

1. To briefly summarize Sandia's current technical understanding of the major components of long-term performance of the WIPP repository. The following areas are specifically addressed:

. . . .

f. radionuclide-transport mechanisms and properties of the Culebra Dolomite, the major pathway for ground-water transport of radionuclides from the WIPP to the biosphere.

. . . .

4. To describe, document, and interpret six sets of calculations estimating the potential health effects to individuals resulting from emplacement of CH-TRU wastes in the WIPP, hydrologic saturation of the repository as a result of either natural processes or human intrusion, direct and indirect exposure during and after drilling (where appropriate), and ground-water transport of radionuclides to a hypothetical stock well south of the WIPP site.

The calculations presented here investigate radionuclide transport and resulting health effects both during undisturbed performance of the WIPP repository and in response to a relatively high-consequence human intrusion into the repository. The human intrusion considered is drilling that results in a long-term interconnection of the repository, an underlying brine reservoir in the Castile Fm., and the overlying Culebra Dolomite. The Culebra Dolomite provides a relatively permeable pathway for ground-water transport of radionuclides to the hypothetical stock well."

LaVenue, A.M., Cauffman, T.L., and Pickens, J.F. 1990. Ground-Water Flow Modeling of the Culebra Dolomite. Volume I: Model Calibration. SAND89-7068/1. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p. i;

" This hydrogeologic modeling study has been performed as part of the regional hydrologic characterization of the Waste Isolation Pilot Plant (WIPP) site in southeastern New Mexico. The study has produced an estimation of the transmissivity and Darcy-velocity distributions in the Culebra Dolomite Member of the Permian Rustler Formation at the WIPP site. The results of this study are intended to support Sandia National Laboratories performance-assessment calculations.

The three-dimensional finite-difference code SWIFT II was employed for the numerical modeling, using a variable-fluid-density and single-porosity formulation. The spatial scale of the model, 21.3 km by 30.6 km, was chosen to allow simulation of regional-scale pumping tests conducted at the H-3 and H-11 hydropads and the WIPP-13 borehole, which are located south, southeast, and northwest, respectively, of the center of the WIPP site. The modeled area includes and extends beyond the controlled area defined by the WIPP-site boundaries.

The work performed in this study consisted of modeling the hydrogeology of the Culebra in two stages: steady-state modeling to develop the best estimate of the undisturbed head distribution (i.e., of the hydraulic conditions before excavation of the WIPP shafts, which began in 1981) and superimposed transient modeling of local hydrologic responses to excavation of the four WIPP shafts at the center of the WIPP site, as well as to various well tests. The transient modeling used the calculated steady-state freshwater heads as initial conditions.

The steady-state calibrated transmissivity field contains transmissivities that vary over seven orders of magnitude increasing westward toward Nash Draw. The most significant feature of the transmissivity field is a high-transmissivity zone in the vicinity of wells H-17, P-17, and H-11. Modeled transmissivities within this zone are approximately 5×10^{-5} m^2/sec. The location of and transmissivities within the zone are similar to those proposed in a previous interim modeling report.

After calibration of the steady-state model, the major drilling and testing activities at the WIPP shafts and well locations were incorporated into the model. The transient simulation of the major hydraulic stresses in the Culebra dolomite extended from January 1, 1981 to June 16, 1989. Calibration of the model to the transient events required additional changes to the steady-state calibrated transmissivity field in order to reduce the differences between the calculated and observed transient heads. The major difference between the transient calibrated transmissivity field and the steady-state calibrated transmissivity field is the extension of the higher transmissivity zone near H-11 northward toward H-15.

The travel times for non-sorbing particles released within the steady-state flow field, using the transient calibrated model, were computed from selected locations within the model to the southern model (down-gradient) boundary. The predicted travel time from a release point within the Culebra that is coincident with the centroid of the waste panels to the southern WIPP-site boundary is 1.4 x 10^4 years. Calculations were performed to assess the sensitivity of the above travel time to the grid-block transmissivities and the pressure assigned to the model boundaries."

Section 7.0 CONCLUSIONS, p 7-1, para 4;
- The model-calculated ground-water-flow directions are predominantly south to southwest. The largest volume of ground water enters the model area through the northern portion of the western model boundary and enters the high- transmissivity area along the western part of the model representing Nash Draw. A significant portion of the ground water within the WIPP-site boundaries passes through the high-transmissivity zone south of H-15 and exits the southern boundary of the model area near H-9. The model-calculated flow directions support conclusions from previous modeling and isotopic studies that the ground-water chemistry is not at steady state with respect to ground-water flow."

LaVenue, A.M., Haug, A., and Kelley, V.A. 1988. Numerical Simulation of Ground-Water Flow in the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) Site: Second Interim Report. SAND88-7002. Sandia National Laboratories, Albuquerque, NM.

EXECUTIVE SUMMARY, p ii;

" This hydrologic modeling study has been performed as part of the regional hydrologic characterization of the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico. The study resulted in an estimation of the transmissivity distribution, hydraulic potentials, flow field, and fluid densities in the Culebra Dolomite Member of the Permian Rustler Formation at the WIPP site.

The three-dimensional finite-difference code SWIFT-II . . ."

Lee, W.T. 1925. "Erosion by Solution and Fill." In Contributions to Geography in the United States: USGS Bulletin, 760-C.

INTRODUCTION, p 107;

" In a region where the rocks are honeycombed surface material may find its way into subterranean cavities on a large scale. In southeastern New Mexico the formation of caverns by the solution of certain kinds of rocks and the transfer of surface material to these caverns have been carried on so extensively that these processes may be considered the chief causes of the formation of a broad valley.

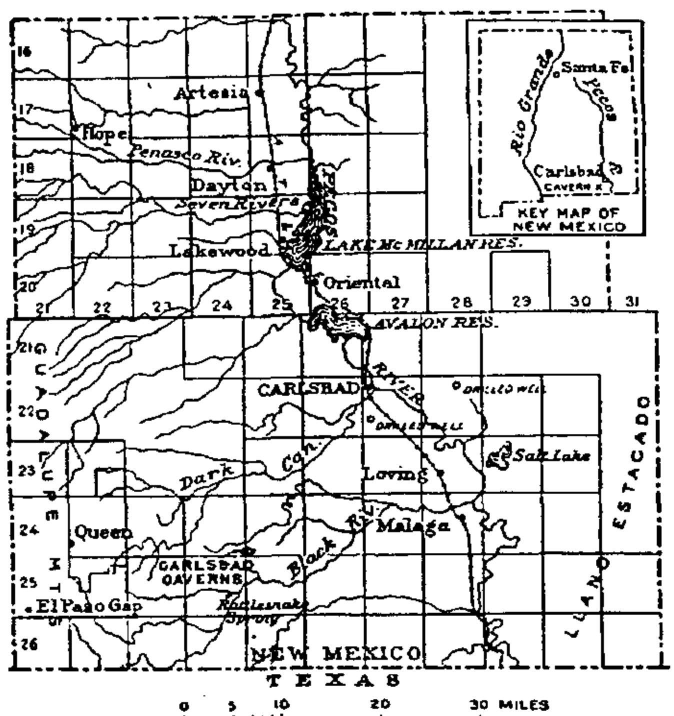


FIGURE 12.—Map of Eddy County, N. Mex.

Pecos Valley lies between the Guadalupe Mountains on the west, which rise to altitudes of nearly 10,000 feet and the Llano Estacado on the east. (See fig. 12) It is the broad, shallow depression through which Pecos River flows, but it is not wholly a valley of erosion in the sense in which the term erosion is generally used.

Streams from the mountains to the west reach the river and erode their channels in the ordinary way. Pecos River also carries much sand and silt and functions in many ways as a normal stream. But no tributary streams were found east of the Pecos in Eddy County, and over a wide area not even the dry bed of a temporary stream was seen."

Leslie, A., Kendall, A., and Harwood, G. 1993. "The Castile Formation: A Continuing Paradox." In Geology of the Carlsbad Region, New Mexico and West Texas, D.W. Love et al., eds., Forty-Fourth Annual Field Conference Guidebook. New Mexico Geological Society, Socorro, NM.

p 13;

" The Upper Permian (Ochoan) Castile Formation consists of laminated couplets of anhydrite and calcite/organic material, interbedded with massive to poorly laminated halite (Anderson, et al., 1972). The Castile Formation ranges in thickness from under 300 m in the west of the basin where halite has been removed to over 600 m in the east. The Castile Formation was deposited in an embayment of the Permian Basin (the Delaware Basin) during a period of restricted circulation with marine waters, causing a rapid increase in salinity and consequent precipitation of evaporite minerals. The laminates display a number of cyclicities on different scales, which have been related to orbital forcing by Anderson (1982).

At the base of the Ochoan . . ."

Long, G.J., and Associates, Inc. 1976. Interpretation of Geophysical Data, Los Medaños and Vicinity, Lea and Eddy Counties, New Mexico. Report to Sandia National Laboratories.

INTRODUCTION, p. 1;

" The geophysical studies discussed herein comprise a portion of a comprehensive evaluation of a proposed nuclear Waste Isolation Pilot Plant site. The area of investigation is located in the northern portion of the Delaware Basin, Eddy and Lea Counties, New Mexico in the Los Medanos vicinity approximately 25 miles east southeast of the town of Carlsbad. This evaluation is being performed by and under the direction of Sandia Laboratories, and Energy Research and Development Administration (ERDA) facility. The acquisition and interpretation of geophysical data can be applied to the identification of potential geological hazards and the evaluation of the economic impact which could be anticipated as the result of a site withdrawal. The objective of these investigations is to gather information which can be used to select a site having maximum geological stability and structural integrity, especially as to long term isolation from ground water invasion and minimal hydrocarbon/mineral potential.

Subsurface salt dissolution cavities, breccia pipes, shallow (late) faulting, igneous activity and adjoining systems constitute some of the major hazards to a WIPP site. The delineation of subsurface structure at established producing formations provides the primary basis for an economic evaluation of potentially undeveloped hydrocarbon reserves. Geophysical data of the type which oil companies acquire as a part of hydrocarbon exploration programs have been used as a basis for the interpretation and evaluation discussed herein."

Lowenstein, T.K. 1987 Post Burial Alteration of the Permian Rustler Formation Evaporites, WIPP Site, New Mexico. EEG-36. New Mexico Health and Environment Department, Santa Fe, New Mexico.

PREFACE, p vii;

" A repository for permanent isolation of defense transuranic wastes is being excavated in southeastern New Mexico, about 40 km 925 miles) east of Carlsbad. The Waste Isolation Pilot Plant (WIPP) repository has been designed for the disposal of waste in the lower part of the Salado (salt) Formation at a depth of 655 meters (2150 ft). The water-bearing zones of the Rustler Formation, which overlies the Salado, are considered to be the main pathway for the transport of radionuclides to the biosphere, if the repository is breached.

The Rustler Formation is 150 meters (490 feet) thick, 6.4 Km (4 miles) east of the center of the WIPP site. The thickness reduces drastically to the west so that it is only 91 meters (300 ft) thick in the western part of the WIPP site. At its thickest location, the Rustler consists of siltstone and anhydrite with two dolomite beds and both clear and clayey halite. Halite is progressively missing from deeper layers from east to west in the Rustler cross-section across the WIPP site. These observations were interpreted by Powers et al (1978), Mercer (1983), Lambert (1983), Chaturvedi and Rehfeldt (1984), Bachman (1984), Snyder (1985), Chaturvedi and Channell (1985) and others as indicating post-burial dissolution of halite and increased gypsification of anhydrite further west. Increased permeability of the water-bearing dolomites from east to west also was thought to result from the increased fracturing as a result of dissolution.

In 1984, Powers and Holt (1984) and Holt and Powers (1984) expressed doubts about the concept of post-burial dissolution of Rustler evaporites, on the basis of detailed mapping in the WIPP Waste Handling Shaft, and stated the following:

> 'Post-depositional dissolution features were not observed in any stratigraphic horizons in the Waste Shaft. In fact, several zones previously identified as dissolution residues in nearby boreholes (e.g. ERDA-9) contain pronounced primary sedimentary features. This is of great significance since dissolution has, historically, been considered as an important process that has greatly modified the Rustler Formation in this area.'
> (Holt and Powers, 1984)

This statement was based on the first detailed sedimentological study of the Rustler stratigraphy, but only at one location, albeit in situ, in a shaft. It clearly signaled the need for further work on the lateral variations in the stratigraphy of the Rustler Formation across the WIPP site. Since the interpretation by Powers and Holt was based on sedimentary features, the need was for a sedimentological study of the Rustler Formation.

To resolve this issue, the Environmental Evaluation Group (EEG) asked Dr. Tim K. Lowenstein to perform a sedimentological study of the available cores of the Rustler Formation. Dr. Lowenstein is a sedimentologist with special interest in the study of evaporites and has studied the Ochoan evaporites of the delaware Basin (Lowenstein, 1982, 1985). For this study, he performed a detailed sedimentological analysis of the Rustler cores from four wells, viz. DOE-2, W-19, H-11 and H-12. This included visual examination of the cores, preparation and petrographic analyses of 52 thin sections from selected locations of the cores, and x-ray diffraction analyses of 40 samples from selected locations of the cores. In addition, descriptive data on the rock cuttings and geophysical logs of borehole P-18 were used for correlation purposes. This report is a result of these analyses and correlation of sedimentary features between the drill-holes.

This study was confined to a miniscule area (only about 0.05%) of the total extent of the Rustler Formation and therefore cannot be considered to be a study of post-burial alteration of the Rustler Formation as a whole. Within the confines of this area, however, detailed stratigraphic correlations by Dr. Lowenstein based on sedimentary structures and textures indicate overall uniformity of depositional setting. Further, the physical and chemical alteration features, based on crosscutting relations, represent the last processes which have operated on these rocks. Four distinct dissolution zones in the Rustler Formation have been interpreted by Dr. Lowenstein. Although the strata above and below the inferred dissolution zones are chemically and physically altered, they contain abundant sedimentary structures and internal stratigraphy that can easily be matched from well to well. Dr. Lowenstein does not see a contradiction between post depositional dissolution and the survival of sedimentary structures. His interpretation is that the dissolved species produced by solution are removed from the site of reaction and the zones in which the effects of dissolution are now seen were at the periphery of main dissolution activity and therefore may exhibit some alteration as well as primary sedimentary structures."

Lowenstein, T.K. 1988. Origin of Depositional Cycles in a Permian "Saline Giant": the Salado (McNutt Zone) Evaporites of New Mexico and Texas. Geological Society of America Bulletin, Vol. 100, No. 4, pp. 592–608.

ABSTRACT, p 592, col 1;

" Two types of metre-scale depositional cycles have been recognized within the McNutt Potash Zone of the Permian Salado evaporites. The cycles record progressive drawdown and concentration of brine in a shallow, marginal marine basin. 'Type I' cycles, made of basal carbonate-siliciclastic mudstone, then anhydrite-polyhalite pseudomorphous after primary gypsum, overlain by halite and capped by muddy halite, are interpreted as marine sea water dominated. They formed by massive spillover of sea water through a connection with the Permian Ocean at high relative sea-level stands (lagoonal mudstone and anhydrite-polyhalite after subaqueous gypsum), followed by relative lowering of sea level and gradual basin restriction (shallow saline-lake and salt-pan halite) and ending with a desiccated basin, isolated from the Permian Ocean (salt-pan halite and saline mudflat muddy halite cycle cap). 'Type II' cycles occur between the Type I cycles and contain halite overlain transitionally by muddy halite. They record a temporal evolution of environments from a shallow saline lake to an ephemeral salt-pan-saline mudflat complex and are interpreted as continental-dominated sequences sourced by meteoric inflow from surrounding land areas that mixed with variable amounts of sea water, either residual or introduced into the Salado basin by seepage.

The vertical stacking of Type I cycles is best explained by periodic invasions of sea water into the Salado basin coincident with eustatic sea-level rises. The continental-dominated Type II cycles formed during intervening periods of eustatic sea-level fall and low stands. The *maximum* time interval between major marine incursions is an average of 10^5 yr."

Lucas, S.G., and Anderson, O.J. 1993. "Triassic Stratigraphy in Southeastern New Mexico and Southwestern Texas." In Geology of the Carlsbad Region, New Mexico and West Texas, D.W. Love et al., eds., Forty-Fourth Annual Field Conference Guidebook, New Mexico Geological Society, Socorro, NM.

ABSTRACT, p 231;

" Upper Triassic strata exposed in southeastern New Mexico and southwestern Texas are assigned to the Santa Rosa, San Pedro Arroyo and Dockum Formations of the Chinle Group. In southeastern New Mexico (Chaves, Eddy and Lea Counties) the Santa Rosa Formation is as much as 25 m thick and is mostly trough-crossbedded extraformational conglomerate and sandstone with minor beds of mudstone or siltstone. It disconformably overlies Upper Permian (Artesia Group or Quartermaster Formation) strata. The San Pedro Arroyo Formation conformably (?) overlies the Santa Rosa Formation and is at least 50 m of variegated smectitic mudstone and minor sandstone/conglomerate. Regional geologic maps have greatly overstated the extent of Upper Triassic exposures in southeastern New Mexico. In southwestern Texas (area from Pecos to Mitchell Counties) the Dockum Formation consists of the basal Camp Spring Member and overlying strata here assigned to a new stratigraphic unit, the Iatan Member. The Camp Springs Member is at least 15 m thick and is dominantly extraformational, siliceous conglomerate. It disconformably overlies the Upper Permian Quartermaster (=Dewey Lake) Formation and is conformably (?) overlain by the Iatan Member, which is 80-100 m thick and characterized by intercalcated, persistent intervals of red smectitic mudstone and trough-crossbedded micaceous sandstone. Fossil vertebrates indicate the Camp Springs and Iatan Members are of late Carnian (Tuvalian) age. Physical stratigraphy and lithology suggest correlation of the Santa Rosa Formation with the Camp Springs Member and the San Pedro Arroyo Formation with the Iatan Member."

Santa Rosa Formation, p 232, col 1;

" We assign the basal sandstones and conglomerates of the Upper Triassic section in southeastern New Mexico to the Santa Rosa Formation, as did Lang (1935) and subsequent workers. The Santa Rosa is as much as 25 m thick and is mostly trough-crossbedded extraformational conglomerate and sandstone with minor beds of mudstone or siltstone. Typical colors are grayish red (10 R 4/2) and pale reddish brown (10 R 5/4) for the sandstones, siltstones and mudstones, whereas conglomerate beds are mostly yellowish gray (5 Y 8/1) to light greenish gray (5G Y 8/1). Sandstones are micaceous subarkoses or litharenites. Conglomerate clasts typically are rip-ups of underlying Permian red beds (Artesia Group or Quartermaster Formation) at the base of the Santa Rosa Formation. Some quartzite clasts (usually in the very coarse to pebbly size range) also are present in basal Santa Rosa conglomerates. Conglomerates higher in the unit contain reworked Triassic siltstone and sandstone clasts.

The base of the Santa Rosa Formation is a disconformity above Permian red beds. Permian strata are finer grained, more texturally and mineralogically mature, gypsiferous, more evenly bedded and a different color (mostly moderate reddish brown) than the Santa

Rosa Formation. Despite these differences, in southeastern New Mexico both Miller (1955) and Vine (1963) incorrectly included uppermost sandstones of the Quartermaster Formation in the Santa Rosa Formation (Schiel, 1988; Lucas and Anderson, this volume).

The top of the Santa Rosa Formation in southeastern New Mexico is visible only at Maroon Cliffs. Here, variegated moderate reddish brown (10 R 4/6) and grayish red purple (5 RP 4/2) mudstone of the San Pedro Arroyo Formation rests directly (conformably ?) on the uppermost conglomerate bed of the Santa Rosa Formation (Fig. 2).

Other than undefinable fragments of petrified wood, bone and coprolites, no fossils have been collected in the Santa Rosa Formation in southeastern New Mexico. Nevertheless, regional correlation suggests this unit is of Late Triassic (late Carnian) age (see below)."

Machette, M.N. 1985. "Calcic Soils of the Southwestern United States." In Soils and Quaternary Geology of the Southwestern United States. D.L. Weide, and M.L. Faber, eds., Special Paper Vol. 203,pp. 1-21. Geological Society of America, Denver, CO.

ABSTRACT, p 1;

" Calcic soils are commonly developed in Quaternary sediments throughout the arid and semiarid parts of the southwestern United States. In alluvial chronosequences, these soils have regional variations in their content of secondary calcium carbonate ($CaCO_3$) because of (1) the combined effects of the age of the soil, (2) the amount, seasonal distribution, and concentration of Ca^{++} in rainfall, and (3) the $CaCO_3$ content and net influx of airborne dust, silt, and sand. This study shows that the morphology and amount of secondary $CaCO_3$ (cS) are valuable correlation tools that can also be used to date calcic soils.

The structures in calcic soils are clues to their age and . . ."

MacLennan, R.B., and Schermer, S.C.. 1979. An Archaeological Survey for the Waste Isolation Pilot Project: Access Roads and Railroad Right-of-Way. Agency for Conservation Archaeology Report 79-23. Eastern New Mexico University, Portales, NM.

ABSTRACT, p i;

" An archaeological reconnaissance of three access rights-of-way for the Waste Isolation Pilot Project in the Los Medanos area of Eddy County, New Mexico was accomplished between February 22 and February 24, 1979. The project involved 15.75 miles of 200 ft wide corridor, an area of 506.66 acres. The surveyed corridors were generally situated in dune covered areas east of Nash Draw, with only the railroad access descending into the Draw.

This survey encountered two sites and 12 isolated artifacts. The sites, ENM 10418 and ENM 10419, were located on the floor of Nash Draw and on a low bench above the floor of Nash Draw respectively. ENM 10418 appears to be a campsite, with possible Jornado Mogollon affiliations. ENM 10419 consists of four small hearths without artifactual associations; it may be a task locus, of recent origin, used in branding cattle. It is recommended that mitigations be conducted for both sites before further WIPP actions proceed in the railroad access right-of-way."

Maley, V.C., and Huffington, R.M. 1953. Cenozoic Fill and Evaporate Solution in the Delaware Basin, Texas and New Mexico. Geological Society of America Bulletin, Vol. 64.

NOTE: Text "bolded" was not legible in the copy of the document available to Long-Term Regulatory Compliance and is the typist's interpretation of the text.

ABSTRACT, p 539;

" The Delaware Basin, containing thick deposits of late Permian salt and anhydrite, is one of the major **geologic** subdivisions of the Permian Basin of West Texas and southeastern New Mexico. At least three **successive** accumulations of Cenozoic fill, with a maximum thickness of approximately 1900 feet, are present **in the** basin. Localization of these major fill deposits is attributed to evaporite solution, particularly of salts. **Subsequent** slump of the Permian Rustler formation, which immediately overlies the evaporite beds, makes **it difficult** to distinguish true tectonic structures in this formation.

Mariah Associates, Inc. 1987. Report of Class II Survey and Testing of Cultural Resources at the WIPP Site at Carlsbad, NM. Prepared for the U.S. Corps of Engineers, Albuquerque District in NM.

ABSTRACT;

" In September of 1985, the Army Corps of Engineers, Albuquerque District, contracted Mariah Associates, Inc. to conduct a Class II cultural resource survey of approximately 3,100 acres in WIPP Zones III, IV, and V in Eddy County, New Mexico. A total of 40 archaeological sites was located; 11 were subsequently tested. Sites included probable PaleoIndian, Archaic, Mogollon, and Protohistoric camps. Seventy-five isolated artifacts were recorded. Ancillary studies included archaeological and historical interviews and archival research.

Site-specific recommendations concerning eligibility to the National Register of Historic Places are made and recommendations for future work in the project area are advanced."

McTigue, D.F., 1993. Permeability and Hydraulic Diffusivity of Waste Isolation Pilot Plant Repository Salt Inferred from Small-Scale Brine Inflow Experiments. SAND92-1911. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p i;

" Brine seepage to 17 boreholes in salt at the Waste Isolation Pilot Plant (WIPP) facility horizon has been monitored for several years. A simple model for one-dimensional, radial, darcy flow due to relaxation of ambient pore-water pressure is applied to analyze the field data. Fits of the model response to the data yield estimates of two parameters that characterize the magnitude of the flow and the time scale over which it evolves. With further assumptions, these parameters are related to the permeability and the hydraulic diffusivity of the salt. For those data that are consistent with the model prediction, estimated permeabilities are typically 10^{-22} to 10^{-21} m^2. The relatively small range of inferred permeabilities reflects the observation that the measured seepage fluxes are fairly consistent from hole to hole, of the order of 10^{-10} m/s. Estimated diffusivities are typically 10^{-10} to 10^{-8} m^2/s. The greater scatter in inferred hydraulic diffusivities is due to the difficulty of matching the idealized model history to the observed evolution of the flows. The data obtained from several of the monitored holes are not consistent with the simple model adopted here; material properties could not be inferred in these cases."

Mercer, J.W. 1987. Compilation of Hydrologic Data From Drilling the Salado and Castile Formations Near the Waste Isolation Pilot Plant (WIPP) Site in Southeastern New Mexico. SAND86-0954. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p 3-4;

" This report compiles and evaluates data from tests performed on the Salado and Castile Formations during site characterization, exclusive of the 'brine reservoirs' in the Castile. It also examines if regional data are consistent with the experience of fluid encounters in the mined facility--especially whether significant volumes of fluid might be involved in the Salado pressure buildups in the same way as small volumes were in the studies in the mined facility at the Waste Isolation Pilot Plant (WIPP). Preliminary analyses of recently completed data from reentry and testing in WIPP-12 and testing of the Salado in DOE-2 are also included. Results of this study indicate that probably no overall interpretive model can be applied to the Salado and Castile Formations. That is, no definitive or unique explanation exists for the brine and/or gas occurrences or pressure buildups or their distribution in the borehole. Because of certain basic problems of well testing from the surface in low-permeability rock and because of the apparent low permeabilities, we do not recommend continued hydrologic testing conducted from the surface and penetrating the halites and anhydrites of concern at the WIPP. However, testing of the halite and marker beds at or near the WIPP mining horizon is practicable and should be carried out with the most sensitive instrumentation developed for that purpose."

Mercer, J.W., Beauheim, R.L., Snyder, R.P., and Fairer, G.M. 1987. Basic Data Report For Drilling and Hydrologic Testing of Drillhole DOE-2 at the Waste Isolation Pilot Plant (WIPP) Site. SAND86-0611. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT;

" Drillhole DOE-2 was drilled to investigate a structural depression marked by the downward displacement of stratigraphic markers in the Salado formation ~2 mi north of the center of the WIPP site. This depression was named informally after the shallow borehole FC-92 in which the structure was described. The presence of the depression was confirmed by drilling. Contrary to several hypotheses, halite layers were thicker in the lower part of the Salado, not thinner as a result of any removal of halite. The upper Castile anhydrite in Drillhole DOE-2 is anomalously thick and is strongly deformed relative to the anhydrite in adjacent drillholes. In contrast, the halite was <8 ft thick and significantly thinner than usually encountered. The lower Castile anhydrite appears to be normal. The depression within the correlated marker beds in the Salado Formation in Drillhole DOE-2 is interpreted as a result of gravity-driven deformation of the underlying Castile Formation.

Several stratigraphic units were hydrologically tested in Drillhole DOE-2. Testing of the unsaturated lower portion of the Dewey Lake Red Beds was unsuccessful because of exceptionally small rates of fluid intake. Drill-stem tests were conducted in five intervals in the Rustler Formation, over the Marker Bed 138-139 interval in the Salado Formation, and over three sandstone members of the Bell Canyon Formation. A pumping test was conducted in the Culebra Dolomite Member of the Rustler Formation. Pressure-pulse tests were conducted over the entire Salado Formation. Fluid samples were collected from the Culebra Dolomite Member and from the Hays Member of the Bell Canyon Formation."

Mercer, J.W. and Orr, B.R. 1977. Review and Analysis of Hydrogeologic Condition Near the Site of a Potential Nuclear-Waste Repository, Eddy and Lea Counties, New Mexico. USGS Open-File Report 77-123. U.S. Geological Survey, Albuquerque, NM.

ABSTRACT, p. 7;

" This interim report reviews and summarizes the hydrogeology of rocks associated with the Permian salt beds (Castile and Salado Formations) of Los Medaños area in southeastern New Mexico. The information will be considered, together with other factors, in the preparation of an analysis of the impact of a potential nuclear-waste repository on the environment.

Most of the geologic units in and adjacent to the Permian salt deposits are characterized by low permeabilities and highly mineralized water. Sandstone of the Delaware Mountain Group which underlies the salt, has an average hydraulic conductivity of 0.16 ft/d and an average porosity of 15.65 percent. Flow is north-northeastward toward the margin of the Capitan Limestone, at velocities ranging from 0.0005 to 0.0008 ft/d.

The Capitan Limestone, a relatively high yielding limestone-reef aquifer adjacent to the study area, has been reported to have transmissivity values ranging from 500 ft^2/d to 10,000 ft^2/d and an average hydraulic conductivity of about 5 ft/d. Water movement west of the Pecos River is northeastward in the reef, with discharge at Carlsbad Springs. East of the Pecos River, water moves at very low rates and the direction of movement is uncertain.

The Castile and Salado Formations, which might be used to contain the nuclear waste, have a few isolated pockets of brine and gas, but generally transmit little or no ground water.

An evaporite residuum near the top of the Salado Formation was developed in localities where ground water has dissolved the upper Permian evaporites. Brine in the residuum moves southward along Nash Draw and discharges about 200 gal/min into the Pecos River at Malaga Bend. The transmissivity of the residuum is 8,000 ft^2/d and the flow rate is 0.2 ft/d.

The Rustler Formation overlies the Salado. The major water-bearing beds in the Rustler Formation are the Culebra Dolomite Member and Magenta Member, which in places are capable of yielding up to 700 gal/min. Values of transmissivity in the formation range from near 0 to 500 ft^2/d. The porosity and permeability in the dolomite is attributed to fracturing and to solution activity. Ground-water movement is south-southwestward toward the Pecos River.

Water in the Dewey Lake Red Beds, which overlie the Rustler Formation, occurs in sand lenses. Movement of water in the formation is restricted by low permeabilities.

The Santa Rosa Sandstone, overlying the Dewey Lake Red Beds, also has a low permeability. The porosity is about 10 percent and the rate of flow is 0.3 ft/d south-southwest toward the Pecos River.

Data on the occurrence of water in the Chinle Formation is sparse; however, its lithology indicates it would be a poor aquifer.

Other potential aquifers adjacent to the proposed repository area include the Ogallala Formation, Gatuna Formation, and alluvial deposits. Most water in the Ogallala moves to

the southeast but some moves westward, recharging the Santa Rosa Sandstone aquifer. The Gatuña Formation contains water in sand and gravel lenses. Ground-water movement in the alluvium is in the approximate direction of surface flow of the Pecos River. An average value of transmissivity for the alluvium is 13,600 ft^2/d, and flow-velocity estimates are generally less than 1 ft/d."

Mercer, J.W., and Orr, B.R. 1979. Interim Data Report on Geohydrology of the Proposed Waste Isolation Pilot Plant Site, Southeast New Mexico. Water Resources Investigations 79-98. U.S. Geological Survey, Albuquerque, NM.

ABSTRACT, p. 1;

" Data were collected during hydrologic investigations at the Waste Isolation Pilot Plant site in southeast New Mexico through September 1977. These data will be considered as part of a site characterization study evaluating the feasibility of nuclear-waste storage within bedded salt of the Salado Formation of Permian age.

Liquids in the rocks overlying the Salado Formation are found at the contact between the Permian-Rustler and Salado Formations, and in the Culebra and Magenta Dolomite Members of the Rustler Formation.

Calculations of hydraulic gradient and direction of flow of water moving along the Rustler-Salado contact have been hindered because heads are stabilizing very slowly. Preliminary calculations of transmissivity range from 10^{-1} feet squared per day on the western margin of the site to 10^{-4} feet squared per day on the eastern margin. Liquids from the Rustler-Salado contact contain from 311,000 to 325,800 milligrams per liter total dissolved solids. Liquid chemistry suggests long residence times and extensive liquid-rock interaction, increasing with decreasing permeability.

Liquids in the Culebra Dolomite Member move southeast at gradients ranging from 7 to 120 feet per mile. Preliminary transmissivity calculations range from 140 feet squared per day on the western margin to 10^{-4} feet squared per day to the east. Total dissolved solids range from 23,721 milligrams per liter along the western margin of the site to 118,292 milligrams per liter to the east. Liquid chemistry within the Culebra varies from well to well probably as a function of fracture distribution.

Liquids in the Magenta Dolomite Member move southwest at a gradient of about 50 feet per mile. Preliminary transmissivity estimates range from less than 1 foot squared per day to 40 feet squared per day. Total dissolved solids range from 10,347 milligrams per liter to 29,683 milligrams per liter.

The extremely low vertical hydraulic conductivity within the Rustler Formation restricts liquid migration between the Magenta and Culebra Dolomite Members, and between the Culebra and the Rustler-Salado contact. Heads are highest in the Magenta and lowest at the Rustler-Salado contact.

Liquid levels in wells tapping the Permian Bell Canyon Formation near the site are lower than levels in wells tapping the Rustler Formation. Liquids from the Bell Canyon Formation contain 189,000 milligrams per liter total dissolved solids. Liquid density and chemistry indicate long residence times and extensive liquid-rock interaction."

Merz, H.A., and Cornell, C.A. 1973. Seismic Risk Analysis Based on a Quadratic Magnitude-Frequency Law. Seismological Society of America Bulletin. Vol. 63, pp. 1999-2006.

ABSTRACT, p 1999;

" The quadratic log frequency versus magnitude relationship is introduced into analytical engineering seismic risk analysis. The analytical risk relationships remain in closed form, and risk analysis remains easily amenable to computer implementation. The availability of both a quadratic relationship and a truncation point or upper bound on the magnitude (or epicentral intensity) permits relatively detailed representation of the large magnitude-low frequency region of the distribution. This region has an important influence on high intensity-low risk site conditions, which are of frequent engineering interest. At lower site intensities, the influence of the quadratic versus a linear form is apparently not significant."

Meyer, R.F. 1966. Geology of Pennsylvania and Wolfcampian Rocks in Southeast New Mexico. Memoir 17. New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.

ABSTRACT;

" The area of this study includes about 38,700 square miles in southeast New Mexico that lie within the Great Plains physiographic province on the east and the Basin and Range province on the west. Pennsylvanian and Wolfcampian rocks are discontinuously exposed in the mountain ranges on the west and in boreholes elsewhere.

Major positive elements of the area during Pennsylvanian and Wolfcampian time included the Pedernal uplift, which extended in a north-south direction through the center of the area, and the Central Basin platform, the northwest corner of which lay in the southeast part of the area. Minor positive features included the domical Roosevelt uplift in the northeast, the Oscura and Joyita uplifts in the northwest, and the Diablo platform in the southwest. Major negative elements were the Permian basin on the east and the Orogrande basin on the west. Subprovinces of the Permian basin were the Northwest shelf and the Delaware basin, which included the Salt Flat embayment. Subprovinces of the Orogrande basin were the Robledo and Sacramento shelves. The Orogrande basin merged northward with the extreme south end of the Estancia basin, and in like manner the Permian basin joined the Tucumcari basin.

. . ."

Mitchell, B.J. 1973. Radiation and Attenuation of Rayleigh Waves from the Southeastern Missouri Earthquake of October 21, 1965. Journal of Geophysical Research. Vol. 78, pp. 886-889.

p 886;

" The southeastern Missouri earthquake of October 21, 1965, generated fundamental mode and higher-mode surface waves that were widely recorded throughout North America. Amplitude radiation patterns for the fundamental and first higher Rayleigh modes were determined and compared with patterns computed for various fault plane solutions. The favored solution is that of a fault 4 km deep, oriented N70°E, dipping 50°S, and having a slip vector oriented 85° downward from the horizontal on the fault face. A least squares fitting process was devised to determine the source spectrum and the values for the Rayleigh wave attenuation coefficient at each period. The fundamental mode attenuation coefficient is slightly greater than 0.001 km^{-1} at a period of 4 sec, decreases rapidly to 0.0002 km^{-1} or less at periods between 17 and 25 sec, and increases slowly to about 0.00017 km^{-1} at 50 sec. The first higher mode attenuation coefficients parallel and are slightly lower than those of the fundamental mode at periods between 4 and 10 sec. The source spectrum peaks between 5 and 9 sec and appears to attain a lower dc level at periods of greater than 20 sec. The similarity in the shapes and the orientations of the short-period radiation patterns and the area of perceptibility for this earthquake suggests that the size of the 'felt area' of an earthquake is related to the nature of the radiation and the attenuation of short-period Rayleigh waves. This observation and the lower short-period Rayleigh wave attenuation coefficient values observed in the eastern United States in comparison with those observed in the western United States indicate that the larger areas of perceptibility of eastern United States earthquakes occur because short-period Rayleigh waves are transmitted more efficiently in that region."

NAS-NRC (National Academy of Sciences-National Research Council), 1957. The Disposal of Radioactive Waste on Land. Publication 519. National Academy of Sciences, Washington, D.C.

ABSTRACT p 1, para. 2;
" Disposal in cavities mined in salt beds and salt domes is suggested as the possibility promising the most practical immediate solution of the problem."

Neill, R.H., Channell, J.K., Chaturvedi, L., Little, M.S., Rehfeldt, K., and Spiegler, P. 1983. Evaluation of the Suitability of the WIPP Site. EEG-23. Environmental Evaluation Group, Santa Fe, NM.

EXECUTIVE SUMMARY, p. ii;

" The determination of the suitability of the site for WIPP is only the first major phase in the evaluation of the radiological impact of the repository on the public health and safety. The Environmental Evaluation Group (EEG) will continue to independently review the design of the facility, the operational procedures (including safety criteria and quality assurance), the criteria for packaging and shipment of the waste, the plans, procedures and results of the WIPP experiments, emergency preparedness, adherence to EPA and pertinent NRC regulations, and other important features of the project.

EEG has concluded from existing evidence that the Los Medanos site for the WIPP project has been characterized in sufficient detail to warrant confidence in the validation of the site for the permanent emplacement of approximately 6 million cubic feet of defense transuranic waste. This conclusion is based on the assumption that the maximum surface dose rate for the unshielded remote-handled transuranic waste (RH-TRU) canisters will be 100 rem per hour with a maximum radionuclide concentration of 23 curies per liter as indicated in Table E-3 of the Final Environmental Impact Statement for WIPP. The Site and Preliminary Design Validation (SPDV) program, through the drilling of two shafts to the selected repository level at 2160 feet below the surface and excavation of about 9000 feet of tunnels, has confirmed the interpretations made about the subsurface geological conditions at the site.

For an assessment of the potential radiation effects of the nuclear waste repository on the public health and safety, it is necessary to understand the regional geological and hydrological setting. A large amount of work has been done to understand these conditions and to address several specific issues which have arisen as a result of such studies. However, in an assessment effort of this magnitude, it is almost inevitable that some questions remain unanswered at a given time in the decision-making process. EEG has identified work which still needs to be done at the Los Medanos site in order to improve confidence in the worst case scenario models of possible breaches of the repository. Also, it is anticipated that some of the additional information will be necessary to assure compliance with the EPA standard when it is promulgated."

Newell, N.D., et al. 1953. The Permian Reef Complex of the Guadalupe Mountains Region, Texas and New Mexico—A Study in Paleoecology. W.H. Freeman and Co., San Francisco.

Summary, p xiii;

" This is an attempt to determine the environmental conditions under which the celebrated Permian reefs and associate deposits of the southern Guadalupe Mountains were formed. Conclusions are based mainly on original studies of stratigraphy, petrology, primary structures, and paleontology.

Three geologic provinces in the area are characterized by unlike, but stratigraphically equivalent, rocks and fossils: (1) the Delaware Basin, containing drab-to-black limestones and quartz sandstones; (2) the rim of the basin, occupied by organic reefs and banks of light-colored, massive limestone and dolomite; and (3) a shelf area covered by light colored, thin-bedded dolomite, sandstone, and evaporites.

The organic reefs . . ."

Nicholson, Jr., A., and Clebsch, Jr., A. 1961. Geology and Ground-Water Conditions in Southern Lea County, New Mexico. Ground-Water Report 6. State Bureau of Mines and Mineral Resources, Socorro, NM.

ABSTRACT, p 1;

" Southern Lea County is at the southeastern corner of New Mexico. Most of the area is in the Pecos Valley section of the Great Plains physiographic province; it also includes the southern margin of the Llano Estacado. There are no perennial streams and no throughgoing surface drainage.

Rocks of Quaternary, Tertiary, and Triassic age are exposed and contain the principle aquifers. The most important aquifer is the Ogallala formation, which underlies the Llano Estacado and forms outliers south of it. In large parts of southern Lea County, however, the Ogallala has been removed by erosion and in the low-lying areas Quaternary alluvium, derived principally from the Ogallala formation, has been deposited and is the main aquifer. The two aquifers are continuous in the eastern part of the area. Below the Cenozoic rocks are sandstones and shales of the Dockum group of Late Triassic age, from which small quantities of water are obtained. No usable ground water is obtained from rocks older than the Triassic, but highly saline water is produced along with oil from Paleozoic rocks.

In 1954 about 6,000 acre-feet of ground water were used. Most of this quantity was needed for irrigation and for gasoline plants, in about equal amounts. Economic growth from a rapidly developing petroleum industry has brought about a demand for water for industrial and public supplies that is expected to continue. Development of adequate supplies is hindered by restricted occurrence and low transmissibility of the sediments. Because of the low recharge rate, most of the water pumped is being removed from storage.

The chemical quality of the ground water from the principal aquifers is generally fair to good. Production of large quantities of oil-field brine (3,700 acre-feet in 1955) has created a waste-disposal problem of major importance. Most of the brine has been discharged into surface pits. Leakage from the pits has caused contamination of the shallow water in some areas and unless other disposal methods are used, the problem will spread."

Nielson, J. 1977. An Archaeological Reconnaissance of a Proposed Site for the Waste Isolation Pilot Plant (WIPP). Sandia National Laboratories, Albuquerque, NM.

INTRODUCTION, p 11;

" An archaeological survey was recently completed by the Agency of Conservation Archaeology (ACA), Eastern New Mexico University, in the Los Medaños area southeast of Carlsbad, New Mexico, on lands administered by the Bureau of Land Management. The area surveyed includes an area 4 square miles in size, plus several rights-of-way emanating from the core area. This locality will be impacted by the construction of a nuclear waste disposal facility by Sandia Laboratories.

The survey was initiated at the request of, and under contract with, Sandia Laboratories and was administered by Dr. Melvin Merritt, Dr. George Griswold, Mr. Joe Magruder, and Mr. Earl Cunningham, of Sandia Laboratories, and Dr. J. Loring Haskell, Operations Director and Principle Investigator, Agency of Conservation Archaeology. Antiquity permit 76-NM-003.

The fieldwork was accomplished between June 14 and July 8, 1976, by Jeffrey Nielsen, Winston Hurst, Miles Linnaberry, and Charles Nelson of the Agency of Conservation Archaeology."

NRC (U.S. Nuclear Regulatory Commission). 1974. Guidance on the License Application, Siting, Design, and Plant Protection for an Independent Spent Fuel Storage Installation. Regulatory Guide 3.24, December, 1974.

A. INTRODUCTION;

" An ‘independent spent fuel storage installation‘ (ISFSI) is a self-contained installation for storing spent fuel. It has its own support services and operates independently of any other facility; i.e., it is not a part of either a nuclear power plant or a fuel reprocessing plant. Such an installation is visualized as being capable of storing 1000 tons or more of spent light-water reactor fuel.

Licensed spent fuel storage installations historically have been integrated parts of either fuel reprocessing plants or nuclear power plants. Such plants have been licensed under 10 CFR Parts 30, 40, and 70 in addition to 10 CFR Part 50.

An ISFSI, independent and separate from either a nuclear power plant or a fuel reprocessing plant, would be licensed under Parts 30, 40, and 70. An applicant for a license for an ISFSI meeting the requirements for a Part 70 license would automatically satisfy the requirements for a Part 30 and 40 license. Therefore, a license application for an ISFSI would be reviewed under the requirements of 10 CFR Part 70.

‘Licensing and Regulatory Policy and Procedures for Environmental Protection.’ 10 CFR Part 51, sets forth the Atomic Energy Commission’s policy and procedures for preparing and processing environmental impact statements and related documents pursuant to section 102(2)(C) of the National Environmental Policy Act of 1969 (83 Stat. 852). Certain limitations on the Commission’s authority and responsibility pursuant to the NEPA are imposed by the Federal Water Pollution Control Act amendments of 1972 (86 Stat. 816). These limitations are addressed in an Interim Policy Statement published in the Federal register on January 29, 1973 (38 FR 2679).

Regulatory Guide 4.2, ‘Preparation of Environmental reports for Nuclear Power Plants,’ is generally applicable as a guide for the preparation of an environmental report for an ISFSI. Subjects that are pertinent only to nuclear power plants are obviously not applicable, however, and subjects that are important to an ISFSI, such as spent fuel transportation, should be emphasized.

This guide discusses the license application, site evaluation, design, and plant protection of an ISFSI. It describes the measures acceptable to the Regulatory staff for meeting the requirements of 10 CFR Part 70. In addition, it identifies the information needed by the staff in its evaluation of an ISFSI application."

c. Seismology - Design Earthquake, p. 3.24-6, col. 2, para 2;

" (3) Definition of Design Earthquake

The ISFSI ‘design earthquake’ is an earthquake event that has a reasonably high probability of occurrence based on studies of historic seismicity and structural geology.

(4) Determination of the Design Earthquake

In evaluating historic seismicity and regional structural geology, the historic earthquakes identified from the above investigations should be associated with tectonic structures to the extent practical.

If historic earthquake data indicate a high incidence of earthquakes along only a particular portion of a tectonic structure, the probability of similar earthquakes in the future should be assumed uniformly throughout the same segment of the tectonic structure. (Where geologic evidence indicates that the structure is a major, continuous, through-going structure with significant displacement, a more conservative assumption may be appropriate.) These earthquakes should be used in determining the maximum vibratory motion at the site that could be caused by an earthquake related to the tectonic structure.

Correlation of tectonic structure and historic seismicity may not be possible because (a) there is insufficient data or (b) seismicity appears uniform over a network of tectonic structures or cannot be correlated with specific structures. If so, the seismicity should be identified with the tectonic province in which it is reported.

(5) Selection of a Design Earthquake

In view of the limited consequences of seismic events in excess of those used as the basis for seismic design, it appears appropriate that the design earthquake developed from the above information should be such as to have a predicted recurrence interval of about once in a thousand years."

Nuttli, O.W. 1973. The Mississippi Valley Earthquakes of 1811 and 1812--Intensities, Ground Motion and Magnitudes. Seismological Society of America Bulletin. Vol. 63, pp. 227-248.

ABSTRACT, p 227;

" Contemporary newspaper accounts of the 1811-1812 Mississippi Valley earthquakes sequence are used to construct a generalized isoseismal map of the first three principle shocks of the sequence, that of December 16, 1811. The map is characterized by an unusually large felt area, with MM intensities of V as far away as the southeast Atlantic coastal area.

By correlating the isoseismal map with that of recent earthquakes for which ground motion data are available, the body-wave magnitude of the December 16, 1811 earthquake is estimated to be 7.2. The other principle shocks, on January 23, 1812 and February 7, 1812, had estimated m_b values of 7.1 and 7.4, respectively. The total energy released by the principle shocks and their larger-magnitude aftershocks is estimated to be equivalent to that of an $m_b = 7.5$ (or $M_g = 8.0$) earthquake.

The anomalously large areas of damage and of perceptibility of the principle shock result from both the surficial geological conditions of the Mississippi Valley and the relatively low attenuation of surface-wave energy in eastern North America.

Estimates of the vertical component of ground motion, for an earthquake of $m_b = 7.2$ occurring in eastern North America, are given. These include values for particle velocity, displacement, and acceleration at frequencies of about 3, 1 and 0.3 Hz."

Nuttli, O.W. 1973. Seismic Wave Attenuation and Magnitude Relations for Eastern North America. Journal Geophysical Research, Vol. 78, pp. 876-885.

ABSTRACT, p 876;

" Observational data on the attenuation of short-period Rayleigh waves in North America east of the Rocky Mountains yield the following average values for the coefficient of anelastic attenuation: $\gamma=0.07$ deg^{-1} for 1-sec-period waves and $\gamma=0.10$ deg^{-1} for waves with a maximum particle velocity in the period range 3-12 sec. By way of comparison, the amplitude data that form the basis of Richter's empirical local magnitude scale for southern California gives $\gamma=0.60$ deg^{-1}. Differences in γ values are sufficient to explain the observation that earthquakes in the eastern United States have a radius of perceptibility as much as 10 times larger than that of earthquakes of the same magnitude in the western United States. Theoretical curves of log A/T versus log Δ are nor linear. Thus magnitude formulas of the type $M = B + C (\log \Delta) + \log A/T$ are valid only over a limited range of distance, for which the curve can be approximated by a straight line. Formulas of this kind, which give m_{σ} and M_s from short-period Rayleigh waves, are proposed for eastern North America."

Olive, W.W. 1957. Solution-Subsidence Troughs, Castile Formation of Gypsum Plain, Texas and New Mexico. Geological Society of America Bulletin, Vol. 68.

ABSTRACT, p 351;

" Solution-subsidence troughs are straight narrow depressions ranging in width from a few hundred feet to 1 mile, and in length from about half a mile to 10 miles. The troughs are formed by subsidence of near-surface earth blocks to fill voids dissolved by underground waters moving along subjacent drainage channels parallel to the troughs. Numerous solution-subsidence troughs are developed in the Castile Formation (upper Permian) of the Gypsum Plain in west Texas and southeastern New Mexico where they characteristically have broad relatively flat bottoms, which occupy about two-thirds of the width of the trough. The bottoms are bounded by gentle slopes rising 15-20 feet to narrow straight divides, which stand 2 or 3 feet above the general level of the Gypsum Plain. The troughs trend roughly parallel to the direction of the regional dip, about 1°-2° eastward. Displacement and local folding in strata of the Castile Formation in and near the troughs are not reflected in the Lamar limestone member of the Bell Canyon Formation (lower Permian), which conformably underlies the Castile. The trends of the underground channels are interpreted as the result of solution along eastward-trending joints parallel to the regional dip. Most of the water that causes the solution is believed to be derived by artesian flow from the mountainous area west of the Gypsum Plain."

Orphal, D.L., and Lahoud, J.A. 1974. Prediction of Peak Ground Motion from Earthquakes. Seismological Society of America Bulletin, Vol. 64, pp. 1563-1574.

ABSTRACT, p 1563;

" A statistical analysis shows that the peak horizontal accelerations recorded from the San Fernando earthquake of February 1971 attenuate with focal distance as $R^{-1.39}$. This attenuation rate is nearly identical to that reported for peak accelerations from underground nuclear explosions. Assuming that the derived attenuation is independent of source parameters and using data from a number of other California earthquakes, the scaling of peak horizontal acceleration with magnitude was determined statistically. Assuming that the attenuation of peak velocity and displacement with distance is identical for earthquakes and underground nuclear explosions, the scaling of earthquake peak velocity and displacement with magnitude was also determined. The equations resulting from these analyses are: $a = 6.6 \times 10^{-2}\ 10^{0.40M}R^{-1.39}$, $v = 7.26 \times 10^{-1}\ 10^{0.52M}R^{-1.34}$ and $d = 4.71 \times 10^{-2}\ 10^{0.57M}R^{-1.18}$, where a, v, and d are maximum acceleration (g), velocity (in centimeters per second) and displacement (in centimeters), respectively. M is the local magnitude, and R is the focal distance (in kilometers). In this analysis, no attempt was made to account for effects of recording site geology."

Palmer, A.R. 1983. The Decade of North American Geology 1983 Geologic Time Scale. Geology, Vol. 11, pp. 503-504.

p. 503;

" Preparation of the 27 synthesis volumes of *The Geology of North America* for the Decade of North American Geology (DNAG) is now in progress. In order to encourage uniformity among DNAG authors in the citation of numerical ages for chronostratigraphic units of the geologic time scale, an ad hoc Time Scale Advisory Committee was established by the DNAG Steering Committee in 1982. This advisory committee, consisting of Z.E. Peterman (Chairman) and J. F. Harrison, U.S. Geological Survey; R. I. Armstrong, University of British Columbia; and W. A. Berggren, Woods Hole Oceanographic Institution, was asked to evaluate numerical dating schemes that were either recently published or in press and to provide recommendations for the best numbers to use in preparation of a DNAG time scale. The chart on the opposite side of this page was developed from the recommendations of the Time Scale Advisory Committee."

Powers, D.W. 1995. Tracing Early Breccia Pipe Studies, Waste Isolation Pilot Plant, Southeastern New Mexico: A Study of the Documentation Available and Decision-Making during the Early Years of WIPP. SAND94-0991. Sandia National Laboratories, Albuquerque, New Mexico.

ABSTRACT, p. i;

" Breccia pipes in southeastern New Mexico are local dissolution-collapse features that formed over the Capitan reef more than 500,000 years ago. During early site studies for the Waste Isolation Pilot Plant (WIPP), the threat to isolation by these features was undetermined. Geophysical techniques, drilling, and field mapping were used beginning in 1976 to study breccia pipes. None were found at the WIPP site, and they are considered unlikely to be a significant threat even if undetected.

WIPP documents related to breccia pipe studies were assembled, inspected, and analyzed, partly to present a history of these studies. The main objective is to assess how well the record reflects the purposes, results, and conclusions of the studies from concept to decision-making. The main record source was the Sandia WIPP Central File (SWCF). Documents reviewed ranged from generally available reports (e.g., SAND reports) to individual memoranda and contracting papers.

The history of WIPP breccia pipe studies is relatively clear. After a potash company mined into breccia during 1975, Sandia and U.S. Geological Survey (USGS) personnel began investigating the threat to WIPP. By 1982, a USGS summary report inferred that breccia pipes are restricted to the Capitan reef, which does not underlie the WIPP site. DOE 2 was later drilled at an alleged dissolution feature. Castile Formation salt was deformed, not dissolved; no further breccia pipe studies have been undertaken.

Available records clearly reveal the efforts to investigate breccia pipes. Early records (about 1975 to 1977) are very limited, however, about details of objectives and plans predating any investigation. Drilling programs from about 1977 were covered by a broadly standardized statement of work, field operations plan, drilling history, and basic data report. Generally standardized procedures for peer, management, and quality assurance review were developed during this time. Agencies such as the USGS conducted projects according to internal standards. Records of detailed actions for individual programs may not be available, though a variety of such records were found in the SWCF. A complete written record cannot be reconstructed. With persistence, a professional geologist can follow individual programs, relate data to objectives (even if implied), and determine how conclusions were used in decision-making."

Powers, D.W., and Holt, R.M. 1993. "The Upper Cenozoic Gatuña Formation of Southeastern New Mexico." In Geology of the Carlsbad Region, New Mexico and West Texas, D.W. Love et al., eds., Forty-Fourth Annual Field Conference Guidebook, pp. 271-282. New Mexico Geological Society, Socorro, NM.

ABSTRACT, p 271;

" The Gatuña Formation of southeastern New Mexico has been studied in the field for two landfill projects and the Waste Isolation Pilot Plant project. Shafts, drilling and field mapping reveal the distribution, thickness and sedimentary features of the unit in an area where it was poorly known or assigned to other units. The Gatuña is at least 300 ft thick in the study area. The formation was deposited in the north and east as clastic beds ranging from conglomerates to laminar claystones. Fining upward cycles are common, though depositional features and facies associations are consistent with braided river/stream environments, not meandering rivers. Laminar and thinly bedded siltstones to claystones were deposited in flood plain to playa environments. Pedogenic features superimposed on many fining upward cycles include soil fractures, slickensides, MnO_2, illuviated clay, bioturbation, probable ped structures and desiccation cracks. The upper Gatuña more consistently includes pedogenic development. Beds of poorly indurated 'orange' sand, consisting of rounded and well-sorted grains, are interpreted as eolian deposits. From southern Nash Draw to Orla, the Gatuña is fine-grained and gypsoferous, including displacive crystals and probable subaqueous deposits. These outcrops represent low energy environments, including playas, which were near local base level. The age of the upper Gatuña is reasonably constrained by the Lava Creek B ash (0.6 Ma) within the Gatuña along Livingston Ridge. The age of basal deposits is poorly or not constrained. An ash within probable Gatuña near Orla, TX, is about 13 Ma based on both radiometric and geochemical data. The Gatuña represents an important piece of the geological history of southeastern New Mexico. Further studies could include efforts to better determine the age of the formation; to obtain paleontological data; and to map Gatuña structural relationships to older and younger beds in detail to determine the timing of and spatial evidence for, dissolution of evaporites and collapse of overlying beds, including the Gatuña."

Powers, D.W., and Holt, R.M., 1995. "Regional Geological Processes Affecting Rustler Hydrogeology," Westinghouse Electric Corp, Carlsbad, NM.

NOTE: Figure 6 is on the following page of this document.

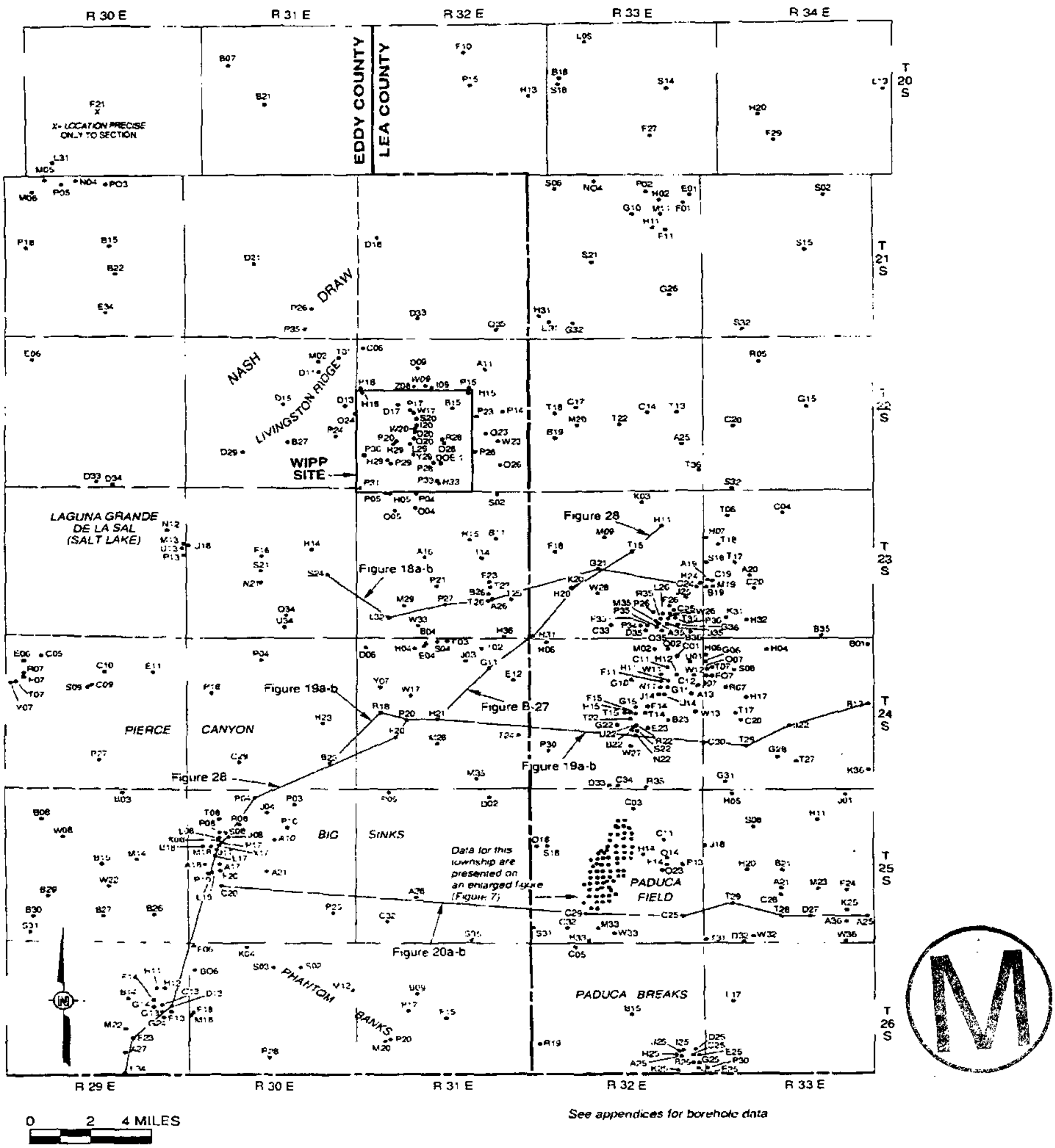


Figure 6
Drillhole Base Map

Powers, D.W., and LeMone, D.V. 1987. A Summary of Ochoan Stratigraphy, Western Delaware Basin. Guidebook 18, pp. 63-68. El Paso Geological Society.

ABSTRACT, p 63, col 1;

" Four formations comprise the Ochoan Series of the northern Delaware Basin. They are, in ascending order, the Castile, Salado, Rustler, and Dewey Lake formations. Boundaries within the series all appear to be transitional, though the uppermost boundary is an erosional unconformity. The faunal evidence for age is very limited, and the regional and broader correlations are for the most part problematical."

Powers, D.W., and Martin, M.L. 1993. A Select Bibliography with Abstracts of Reports Related to Waste Isolation Pilot Plant (WIPP) Geotechnical Studies (1972-1990). SAND92-7277. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p i;

" This select bibliography contains 941 entries. Each bibliographic entry contains the citation of a report, conference paper, or journal article containing geotechnical information about the Waste Isolation Pilot Plant (WIPP). The entries cover the period from 1972, when investigations began for a WIPP Site in southeastern New mexico, through December 1990.

Each entry is followed by an abstract. If an abstract or suitable summary existed, it has been included; 316 abstracts were written for other documents. For some entries, an annotation has been provided to clarify the abstract, comment on the setting and significance of the document, or guide the reader to related reports. An index of key words/phrases is included for all entries."

Powers, D.W. and Holt, R.M. 1990. Sedimentology of the Rustler Formation Near the Waste Isolation Pilot Plant (WIPP) Site. pp. 77-106. GSA Field Trip #14. Geological Society of America 1990 Annual Meeting. October 29-November 1, 1990. Dallas, TX.

Section Regional Relationships, p 100, col 1, para 7;

" About 600 geophysical logs (natural gamma and acoustic) of the Rustler Formation were interpreted to understand the regional relationship between various units (Holt and Powers, 1988; Powers and Holt, in prep.). Geophysical logs near the site were carefully compared to lithofacies described from cores and shafts, easily relating many subdivisions. Several extended cross-sections were drafted to show lateral relationships in some detail (Holt and Powers, 1988). Structure contour and isopach maps for different units were drafted and compared. . . ."

M

Register, J.K., and Brookins, D.G. 1980. Rb-Sr Isochron Age of Evaporite Minerals from the Salado Formation (Late Permian), Southeastern New Mexico. Isochron/West, 29, pp. 39-42.

p. 39;

" The bedded evaporites of southeastern New Mexico have been extensively studied in conjunction with potash deposit exploration, and, more recently, for consideration for a Waste Isolation Pilot Plant (WIPP) for radioactive waste disposal. An important facet of the latter study is the chemical and isotopic integrity of the evaporite minerals. Experience elsewhere with evaporite minerals (see discussion in Brookins and others, 1980) suggests post-formational, open-system conditions resulting in anomalously young ages for both halide and sulfate minerals by the K-Ar and Rb-Sr methods. Many of these young dates elsewhere (i.e. Federal Republic of Germany) have been attributed to metamorphic events or, alternatively, to both episodic and/or continuous loss of radiogenic ^{40}Ar and ^{87}Sr by unspecified, though subtle, events. Tremba (1969) and Bodine (1978) have suggested episodic and continuous recrystalization events for the southeastern New Mexico evaporites.

It is the purpose of this report to present our Rb-Sr isochron findings for 41 samples including sylvite-halite rich mixtures, polyhalite-rich samples, and anhydrites. The locations are given in Table 1, the data in Table 2, and the mineralogy in Table 3. Figure 1 shows the isochron. Sample procedures are given in Register (1979). The decay constant of 1.42 x $10^{-11}y^{-1}$ was used, and the York (1969) method for isochron construction was employed."

Reilinger, R., Brown, L., and Powers, D. 1980. New Evidence for Tectonic Uplift in the Diablo Plateau Region, West Texas. Geophysical Research Letters, Vol. 7, No. 3.

ABSTRACT, p. 181;

" Recent releveling measurements conducted by the National Geodetic Survey in West Texas and southeastern New Mexico indicate uplift of the Diablo Plateau-Salt Basin region relative to benchmarks to the northeast in the Great Plains. These new measurements confirm and enhance the previously reported interpretations of releveling data in this area. Total relative uplift measured between 1934 and 1977 reaches 19 $\pm$ 3 cm. Combining this new information with leveling data from 1934, 1943, and 1958 along this same route indicates that: (1) the uplifted area extends 120 km in the east-west direction (there is presently no control on any north-south component of tilting), with maximum relative uplift occurring approximately 12 km west of the boundary between the Diablo Plateau and Salt Basin graben; and (2) on the time scale between measurements ($\sim$20 yrs.), uplift appears to be occurring more or less continuously, although not at a constant rate. The progressive deformation indicated by the releveling measurements, the large magnitude relative to possible leveling errors, and the spatial dimensions of the uplift rule out systematic errors or near-surface effects (water table variations, sediment compaction, etc.) as an explanation and favor a tectonic origin. Intracrustal magmatic activity of some form of preseismic deformation (dilitancy, fault creep at depth, etc.) appear to be the most reasonable explanations in view of presently available geologic and geophysical information.

The pattern of uparching is perturbed at the Salt Basin graben, indicating 4.2 $\pm$ 0.3 cm of subsidence relative to its margins between 1958 and 1977. This subsidence could be related to the regional tectonic uparching, although near-surface, non-tectonic effects cannot be excluded."

Reiter, M. Barroll, M.W., and Minier, J. 1991. "An Overview of Heat Flow in Southwestern United States and Northern Chihuahua, Mexico." In Neotectonics of North America, D.B. Slemmons, E.R. Engdahl, M.D. Zoback, and D.D. Blackwell, eds., pp. 457-466. Geological Society of America, Boulder, CO.

The Rio Grande rift and northern Chihuahua, Mexico, p. 463, col. 1, para. 2;

" In the southern part of the Rio Grande rift there are a few heat-flow measurements and estimates that are intermediate in value (about 70 to 80 mW m_{-2}); most of the data are above the average heat flow (89 mWm_{-2}) for the entire Basin and Range Province (Fig. 7, bottom; see also Plate 1 in Reiter and others, 1986). Between Socorro and Las Cruces there are eight sites where the heat-flow estimates are about 90 to 100 mW m_{-2}. Four of the sites are located in the northern part of the Jornada del Muerto, north of the Jornada Basin. The other four sites are scattered widely. Higher heat-flow estimates (117 to 135 mW m_{-2}) are also made at sites scattered over the region from Socorro to Las Cruces. From these data it is suggested that the regional or background heat flow for the rift area between Socorro and Las Cruces is about 95 mW m_{-2}, a value that closely agrees with the interpretation of previous data by Decker and Smithson (1975). It is also interesting to note that the mean of 15 measurements in extreme southwest New Mexico is 94 $\pm$ 21 mW m_{-2}. Some of the sites with higher heat-flow estimates in the southern Rio Grande rift (117 to 135 mW m_{-2}) are near large normal faults that may act as conduits for hydrothermal circulation to enhance geothermal gradients; but again the actual cause of the elevated geothermal gradients is generally ambiguous . . ."

Richey, S.F. 1989. Geologic and Hydrologic Data for the Rustler Formation Near the Waste Isolation Pilot Plant, Southeastern New Mexico. Open-File Report 89-32. U.S. Geological Survey, Albuquerque, NM.

ABSTRACT, P 1;

" The U. S. Geological Survey is investigating the geohydrology in the vicinity of the Waste Isolation Pilot Plant in southeastern New Mexico. Data presented in this report were compiled in support of a regional ground-water flow model. The data include water-level measurements obtained from the U. S. Geological Survey's Ground-Water Site-Inventory and OMNIANA data bases and stratigraphic information interpreted from commercial geophysical logs."

DATA PRESENTED, p. 3;

" Data presented in the water-level table (table 1) include well identifier and name, well location, water-bearing unit, land-surface altitude, total well depth, date of water-level measurement, and water level. These data were obtained from two U.S. Geological Survey data bases. The Ground-Water Site-Inventory data base (GWSI) is a national data base for storing site and water-level data. OMNIANA is an older data base used by the Survey for the same purpose; the data currently are being transferred to GWSI. Accuracy of land-surface altitude in GWSI and OMNIANA is unknown because they generally were obtained by locating the wells on topographic maps of various scales.

Data presented in the stratigraphic information table (table 2) include well identifier and name, well location, land-surface altitude at the well, total well depth, and stratigraphic depths to top, which were interpreted from commercial geophysical logs by C.L. Jones and R.P. Snyder of the Survey's Geologic Division. Well name, location, datum altitude, and total well depth usually were obtained from the log headers, and their accuracies are dependent on the drilling and logging companies. Occasionally the datum on a log was missing or ambiguous, in which case the land-surface altitude was obtained from a 1:24,000-scale Survey topographic map. A correction for kelly bushing was added when necessary."

Robinson, T.W., and Lang, W.B. 1938. Geology and Ground-Water Conditions of the Pecos River Valley in the Vicinity of Laguna Grande de la Sal, New Mexico, With Special Reference to the Salt Content of the River Water. Twelfth and Thirteenth Biennial Reports of the State Engineer Engineer of New Mexico for the 23rd, 24th, 25th, and 26th Fiscal Years, July 1, 1934 to July 30, 1938. State Engineer, Santa Fe, NM.

INTRODUCTION, p 79;

" At the request and in cooperation with the State Engineer of New Mexico, a study of ground-water conditions in the Pecos River Valley southeast of Carlsbad, Eddy County, New Mexico, has been under way since the spring of 1937. The results of that study are presented in this report. The area involved lies largely in Townships 21, 22, 23 and 24 south, Ranges 26, 27, 28 and 29 east, New Mexico principle meridian. (See plate 1). Intensive work was done chiefly in the vicinity of the Laguna Grande de la Sal and the area lying between it and the Malaga Bend of the Pecos River, about five miles south. The area is crossed by the Pecos River flowing southeastward from Carlsbad. During the growing season, the entire flow of the Pecos River above Carlsbad is normally diverted for irrigation at Lake McMillan and Lake Avalon. During this period the Pecos River from Carlsbad south is fed chiefly by large springs. The largest spring, known as Carlsbad Spring, is located in the river channel just below Lake Avalon. The Black River enters the area from the west and flows eastward to its confluence with the Pecos River northeast of Malaga. It is also spring-fed, deriving most of its water from Blue Spring and Castle Spring, near Black River village. The drainage pattern is well developed on the west, and during rainy periods many normally dry arroyos and draws discharge flood water into the Pecos River. Drainage from the east is by poorly developed draws which carry water to the Pecos only during exceptionally heavy rainfall. A prominent feature east of the river is Laguna Grande de la Sal, which is a shallow salt lake in a playa covering about 3½ square miles.

Carlsbad, the largest town in the area and the county seat of Eddy County, had a population of 3,708 in 1930. However, owing largely to the development of the potash mines located about 20 miles east, the population in 1938 is about double that of 1930. Loving, located about 12 miles south, and Malaga, about 18 miles south of Carlsbad, each had less than 1,000 inhabitants in 1930. Carlsbad is served by the Atchison, Topeka, and Santa Fe Railroad and by main highways leading north to Roswell, New Mexico, southwest to El Paso, Texas, south to Pecos, Texas, and east to Hobbs, New Mexico.

Cotton and hay are raised in the irrigated section along the Pecos River, while cattle, sheep and goat raising predominate in the unirrigated upland areas to the east and west. The principle mineral industry is the mining and refining of potash. A large number of tourists are attracted annually to the famous Carlsbad Caverns, located about 25 miles southwest of Carlsbad, near the highway leading to El Paso, Texas.

A group of farmers who pump water from the river for irrigation report that in recent years the water, because of its salinity, has been injurious to their cotton crop. In September 1932 the U.S. Potash Company began operations, using the Laguna Grande de la Sal as a disposal area for the waste brine from their potash refining operations. The reported difficulty with salt, shortly after refinery operations began, naturally cast suspicion on the brine in the Laguna Grande. There is no visible outlet from the Laguna Grande, and therefore the problem arose as to whether the lake brine may be percolating underground to the Pecos River.

A study of the chemical character of the water of the Pecos River has been made by C.S. Howard and W.F. White, Jr., and numerous analyses were made of the surface and ground waters in this area (see report on chemical character of Pecos River under 'Quality of Water,' to be found elsewhere in this volume). The ground-water studies by T.W. Robinson were begun on April 13, 1937, and the geologic studies by W.B. Lang on October 15, 1937."

Salvador, A. 1985. Chronostratigraphic and Geochronometric Scales in Colorado SUNA Stratigraphic Correlation Charts of the United States. American Association of Petroleum Geologists Bulletin, Vol. 69.

INTRODUCTION, p 181, col 1;

" During 1976, the American Association of Petroleum Geologists undertook the ambitious task of preparing a new set of stratigraphic correlation charts for the United States. The project named 'Correlation of Stratigraphic Units of North America,' or COSUNA for short, was as needed as it was ambitious. The last comprehensive set of stratigraphic correlation charts had been published by the Geological Society of America between 1942 and 1960. The charts were in urgent need of revision.

Otis E. Childs accepted the post of project director, and a Steering Committee was created that included representatives from the American Association of Petroleum Geologists, Association of American State Geologists, U.S. Geological Society, American Association of Stratigraphic Palynologists, North American Commission on Stratigraphic Nomenclature, JOIDES Planning Committee, Geological Society of America, and Society of Economic Paleontologists and Mineralogists. Grant Steele served as chairman of the Steering Committee for the entire life of the project. To advise the project director on technical matters, a Stratigraphic Technical Committee also was established.

The United States was divided into appropriate geologic provinces, and . . ."

Sandia National Laboratories. 1992. Preliminary Performance Assessment for the Waste Isolation Pilot Plant, December 1992, Volume 3: Model Parameters. SAND92-0700/3. Sandia National Laboratories, Albuquerque, NM.

Volume 3
Section 1.3.2 Construction of Distributions, p 1-15;
" The steps below describe the procedure developed by the PA Department to construct probability distributions (CDFs) for the uncertain parameters in consequence and probability models (Figure 1.3-1)(modified from Tierney, 1990).
STEP 1 Determine whether site-specific data for the parameter in question exist, i.e., find a set of site-specific sample values for the parameter. Data and information are usually either documented in a formal report or are described in an internal memorandum (see Appendix A). If data sets exist, go to Step 3; if no data sets are found, go to Step 2.
STEP 2 Request that the investigator supply a specific shape (e.g., normal, lognormal) and associated numerical parameters for the distribution of the parameter. If the investigator assigns a specific shape and numerical values for the distribution's parameters, go to Step 5; if the investigator cannot assign a specific shape and appropriate parameters, go to Step 4. In responding to this request, the investigator may use his or her knowledge of global data to form an answer. Distributions supplied by investigators may be documented by a memorandum (see Appendix A).
STEP 3 Determine the size of the combined data sets. If the number of values in the combined data set is > 3, use the combined data to construct a piecewise-linear cumulative distribution function or, alternatively, a discreet cumulative distribution function, and then go to Step 5. If the number of variables in the combined data set is ≤ 3, go to Step 4.
STEP 4 Request that the investigator provide subjective estimates of (a) the range of the variable (i.e., the minimum and maximum values taken by the variable with at least 99% confidence and preferably 100% confidence) and (b) if possible, one of the following (in decreasing order of preference): (1) percentile points for the distribution of the variable (e.g., the 25th, 50th [median], and 75th percentiles), (2) the mean value and standard deviation of the distribution, or (3) the mean value. Again, in responding to this request, the investigator may use his or her knowledge of global data to form an answer and may document that answer in a memorandum (see Appendix A). Then, using the maximum entropy formulation (MEF), construct one of the following distributions depending upon the kind of subjective estimate that has been provided (Tierney, 1990; Harr, 1987):

- Uniform probability distribution function (PDF) over the range of the variable,
- Piecewise-linear cdf based on the subjective percentiles,
- Exponential pdf (truncated) based on the subjective range and mean value,
- Normal pdf based on subjective mean value and standard deviation.

Then go to Step 5.
STEP 5 End of procedure; distribution is assigned. Computational considerations and limitations on the data itself may require later modification to some distributions. Some of these limitations are discussed in the next section."

Sandia National Laboratories and D'Appolonia Consulting Engineers. 1982. Basic Data Report for Drillhole WIPP 12 (Waste Isolation Pilot Plant—WIPP). SAND82-2336. Sandia National Laboratories, WIPP Performance Assessment Division, Albuquerque, NM.

ABSTRACT, p 1;

" WIPP 12 is a borehole drilled in eastern Eddy County, New Mexico, to investigate the stratigraphy, structure and lithology in the WIPP area. WIPP 12 was drilled in section 17, T22S,R31E, between November 9 and December 7, 1978. The hole was drilled to a depth of 2785.8 ft. It encountered from top to bottom, 16.2 ft of sand, 3 ft of Mescalero Caliche and 9.6 ft of the Gatuna Formation, all of Quaternary age; 138.2 ft of the Triassic Santa Rosa Formation, 483 ft of the Dewey Lake Red Beds, 326 ft of the Rustler Formation, 1771.5 ft of the Salado Formation, and 48.3 ft of the Castile Formation, all of Permian age. Cores or cuttings were obtained for the entire hole. A suite of geophysical logs, including neutron gamma and density curves, was run to the full depth of WIPP 12. The borehole demonstrated that the elevation of the top of the Castile is about 160' above the same horizon in ERDA 9.

The WIPP is a demonstration facility for the disposal of transuranic (TRU) waste from defense programs. The WIPP will also provide a research facility to investigate the interactions between bedded salt and high level wastes."

Sandia National Laboratories and D'Appolonia Consulting Engineers. 1982. Basic Data Report for Drillhole WIPP 14 (Waste Isolation Pilot Plant—WIPP). SAND82-1783. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p 1;

" Borehole WIPP 14 is an exploratory well drilled in eastern Eddy County, New Mexico, in section 9, T22S,R31E. The borehole was drilled to a depth of 1000.0 ft measured from ground level. It penetrates, from top to bottom, 15.4 ft of Quaternary sands, 125.6 ft of the Triassic Santa Rosa Sandstone, and in the Permian strata, 497.7 ft of the Dewey Lake Red Beds, 312.9 ft of the Rustler Formation and 48.4 ft of the Upper Salado Formation. Seven hundred feet of the well were cored, at consecutive and nonconsecutive 10-ft intervals to a depth of 925.5 ft. Cuttings were collected where core was not taken. Density, gamma ray neutron and caliper logs were run the full depth of the hole.

The WIPP is a demonstration facility for the disposal of transuranic (TRU) waste from defense programs. The WIPP will also provide a research facility to investigate the interactions between bedded salt and high level wastes."

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Sandia National Laboratories and D'Appolonia Consulting Engineers. 1983. Basic Data Report for Drillhole ERDA 10 (Waste Isolation Pilot Plant—WIPP). SAND79-0271. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p 1;

" Borehole ERDA 10 was drilled to obtain information on possible dissolution of halite within the Castile Formation and on the hydrologic characteristics of the fluid-bearing zones in the Bell Canyon Formation. The borehole is located in Section 14, T22S,R30E in southern Eddy County, New Mexico. ERDA 10 was drilled to a depth of 4431.5 feet. Cores from the Castile were taken to obtain direct information which was supplemented by geophysical logging. Based on preliminary analysis of the data, the ERDA 10 stratigraphic section is interpreted as a sequence of sandstones, siltstones, claystones, and evaporites normal for the area. No evidence of dissolution of significant amounts of halite was observed."

Sandia National Laboratories and UNM (University of New Mexico). 1981. Basic Data Report for Drillhole WIPP 15 (Waste Isolation Pilot Plant - WIPP). SAND79-0274. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p 1;

" WIPP 15 is a borehole drilled in March, 1978, in section 18, T.23S., R. 35E. of south-central Lea County. The purpose of WIPP 15 was to examine fill in San Simon Sink in order to extract climatic information and to attempt to date the collapse of the sink. The borehole was cored to total depth (810.5 feet) and encountered, from top to bottom, Quaternary calcareous clay, marl and sand, and claystones and siltstones of the Triassic Santa Rosa Formation (?). Neutron and gamma ray geophysical logs were run to measure density and radioactivity.

The sink has about 547 feet of Quaternary fill indicating subsidence and deposition. Diatomaceous beds exposed on the sink margin yielded samples date by ^{14}C at 20,570 $\pm$ 540 years BP and greater than 32,000 years BP; these beds are believed stratigraphically equivalent to diatomaceous beds at 153-266 feet depth in the core. Aquatic fauna and flora from the upper 98 feet of core indicate a pluvial period (probably Tahokan) followed by an arid or very arid time before the present climate was established.

Aquifer pump tests performed in the Quaternary sands and clays show transmissivities to be as high as 600 feet squared per day. As the water quality was good, the borehole was released to the lessee as a potential water well."

Sandia National Laboratories and USGS (U.S. Geological Survey). 1979. Basic Data Report for Drillhole WIPP 13 (Waste Isolation Pilot Plant - WIPP). SAND79-0273. Sandia National Laboratories, Albuquerque, NM.

Section 1.0 ABSTRACT, p 1;

" The borehole WIPP-13 was drilled in the SW 1/4 section 17, T22S, R31E of eastern Eddy County during July and August, 1978, to investigate the nature of a resistivity anomaly. The stratigraphic section was normal, consisting of 13 feet of Quaternary deposits (including artificial fill for drill pad), 53 feet of the Triassic Santa Rosa Sandstone, 451 feet of Dewey Lake Red Beds, 269 feet of the Rustler Formation, and 179 feet of the upper member of the Salado Formation. Consecutive cores were taken from 570 to 595, 656 to 729, and 827 to 878 feet. Cuttings were collected at 10-foot intervals throughout the rest of the hole. Geophysical logs were run to aid in interpretation of the stratigraphy.

The WIPP is to demonstrate (through limited operations) disposal technology for transuranic (TRU) defense wastes. Eventual conversion of the facility to a repository for TRU defense wastes is anticipated. The WIPP will also provide research facilities for interactions between high-level waste and salt."

Sandia National Laboratories and USGS (U.S. Geological Survey). 1980. Basic Data Report for Drillhole WIPP 18 (Waste Isolation Pilot Plant—WIPP). SAND79-0275. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT;

" WIPP 18 is an exploratory borehole whose objective is to determine the nature of the near-surface formations after seismic information indicated a possible fault. The borehole is located in section 20, T.22S., R.31E., in eastern Eddy County, New Mexico and was drilled between March 14 and 30, 1978. The hole was drilled to a depth of 1060 feet and encountered, from top to bottom, surficial Holocene deposits (5', including artificial fill for drill pad), the Mescalero caliche (4'), the Santa Rosa Sandstone (129'), the Dewey Lake Red Beds (475'), the Rustler Formation (315'), and the upper portion of the Salado Formation (132'). Cuttings were collected at 10-foot intervals. A suite of geophysical logs was run to measure acoustic velocities, density, and radioactivity. On the basis of comparison with other geologic sections drilled in the area, the WIPP 18 section is a normal stratigraphic sequence and it does not show structural disruption.

The WIPP is to demonstrate (through limited operations) disposal technology for transuranic defense wastes. The WIPP will also provide facilities to research interactions between high-level waste and salt."

Sandia National Laboratories and USGS (U.S. Geological Survey). 1980. Basic Data Report for Drillhole WIPP 32 (Waste Isolation Pilot Plant - WIPP). SAND80-1102. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p 4;

" WIPP 32 is an exploratory borehole drilled to examine the subsurface at a small topographic high in Nash Draw. The borehole is located in east-central Eddy County, New Mexico, in NE 1/4 SE 1/4 Sec. 33, T.22S., R.29E. and was drilled in August, 1979. The hole was drilled to a depth of 390 feet, and encountered, from top to bottom, the Rustler Formation, (166') and the upper Salado Formation (224'). Core was taken from 4 to 353 feet. Geophysical logs were run the full length of the hole to measure formation properties.

The WIPP is to demonstrate (through limited operations) disposal technology for transuranic defense wastes. The WIPP will also provide facilities to research interactions between high-level waste and salt."

Sandia National Laboratories and USGS (U.S. Geological Survey). 1981. Basic Data Report for Drillhole WIPP 33 (Waste Isolation Pilot Plant—WIPP). SAND80-2011. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p 1;
" WIPP 33 is an exploratory borehole to investigate the nature of unusually thick fill material in the northwest portion of the WIPP site; a breccia pipe was considered a possibe, (sic) though unlikely, cause of the fill. The borehole is located in Section 13, T22S, R30E, in east central Eddy County, New Mexico and was drilled during July, 1979. The hole was drilled to a depth of 840 feet, and encountered, from top to bottom, surficial Holocene deposits (44' including artificial fill for drill pad), the Dewey Lake Red Beds (357'), the Rustler Formation (276') and the upper portion of the Salado Formation (163'). Selected intervals were cored, and cuttings were taken for examination by geologists. Geophysical logs were taken the full length of the borehole to measure radioactivity, resistivity and density. The stratigraphic profile was found to be normal, and no breccia was observed."

Sandia National Laboratories and USGS (U.S. Geological Survey). 1982. Basic Data Report for Drillhole WIPP 11 (Waste Isolation Pilot Plant—WIPP). SAND79-0272. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p 1;

" Seismic reflection data from petroleum industry sources showed anomalous reflectors in the Castile Formation over a small area about 3 miles north of the center of the Waste Isolation Pilot Plant (WIPP) site. Additional corroborative seismic reflection data were collected as part of WIPP investigations, and WIPP 11 was drilled to investigate the anomaly. WIPP 11 was drilled near the northwest corner of Section 9, T.22.S., R.31E. it penetrated, in descending order, sand dune deposits and the Gatuna Formation (29'), Santa Rosa Sandstone (132'), Dewey Lake Red Beds (502'), Rustler Formation (288'), Salado Formation (1379'), and most of the Castile Formation 1240'). Beds within the lower part of the Salado, and the upper anhydrite of the Castile, are thinner than normal; these beds are displaced upward structurally by the upper Castile halite which is highly thickened (about 968'). The lowest halite is thin (51') and the basal anhydrite was not completely penetrated. Subsequent seismic and borehole data has shown WIPP 11 to be in a structural complex now identified as the 'disturbed zone.'

The WIPP is a demonstration facility for the disposal of transuranic (TRU) waste from defense programs. The WIPP will also provide a research facility to investigate the interactions between bedded salt and high level waste, though there are no plans at this time to dispose of high level waste or spent fuel at WIPP."

Sanford, A., Sandford, S., Wallace, T., Barrows, L., Sheldon, J., Ward, R., Johansen, S., and Merritt, L. 1980. Seismicity in the Area of the Waste Isolation Pilot Plant (WIPP). Report by the New Mexico Institute of Mining and Technology to Sandia National Laboratories. SAND80-7096. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p 1;

" The Rio Grande rift zone is the most probable area of New Mexico to have substantial seismic activity. The principal data used in establishing the seismicity of this region were: (1) reports of strong earthquakes before 1960, (2) instrumental studies of moderate shocks ($M_L > 2.7$) after 1960, (3) analyses of microearthquakes ($M_L < 2.7$) recorded at Albuquerque, Socorro, and Las Cruces, and (4) analysis of fault scarps offsetting the Quaternary geomorphic surfaces in the Socorro area.

Historical reports indicate a moderately high seismic risk in a zone from Albuquerque to Socorro. In this region, particularly near Socorro, the largest shock in a 100-year period is likely to be magnitude 6. Instrumental data on earthquakes ($M > 2.7$) since 1960 show that activity is highest near Socorro and Las Cruces. However, estimated seismic risk from these data is low, with a maximum magnitude shock of about 5 each 100 years over the entire extent of the rift zone. Analyses of microearthquakes ($M_L < 2.7$) also lead to low estimates of seismic risk in the rift zone, e.g. a maximum magnitude shock of 4.6 in the Socorro-Bernardo region each 100 years.

Historical reports, spanning a century, are probably more reliable indicators of seismic risk than the relatively short-term instrumental data spanning only about a decade. The historical data indicate probability of a magnitude 6 earthquake each 100 years. Both categories of data indicate seismic risk is not uniform and is greatest in the following regions: (1) Socorro-Bernardo, (2) Albuquerque-Belen, and (3)El Paso-Las Cruces.

In the region of highest seismic risk, Socorro-Bernardo, little direct correlation exists between the distribution of microearthquakes and faults. Analyses of data for faults offsetting recent geomorphic surfaces indicates seismic activity has been occurring in the Socorro-Bernardo region for thousands of years. Estimates of seismicity based on the fault scarps cover a fairly wide range because of the uncertainty in the age of the scarps. However, the most reasonable estimates for the age yield seismicity values comparable to those calculated from earthquake data."

Sanford, A.R., and Toppozada, T.R. 1974. Seismicity of Proposed Radioactive Waste Isolation Disposal Site in Southeastern New Mexico. New Mexico Bureau of Mines and Mineral Resources, Circular 143, pp. 1-15.

ABSTRACT, p. iv;

" Seismicity was determined for the area within a 300-km radius from the proposed nuclear waste disposal site in southeastern New Mexico. The primary data used to establish seismic risk were: reports of felt shocks prior to 1961; instrumental epicenters and magnitudes from 1961 through 1972; and lengths, displacements, and ages of fault scarps cutting Quaternary geomorphic surfaces. The principle results of this study were: 1) earthquakes exceeding local magnitude 3.5 have not occurred within 40 km of the site in the past 12 years; probably not in the past 50 years, 2) on the average of once every 50,000 years major earthquakes (magnitude 7.8) are possible within 115 km of the site, but these events will produce accelerations of only about 0.07 g at the site; and 3) some evidence indicates that earthquakes located on the Central Basin Platform, 80 to 100 km southeast of the site, could be related to water injection for secondary recovery of oil."

Sanford, A.R., Toppozada, T.R., Ward, R.M., and Wallace, T.C. 1976. The Seismicity of New Mexico 1962 through 1972. Geological Society of America Abstracts with Programs, Vol. 8, p. 625.

ABSTRACT, p. 626;

" Epicenters and magnitudes have been determined for 183 earthquakes that occurred within or bordering New Mexico from January 1, 1962 through 1972. The crustal model used for earthquake locations consisted of a 42 km thick layer with a velocity of 6.15 km/sec overlying a semi-infinite layer with a velocity of 8.10 km/sec. Because of the small number of seismograph stations, Pg arrivals beyond the crossover distance were used in the location procedure, a computer adaptation of the arc method. Locations obtained are believed to be better than ± 15 km in nearly all cases.

The majority of seismic activity appears to follow two broad belts. One belt extends southwestward from the northeast corner of New Mexico across the Rio Grande valley to the vicinity of Grants and then southward to the Silver City area. This diffuse zone of epicenters may be associated with Late Cenozoic volcanics. The other belt of seismicity follows the Rio Grande valley which has been an active rift structure since Miocene time. Shocks with $M_L \geq 3.4$ have also occurred in the High Plains and the Colorado Plateau.

Recurrence rates have been calculated for regions of 697,000, 311,000, 125,000, and 49,000 sq. km centered on stations located at Socorro and Albuquerque. The maximum Magnitude earthquakes/100 years/100,000 sq. km for the four areas are 5.1, 4.7, 4.7, and 5.1 respectively. These levels of seismic activity are less than 1/100 of that observed in Southern California."

Sanford, A.R., Jaksha, L.H., and Cash, D.J. 1991. "Seismicity of the Rio Grande Rift in New Mexico." In Neotectonics of North America. D.B. Slemmons, E.R. Engdahl, M.D. Zoback, and D.D. Blackwell, eds., pp. 229-244.

GENERAL FEATURES OF RIO GRANDE RIFT SEISMICITY, p. 230, col. 1, para. 2;

" Starting about 10 years ago, geophysical data began to accumulate that indicated that the RGR boundaries could be extended beyond those proposed by Chapin (1971) in Figure 1. Cordell (1978) summarized geophysical evidence for a broad astenospheric-lithospheric structure centered beneath the chain of grabens shown in Figure 1. Cordell found that the main feature of east-west gravity profiles through New Mexico is a broad negative Bouguer anomaly centered roughly on the axis of the rift. According to Cordell (1978), the anomaly is a consequence of subcrustal structure related to a Rio Grande rift system, which includes a broad uplifted region as well as the obvious grabens and basins usually considered to be RGR. The width of the anomaly appears to be at least 500 km along the New Mexico-Colorado border and broadens progressively to the south. Thus, the gravimetric signature of the rift system, and possibly the structure that produced it, extends beneath the presumably stable Colorado Plateau and Great Plains Provinces, well beyond Chapin's boundaries of the rift shown in Figure 1.

Other geophysical observations support the existence of a broad astenospheric-lithospheric structure beneath the RGR. Davis and others (1984) found a traveltime residual anomaly for teleseismic P-wave arrivals along a profile crossing the RGR. The anomaly has a maximum delay of 1.5 seconds and an east-west extent of approximately 340 km, of which about 60 km underlies the Colorado Plateau and about 70 km underlies the Great Plains.

Shown in Figure 2 is a magnetic map for New Mexico based on the composite magnetic anomaly map of the United States by Taylor and others (1983). The broad north-south-oriented low that appears to be associated with the RGR is one of the strongest and most clearly defined in the conterminous United States. The boundaries for this anomaly are somewhat subjective but clearly fall beneath the Colorado Plateau and the Great Plains and well beyond the maximum boundaries of the RGR in Figure 1.

Gable and Hatton (1983) presented geologic evidence for surface uplift during the past 10 m.y. over a broad region centered on the RGR (Fig, 3). The general character of the uplift extends uninterrupted north through Colorado and south-southeast through west Texas. The east-west extent and generally north-south orientation of the uplift suggests a relation between it and the asthenospheric-lithospheric structures underlying it.

On the basis of geophysical, topographical, and geological information, Eaton (1986) concluded that the Southern Rocky Mountains extend southward through the entire length of New Mexico. Accordingly, the broad geophysical anomalies and surface uplift described above are the signature of the Southern Rocky Mountains, and the RGR is a system of axial grabens along this major north-trending structure."

Saulnier, Jr., G.J., and Avis, J.D. 1988. Interpretation of Hydraulic Tests Conducted in the Waste-Handling Shaft at the Waste Isolation Pilot Plant (WIPP) Site. SAND88-7001. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p ii;

" A series of sub-horizontal boreholes from 8- to 41-feet deep were drilled from four depth levels in the waste-handling shaft at the Waste Isolation Pilot Plant (WIPP) site in southeastern New Mexico. The waste-handling shaft is one of three shafts built at the WIPP site to provide surface access to the underground waste repository under construction 2150 feet below the ground surface. The boreholes were drilled at the 782- and 805-foot depth levels in a mudstone and a claystone of the unnamed lower member of the Rustler Formation; at the 850-foot depth level in bedded halite in the upper Salado Formation; and at the 1350-foot depth level in halite, anhydrite, and polyhalite of the Salado Formation. Examination of the cores recovered from one borehole at each level indicated no direct evidence of construction-induced fracturing. Pulse-injection tests were conducted in packer-isolated intervals in six of the boreholes to estimate the formation's hydraulic conductivity and apparent formation pressure, and to determine whether or not there was evidence of construction-enhanced permeability up to one shaft diameter from the shaft wall.

The pulse-injection tests . . ."

Saulnier, Jr., G.J., Domski, P.S., Palmer, J.B., Roberts, R.M., and Stensrud, W.A. 1991. WIPP Salado Hydrology Program Data Report #1. SAND90-7000. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT;

" WIPP Salado Hydrology Program Data Report #1 presents hydrologic data collected during permeability tests of the Salado Formation performed from August 1988 through December 1989. Analysis and interpretation of the test data are presented in a separate report. The report presents the results of the drilling and testing of six boreholes drilled from the WIPP underground facility 655 m below ground surface in the Salado Formation. Permeability tests were conducted using multipacker test tools with inflatable packers to isolate borehole intervals to allow formation pore-pressure buildup and subsequent pulse-withdrawal tests. Test data include pressures and temperatures in brine-filled, packer-isolated test intervals and borehole-closure and axial test-tool-movement measurements. The test boreholes are 4.0-inch (10.2-cm) in diameter, and were cored in halite and associated anhydrite interbeds and clay seams. The boreholes are oriented vertically downward, angled downward, and horizontal. The boreholes were drilled and cored using compressed air to remove drill cuttings. Three boreholes were drilled in Room C2:C2H01, C2H02, and C2H03. Borehole C2H01 was initially drilled to a depth of 5.68m below the floor of Room C2 and later deepened to 8.97 m to include Marker Bed 139 in the test interval. Borehole C2H02 was drilled to a depth of 10.86 m (7.68 m vertical projection from the floor of Room C2) at a 45° downward angle from the junction of the west wall and floor of Room C2. Marker bed 139 was included in the test interval in borehole C2H02. Borehole C2H03 was drilled horizontally into the west wall of Room C2. Vertically downward boreholes were drilled from the floor in the North 1420 drift (borehole N4P50); the South 1300 drift (borehole S0P01); and in Room 7, Waste Panel 1 in the waste-storage area (borehole S1P71).

Permeability tests were performed after installing multipacker test tools in test boreholes, inflating the packers, and allowing pressures to build up in the isolated intervals. Pulse-withdrawal tests were performed after buildup pressures approached the apparent formation pore pressure. Pulse injections were sometimes performed to increase the fluid pressures in isolated intervals.

Compliance tests were conducted in lengths of steel and stainless-steel casings to evaluate the mechanical performance of the multipacker test tools. The stainless-steel compliance-test chamber was installed with externally mounted thermocouples in a downward-angled borehole in Experimental Room 4. Compliance tests included leak tests and simulated pulse-injection and pulse-withdrawal sequences."

Schaller, W.T., and Henderson, E.P. 1932. Mineralogy of Drill Cores from the Potash Field of New Mexico and Texas. U.S. Geological Survey Bulletin, Vol. 833.

SUMMARY, p VII;

" The potash field of southeastern New Mexico and adjacent parts of Texas is confined to the southern part of the Permian salt basin, covering about 40,000 square miles. The potash and associated minerals lie in a body of Permian halite, whose top is at least several hundred feet below the present surface.

The material described in this report was obtained from drill cores and well cuttings. All the specimens illustrated are parts of the drill cores that were shipped to Washington for examination and chemical analysis of their potash content.

The minerals identified . . ."

Schermer, S.C. 1980. A Report on the Archaeological Site Locations in the WIPP Core Area with Mitigation Recommendations for Bechtel National, Inc. Report 80-176. Agency for Conservation Archaeology, Eastern New Mexico University, Portales, NM.

INTRODUCTION, p 1;

" During the week of January 7, 1980, ACA conducted a project designed to relocate, accurately, 28 sites originally recorded by ACA crews during the summer of 1976. The project was conducted at the request of Bechtel National, Inc. and was administered by Mr. David Gieffer for Bechtel and Scott Schermer, Assistant Director, Agency for Conservation Archaeology. The project archaeologists, Miles Linnabery and Rodrick MacLennan, were able to relocate all but one site, which had apparently been obliterated by the construction of a caliche road. The archaeologists noted that the surface configuration of several sites had been changed by the movement of sand due to wind action.

METHODOLOGY

This project was designed to relocate previously recorded sites extant in the core area of the WIPP project, define their current surface configuration and condition, and accurately locate site center. . . ."

Schiel, K.A. 1988. The Dewey Lake Formation: End Stage Deposit of a Peripheral Foreland Basin [M.S. thesis]. University of Texas at El Paso, El Paso, TX.

ABSTRACT, p iv;

" The red siltstones and fine grained sandstones of the Dewey Lake Formation (Late Permian?) have always been relegated to a rather insignificant role in the geologic history of the Permian Basin. The present study suggests that they are, in fact, an important key to understanding the tectonic evolution of the southwestern United States.

Field work, in southeastern New Mexico, reveals that the Dewey Lake is fluvial in origin. Broad, shallow channels filled with thin horizontal laminations and flanked by laterally thinning wings comprise a large portion of the formation. Floodplain deposits, consisting of interbedded siltstone and silty claystone, are also very common.

The Dewey Lake displays many of the sedimentologic and morphologic characteristics associated with ephemeral fluvial systems. Some of these characteristics are an abundance of horizontal laminations and silty claystone drapes, the existence of interbedded siltstone and silty claystone interpreted to be the distal portion of sheet floods, and the presence of broad channels with laterally thinning wings. The Dewey Lake is, therefore, believed to have been deposited on a very extensive northwest sloping fluvial plain. Movement of sediment across this plain occurred only sporadically, during brief and localized flash floods.

It has previously been theorized that the Dewey Lake was extensively eroded prior to the deposition of the Santa Rosa Formation (Middle to Late Triassic). The results of the present study suggest that the thickness variations in the Dewey Lake are not a reflection of post depositional erosion but syndepositional differences in the subsidence rates of the Central Basin Platform and Delaware Basin. Increased subsidence of the Delaware Basin is reflected by the fact that the base of the Dewey Lake Formation is offset 100 m (300 ft) along the major northwest trending fault zone separating the Delaware Basin and Central Basin Platform. The Delaware Basin, therefore, appears to have been tectonically active throughout the deposition of the Dewey Lake Formation.

If the thickness variations in the Dewey Lake are due to subsidence rather than erosion then the contact between the Dewey Lake and the overlying Santa Rosa Formation is conformable. The Santa Rosa has been dated as Middle to Late Triassic in northeastern New Mexico; if this date is applicable to the Santa Rosa in southeastern New Mexico it dictates that the deposition of the Dewey Lake Formation continued into the Early Triassic.

A major unconformity separates Lower Permian and Cretaceous strata in the Fort Worth, Val Verde and Marfa Basin of Texas. This unconformity, which also exists in northwestern Chihuahua, clearly indicates that a large region of central Texas and northern Mexico was uplifted and eroded during the latest Permian ? and early Mesozoic. The location and timing of this uplift suggests that it was the source of the silt and fine sand comprising the Dewey Lake Formation. A close geographic and temporal relationship between this uplift and Late Triassic rift basins suggests that it originated as a pre-rift bulge.

The very extensive nature of this uplift suggests that the alluvial plain to the north (i.e. the Dewey Lake and Quartermaster Formations) extended significantly beyond the area

of west Texas and eastern New Mexico. The western portion of this plain is theorized to be the redbed facies of the Moenkopi Formation (Early Triassic). Apparent similarities in age, stratigraphic position, lithology and paleoscope all support the concept that the Dewey Lake and Moenkopi Formations are components of a single lithologic unit."

Schiel, K.A. 1994. A New Look at the Age, Depositional Environment and Paleogeographic Setting of the Dewey Lake Formation (Late Permian). West Texas Geological Society Bulletin, Vol. 33, No. 9, pp. 5-13.

ABSTRACT, p 5;

" The Dewey Lake Formation (Late Permian?) was studied, using surface and subsurface techniques, to more clearly define its depositional environment and tectonic/paleogeographic setting. The Formation contains numerous wide, shallow channels filled with horizontally laminated siltstone and flanked by laterally thinning 'wings' of micro-cross laminated siltstone. This morphology indicates that the Dewey Lake was deposited in a fluvial plain dominated by localized, ephemeral flows. The 'wings' represent distally thinning, floodplain deposits, formed as the channel filled with sediment and the water overflowed onto the surrounding plain.

The Dewey Lake is generally restricted to the Late Permian; however, the supporting evidence is weak. Lateral thickness variations in the Dewey Lake reflect syndepositional subsidence (i.e, the Delaware Basin was still active), not post-depositional erosion. Ash beds in the lower Quartermaster Formation (lateral equivalent), with ages near the Permo-Triassic boundary, date the initiation of sedimentation, not its duration. These observations suggest that although deposition of Dewey Lake sediments may have begun in the latest Permian, it continued through the Early Triassic.

The silts and fine grained sands comprising the Dewey Lake were derived from an uplift, to the south/southeast, encompassing the Pennsylvanian Ouachita/Marathon thrust belt and fore-deep basins. Triassic uplift of this region is indicated by an erosional unconformity between Late Permian and Cretaceous strata in several fore-deep basins and Triassic conglomerates in the Glass Mountain and Llano Uplift regions interpreted as alluvial fans. Timing and location of this uplift suggest that it may have originated as a pre-rift bulge. Lithologic, stratigraphic, and sedimentologic similarities between the Dewey Lake and Moenkopi Formation suggest that the alluvial plain north of this uplift may have extended throughout the southwestern United States."

Seed, H.B., Idriss, I.M., and Kiefer, R.W. 1976. Characteristics of Rock Motions during Earthquakes. Report No. 68-5. Earthquake Engineering Research Center.

INTRODUCTION, p 1;

" The behavior of soil deposits during earthquakes can often be assessed with the aid of appropriate analyses of their response to the motions developed in underlying rock formations. Methods of analysis based on this approach have been proposed for evaluating the characteristics of ground surface motions (13,21,24,26,28,29,30,37,38),[4] the liquification potential of sand deposits (34) and the stability of slopes of earth banks (18,19,32,35) and embankments (1,6,7,11,33,36). The relatively good agreement between analytical results and observed field performance in a number of cases (22,34,36,37) has indicated that such analyses are often capable of providing a satisfactory guide to appropriate design conditions.

In order to make an analysis of the response of any soil deposit, it is first necessary to determine:

(1) The surface topography, the underlying rock configuration and any irregularities in the boundaries between soil layers,

(2) The types of soil comprising the deposit and the characteristics determining their response under dynamic loading conditions, and . . ."

Schnabel, P.B., and Seed, H.B. 1973. Accelerations in Rock for Earthquakes in the Western United States. Seismological Society of America Bulletin, Vol. 63, pp. 501-516.

ABSTRACT, p 501;

" Maximum accelerations recorded on rock sites during earthquakes in the western part of the United States are summarized, and attenuation curves showing the decrease in maximum acceleration with increasing distance from the zone of energy release are developed for different magnitude earthquakes. Changes in acceleration level and predominant periods of rock motions with distance are also analyzed. The significance of maximum acceleration level as an indicator of intensity of ground shaking is discussed."

Sewards, T., Glenn, R., and Keil, K. 1991. Mineralogy of the Rustler Formation in the WIPP-19 Core. SAND87-7036. Sandia National Laboratories, Albuquerque, NM.

IX. SUMMARY AND CONCLUSIONS, p IX-1;

" We have reported here the species, quantities, distribution, and compositions of the minerals of the Rustler Formation as seen in the WIPP-19 borehole, one of the boreholes closest to the WIPP facility that was completely cored through the Rustler section. The major components, as determined by x-ray diffraction are halite, anhydrite, gypsum, dolomite, magnesite, quartz, and clay. Minor components include calcite, pyrite, feldspar, and phyllosilicates of metamorphic origin (muscovite, biotite, and chlorite). Clay minerals, identified by XRD, include illite, serpentine, chlorite, and mixed-layer chlorite/smectite (including corrensite).

Quartz and clay, with some halite and anhydrite, dominate the lower member; the Culebra and Magenta units are primarily dolomite with some quartz and clay, while the Forty-niner Member consists of quartz, clay, and sulfates (anhydrite and gypsum).

Halite occurs in four textural styles: bedded, recrystallized halite; displacive halite; as a cement in mud/siltstones; and as a fracture filling, and is largely restricted to the lower member. Anhydrite occurs primarily as a massive, crudely banded nodular structure, although there is often evidence of partial alteration to gypsum. Gypsum also is usually massive, in a crudely banded form. The massive areas consist of fine-grained irregular crystals ('patchy' gypsum); these areas are separated by veins of 'fibrous' gypsum, usually parallel to bedding. Fibrous gypsum vein filling in other lithologies is very common. Dolomite is unfossiliferous, laminated, and very fine-grained; it contains numerous vugs and fractures: these are usually lined with clay, gypsum, and powdery dolomite. Magnesite, a relatively minor component, occurs as microcrystalline nodules and as euhedral elongated platy crystals included in halite. Quartz and clay always occur together with minor amounts of feldspar and detrital phyllosilicate grains. Calcite is restricted to a thin bed above the Culebra Dolomite in the samples studied.

Halite, anhydrite, and gypsum have nearly ideal compositions, whereas dolomite has a nonideal ratio of calcium to magnesium, plus a significant amount of iron; similarly, magnesite contains some iron.

In general, this study should be considered a detailed analysis of the Rustler section mineralogy. It is unlikely that any other minerals are present in any great quantity elsewhere in the Rustler Formation. Abundances of individual minerals, however, may vary considerably in other areas of the formation."

Shah, H.C., Mortgat, C.P., Kiremidjian, A., and Zsutty, T.C. 1975. A Study of Seismic Risk for Nicaragua. Report 11. Department of Civil Engineering, Stanford University, Palo Alto, CA.

ABSTRACT, (from Report Documentation page);

" The geological setting for the country in general and the Managua area in particular is described. The data base for past seismic events was extensively studied. Limitations of the data and approximations are discussed. Seismic recurrence for ten line sources and three area sources was developed. Based on the assumption of the Poisson occurrence of seismic events, probabilities of exceeding different magnitude levels as functions of time for different regions were derived. Using Esteva's attenuation relationship, isoacceleration maps for the country were constructed. Eleven cities in Nicaragua were considered in this mapping process. Cumulative distribution functions of peak ground accelerations for 20 and 50 years were established. This is shown to be one way of presenting seismic risk for Nicaragua. Based on isoacceleration maps, the Acceleration Zone Graphs (AZG) were developed for the eleven cities. A method for determining load levels for consistent risk for the whole country is discussed and suggested. It is proposed that charts such as AZG be used for seismic zoning of Nicaragua. Ground acceleration values from AZG were employed to set the level of the design spectra for structural damage prevention and condemnation control. A design methodology is proposed based on ultimate strength and loads resulting from the above inelastic design spectra."

Shumard, G.G. 1858. "Observations on the Geological Formation of the Country between the Rio Pecos and the Rio Grande, in New Mexico, Near the Line of the 32nd Parallel, Being an Abstract of Portion of the Geological Report of the Expedition Under Capt. John Pope, Corps of Topographical Engineers, U.S. Army, in the Year 1855." In St. Louis Academy of Sciences Transactions, Vol. 1.

p 273;

" The Expedition remained, for several months, encamped on the Rio Pecos, near the mouth of Delaware Creek, and a favorable opportunity was thus afforded for examining minutely the geological structure of that vicinity. The Llano Estacado was to be seen from our camp, stretching for an indefinite distance eastward, in the form of an elevated and gently undulating plateau, thinly covered with short grass, and presenting, generally, but little variety of surface. It is abruptly terminated, on the west, by the Pecos River, which flows, in a tortuous course, with an average width of about eighty feet, amid low hills and bluffs of conglomerate and limestone. Beyond the Pecos, the country assumes a more broken and hilly appearance, and, at the distance of sixty miles, rise the lofty summits of the Guadalupe Mountains, of which the highest points had been observed long before we arrived at the mouth of Delaware Creek.

The following is a section taken near the mouth of Delaware Creek:

1. Quaternary Conglomerate, composed of limestone from the Guadalupe Mountains	70 feet.
2. Upper Cretaceous limestone	100* "
3. Lower Cretaceous marls and sandstone (as far as bored)	800 "
Total thickness. . . .	1000 feet.

The rocks of this vicinity, save the limestone . . . "

Siegel, M.D., Lambert, S.J., and Robinson, K.L. eds., 1991. Hydrogeochemical Studies of the Rustler Formation and Related Rocks in the Waste Isolation Pilot Plant Area, Southeastern New Mexico. SAND88-0196. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT, p i;

" Chemical, mineralogical, isotopic, and hydrological studies of the Culebra dolomite member of the Rustler Formation and related rocks are used to delineate hydrochemical facies and form the basis for a conceptual model for post-Pleistocene groundwater flow and chemical evolution. Modern flow within the Culebra in the Waste Isolation Pilot Plant (WIPP) area appears to be largely north-to-south; however, these flow directions under confined conditions are not consistent with the salinity distribution in the region surrounding the WIPP Site. Isotopic, mineralogical, and hydrological data suggest that vertical recharge to the Culebra in the WIPP area and to the immediate east and south has not occurred for several thousand years. Eastward increasing $^{234}U/^{238}U$ activity ratios suggest recharge from a near-surface Pleistocene infiltration zone flowing from the west-northwest and imply a change in flow direction in the last 30,000 to 12,000 years.

Culebra groundwaters are in chemical equilibrium with gypsum and are undersaturated with halite and anhydrite. A partial-equilibrium model for the chemical evolution of the groundwater suggests that Na, Cl, Mg, K, and SO_4 are added to the Culebra by dissolution of evaporite salts in adjacent strata. Equilibrium is maintained with gypsum and calcite, but dolomite supersaturation increases as the salinity of the water increases. Stable-isotope compositions of carbonates are consistent with this model and indicate that no recrystallization of dolomite in equilibrium with the groundwater has occurred. Major and minor element correlations are consistent with several plausible mechanisms of water/rock interaction, including sorption of lithium and boron by clays and dissolution of Mg-rich clays."

Siemers, W.T., Hawley, J.W., Rautman, C., and Austin, G. 1978. Evaluation of the Mineral Potential (Excluding Hydrocarbons, Potash, and Water) of the Waste Isolation Pilot Plant Site, Eddy County, New Mexico. Open-File Report 87. New Mexico Bureau of Mines and Mineral Resources, Socorro, NM.

ABSTRACT;

" The mineral potential of a proposed WIPP site, located 40 km east of Carlsbad, Eddy County, New Mexico, has been evaluated on the basis of information obtained from onsite field studies, the examination of records provided by Sandia Laboratories, and pertinent literature. The site is located near the northern edge of the Delaware Basin; the upper part of the stratigraphic section is comprised of marine and continental redbeds underlain by marine Ochoan evaporites.

Available data indicate that the only WIPP site-related commodities that may have any economic potential are (1) caliche, (2) salt, (3) gypsum, (4) lithium-bearing brines, (5) sulfur, and (6) uranium. A more detailed study however, indicates that for one or more of several reasons including (1) commodity abundance, (2) commodity accessibility, (3) low demand for the commodity, and (4) adequate supplies of the commodity elsewhere, these six commodities are uneconomic at present and for the foreseeable future."

Snider, H.I. 1966. Stratigraphy and Associated Tectonics of the Upper Permian Castile-Salado-Rustler Evaporite Complex, Delaware Basin, West Texas and Southeast New Mexico [Ph.D. dissertation]. University of New Mexico, Albuquerque.

ABSTRACT, P 1;

" The Delaware basin of west Texas and southeast New Mexico is roughly pear-shaped with a northwest-southeast length of about 140 miles and a width of 100 miles in the northwest tapering to 60 miles in the southeast--an area of about 10,000 square miles. In late Permian time the basin was essentially encircled by a carbonate depositional environment or reef zone.

The Upper Permian evaporite complex within the Delaware basin consists of Castile, Salado, and Rustler Formations. The Castile Formation contains laminated calcareous anhydrite, halite, and limestone. The Castile Formation was subdivided into seven units: Anhydrite I, Halite I, Anhydrite II, Halite II, Anhydrite III, Anhydrite IV, and Anhydrite V. The lowest four units can be traced over two-thirds of the basin. The upper three units can only be differentiated in the eastern part of the basin. The Salado Formation consists of halite and anhydrite with minor clastics, magnesite, and potassium minerals in the north and east parts of the basin. In the south and west parts of the basin, the Salado consists mainly of anhydrite dolomite, and clastics. The Rustler Formation contains anhydrite, dolomite, clastics, and halite.

. . .

The distribution of halite may reflect tectonism during Castile time. Little to no halite is found on the intrabasin shelf, while thick halite beds are found in the Ochoa trough. Halite units of the Castile Formation may have overlapped to the south due to differential subsidence or 'tilting' southward of the Ochoa trough. A reversal of this tilting occurred in Salado time.

Evidence of local movement in Castile units is abundant. Four models are analyzed to account for salt structures found: 1. salt movement contemporaneous with deposition--'down building'; 2. post-depositional halite piercement; 3. post-depositional lateral movement of upper halite over lower halite stock, dome, or anticline; and 4. gravity flow of upper halite over a lower halite structure--'anticline on anticline.' Tectonic 'triggering' is suggested as the major cause of Castile halite movement. Regional movement resulting in structures similar to 'salt pillows' or 'salt stocks' is believed to have occurred in the northeast part of the Delaware basin in Lea County, New Mexico."

Snyder, R.P., 1985. Dissolution of Halite and Gypsum, and Hydration of Anydrite to Gypsum, Rustler Formation, in the Vicinity of the Waste Isolation Pilot Plant, Southeastern New Mexico. Open-File Report 85-229. U.S. Geological Survey, Denver, CO.

ABSTRACT, p 1;

" Data from selected drill holes spaced at intervals of 1.5 to 15 km (5,000 to 50,000 ft) in southeastern New Mexico demonstrate a progressive removal of halite by dissolution, hydration of anhydrite to gypsum, and removal of gypsum by dissolution in the Permian Rustler Formation. Thickness of the Rustler decreases as halite is removed, but increases after complete removal due to the hydration of anhydrite to gypsum."

Snyder, R.P., and Gard, Jr., L.M. 1982. Evaluation of Breccia Pipes in Southeastern New Mexico and Their Relation to the Waste Isolation Pilot Plant (WIPP) Site, with Section on Drill-Stem Tests. Open-File Report 82-968. U.S. Geological Survey, Denver, CO.

INTRODUCTION, p. 1;

" The Waste Isolation Pilot Plant (WIPP) site is located about 40 km (25 mi) east of Carlsbad, N. Mex. (fig. 1). The site geography has been described in detail by Powers and others (1978) and U.S. Department of Energy (1980, 1981). Site selection was based principally on the existence of a thick section of Permian evaporites, mainly halite. The purpose of establishing this site is to demonstrate whether or not an evaporite environment is acceptable for the disposal of trans-uranic waste generated by the Nation's defense programs.

The primary concern regarding safe disposal of nuclear waste is to isolate the waste from the biosphere until it is no longer a danger to mankind. One of the most probable methods of accidental release of radiation from nuclear waste isolated in a geologic medium is leaching and transport of the waste by moving ground water. It is therefore of primary importance to identify any potential channelways that might allow water to enter a repository site located on bedded salt of the Salado Formation of southeastern New Mexico. The presence of the thick Permian (225 m.y.) rocks attests to the fact that major dissolution of the halite by unsaturated ground water has not occurred at the WIPP site.

Focus of Current Study

This report describes several dissolution features in the Delaware Basin and elsewhere that have been referred to as breccia pipes. Breccia pipes (also called breccia chimneys) as they occur in evaporites are vertical cylindrical pipes or chimneys that may or may not involve more than one geologic formation. The chimneys are filled with downward-displaced brecciated rock. In this context, the rock is brecciated by having collapsed into a void at depth that was probably created by ground-water solution and removal of deep-lying evaporite or carbonate rocks in an underlying aquifer system (Anderson and Kirkland, 1980; Bachman, 1980). Such features have been described in evaporite deposits in many areas of the world.

The current study was done for the U.S. Department of Energy (DOE) in response to a suggestion that because breccia pipes are thought to be the result of deep dissolution, they may represent channelways for future ingress of ground water, and that they should be considered in risk assessment programs for the evaluation of proposed waste repositories in bedded evaporite rocks. To this end, features referred to as breccia pipes in southeastern New Mexico have been assessed in relation to the integrity of the WIPP site. Reports by Anderson (1978), Bachman (1980), and Vine (1960) described dissolution and karst features in the Pecos region of southeastern New Mexico and discussed the origin and history of breccia pipes. The present report is intended to supplement these studies and provide detail that was not available to them at the time their reports were written.

Using the data from exploratory work, answers may be found to the following questions concerning breccia pipes:

1. Do breccia pipes penetrate through the evaporite section?
2. What is the physical description of a pipe?
3. How are they formed?
4. How deep do they go?
5. When are they formed, and are they forming at present?
6. Are they permeable?
7. Where are they formed, can they form at the WIPP site?
8. Do they represent a threat to the WIPP site?"

Stensrud, W.A., Dale, T.F., Domski, P.S., Palmer, J.B., Roberts, R.M., Fort, M.D., and Saulnier, Jr., G.J. 1992. Waste Isolation Pilot Plant Salado Hydrology Program Data Report #2. SAND92-7072. Sandia National Laboratories, Albuquerque, NM.

ABSTRACT;

" WIPP Salado Hydrology Program Data Report #2 presents hydrologic data collected during permeability testing of the Salado Formation performed from August 1989 through July 1992. The report presents the results of the drilling and testing of six boreholes drilled from the WIPP underground facility 655 m below ground surface in the Salado Formation. Permeability tests were conducted using multipacker test tools with inflatable packers to isolate borehole intervals to allow formation pore-pressure buildup and subsequent pressure-pulse and constant-pressure-withdrawal tests. The tests performed in boreholes L4P51, L4P52, SCP01, S1P71, S1P72, and S1P73 involved Marker Beds 138 and 139, anhydrites 'a,' 'b,' and 'c,' clays B, D, E, G, H, J, and K, and several halitic strata. Test data include pressure and temperature from the brine-filled, packer-isolated test intervals, fluid and gas production during constant-pressure-withdrawal tests, and borehole-closure and axial test-tool-movement measurements. The boreholes were drilled and/or cored to nominal 10.2-cm diameters using compressed air to remove drill cuttings. Compliance tests were conducted in lengths of steel and stainless-steel casing to evaluate the mechanical performance of the multipacker test tools. Compliance tests included leak tests and pulse-injection and pulse-withdrawal sequences. Following permeability testing, fluid pressures were monitored in packer-isolated sections of test boreholes C2H01, C2H02, SCP01, S1P71, S1P72, DPD01, DPD02, and DPD03."

Thompson, G.A., and Zoback, M.L. 1979. Regional Geophysics of the Colorado Plateau. Technophysics, Vol. 61, Nos. 1-3, pp. 149-181.

ABSTRACT, p. 149, Para. 2;

" The Colorado Plateau (CP) is a relatively coherent block surrounded on three sides by the extensional black faulted regime of the Basin and Range Province (BRP) and the Rio Grande Rift (RGR). The CP appears to be part of an inter-related system including the Sierra Nevada, BRP, and the RGR which has undergone major uplift and extension during the last 20 m.y. The final elevation in any area probably depends upon which processes dominate there.

In most geophysical properties the CP is intermediate between the BRP/RGR and the stable platform of the southern Great Plains. However, many BRP/RGR geophysical characteristics appear to extend well inward of the classical Plateau physiographic boundary. Geologically these 50-100 km wide zones of transition are marked by normal faulting and late Tertiary and Quaternary volcanism. The interior of the Plateau is characterized by a 40 km-thick crust, a P_n velocity of about 7.85 km/sec, and an average heat flow of 1.5-1.6 HFU. Available data on the modern stress field in the Plateau interior indicate high horizontal stresses and a stress field oriented differently from that in the surrounding BRP/RGR, inconsistent with the theory that the plateau is merely an inherited, more coherent subplate subjected to the same stresses as it's surroundings."

Tóth, J., 1963. "A Theoretical Analysis of Groundwater Flow in Small Drainage Basins," Journal of Geophysical Research, Vol. 68, no. 16, pp. 4795-4812.

ABSTRACT, p 4795;

" Theoretically, three types of flow systems may occur in a small basin: local, intermediate, and regional. The local systems are separated by subvertical boundaries, and the systems of different order are separated by subhorizontal boundaries. The higher the topographic relief, the greater is the importance of the local systems. The flow lines of large unconfined flow system do not cross major topographic features. Stagnant bodies of groundwater occur at points where flow systems meet or branch. Recharge and discharge areas alternate; thus only part of the basin will contribute to the baseflow of its main stream. Motion of groundwater is sluggish or nil under extended flat areas, with little chance of the water being freshened. Water level fluctuations decrease with depth, and only a small percentage of the total volume of the groundwater in the basin participates in the hydrologic cycle."

Urry, W. D. 1936. Post-Keweenawan Timescale. Exhibit 2, pp. 35–40. National Research Council, Report Committee on Measurement of Geologic Time 1935-36.

REPORT OF THE COMMITTEE ON THE MEASUREMENT
OF GEOLOGIC TIME
May 2, 1936
(Appendix K of Annual Report of
the Division with Exhibits 1-13)
(Reissued July, 1952-1953)

p. 35;

" The progress of the principle application of the helium method during the past year to the setting up of a Post-Keweenawan time scale by selecting material from authenticated horizons is summed up in the accompanying chart, which constitute the basis of a paper presented by Wm. D. Urry at the December Meeting of the Geological Society of America. Due acknowledgement to the contributors of the material will be made in the manuscript now in preparation."

p. 40;

" Low Results

Five results are low. For three of these, plausible explanations are forthcoming and possibly for the fourth. The fifth low result is not yet explained.

		Millions of years
1).	Sill or dike basaltic intrusion into Permian Salts. Carlsbad, N.M. Churn drill 1/2 to 1 mm pieces.	30 $\pm$ 1.5 "

USBM (U.S. Bureau of Mines). 1977. Valuation of Potash Occurrences within the [WIPP] Site in Southeastern New Mexico. Prepared for the U.S. Energy Research and Development Administration.

ABSTRACT, p. 1;

" Current production costs and market conditions in the potash industry of the Carlsbad area were studied to determine the potential values of the potash mineral resource that would be lost or foregone if the Waste Isolation Pilot Plant (WIPP) facility is constructed on the proposed site in that area. The purpose of the WIPP project is to investigate the possibility of developing a nuclear waste disposal plant in the salt formations at the site. Analyses were made of all potash deposits determined to be in the site. Mining and processing under the most favorable recovery systems were considered. Value determinations were based upon estimated operating and capital costs of current mine-mill operations in the Carlsbad area. This study was made for the Energy Research and Development Administration (ERDA) by members of the Federal Bureau of Mines Minerals Availability System staff."

Vail, P.R., Mitchum, Jr., R.M., Thompson, III, S., 1977. "Seismic Stratigraphy and Global Changes of Sea Level, Part 4: Global Cycles of Relative Changes of Sea Level," In Seismic Stratigraphy-Applications to Hydrocarbon Exploration, C.E. Payton ed., AAPG Memoir 26, pp. 83-97, American Association of Petroleum Geologists.

Abstract; p. 83, para. 2, col.1;

" Cycles of relative change of sea level on a global scale are evident throughout Phanerozoic time. The evidence is based on the facts that many regional cycles determined on different continental margins are simultaneous, and that the relative magnitudes of the changes generally are similar. Because global cycles are records of geotectonic, glacial, and other large-scale processes, they reflect major events of Phanerozoic history.

A global cycle of relative change of sea level is an interval of geologic time during which a relative rise and fall of mean sea level takes place on a global scale. A global cycle may be determined from a modal average of correlative regional cycles derived from seismic stratigraphic studies.

On a global cycle curve for Phanerozoic time, three major orders of cycles are superimposed on the sea-level curve. Cycles of first, second, and third order have durations of 200 to 300 million, 10 to 80 million, and 1 to 10 million years, respe4ctively. Two cycles of the first order, over 14 of the second order, and approximately 80 of the third order are present in the Phanerozoic, not counting late Paleozoic cyclothems. Third-order cycles for the pre-Jurassic and Cretaceous are not shown. Sea-level changes from Cambrian through Early Triassic are not as well documented globally as are those from Late Triassic through Holocene.

Relative changes of sea level from Late Triassic to the present are reasonably well documented with respect to the ages, durations, and relative amplitudes of the second-and third-order cycles, but the amplitudes of the eustatic changes of sea level are only approximations. Our best estimate is that sea level reached a high point near the end of the Campanian (Late Cretaceous) about 350 m above present sea level, and had low points during the Early Jurassic, middle Oligocene, and late Miocene about 150, 250, and 200 m, respectively, below present sea level.

Interregional unconformities are related to cycles of global highstands and lowstands of sea level, as are facies and general patterns of distribution of many depositional sequences. Geotectonic and glacial phenomena are the most likely causes of the sea-level cycles.

Major applications of the global cycle cart include (1) improved stratigraphic and structural analyses within a basin, (2) estimation of the geologic age of strata prior to drilling, and (3) development of a global system of geochronology."

Vine, J.D., 1963. Surface Geology of the Nash Draw Quadrangle, Eddy County, New Mexico. U.S. Geological Survey Bulletin 1141-B.
ABSTRACT, p B1;

" Outycropping rocks and surficial deposits of the Nash Draw quadrangle were mapped to provide geologic information for the U.S. Atomic Energy Commission's Plowshare program. The quadrangle is near the north margin of the Delaware basin and about 15 miles east of Carlsbad, N. Mex. The region is sparsely inhabited and has an arid climate.

As much as 4,000 feet of salt and anhydrite of Permian age is present below the surface, but does not crop out in normal thickness in this area or elsewhere because of their high solubility. These rocks have been divided into the Castile formation below and the Salado formation above. Rocks exposed at the surface overlie these soluble rocks and include the Rustler formation of Late Permian age, the Pierce Canyon redbeds of Permian or Triassic age, the Santa Rosa sandstone of Late Triassic age, and the Gatuna formation, caliche, and a variety of unconsolidated deposits of late Cenozoic age.

The Rustler formation of Late Permian age is subdivided into four easily distinguishable members, excluding about 120 feet of the lower part, which is not exposed at the surface in this area. The oldest member exposed is the Culebra dolomite member, about 30 feet thick, identified only in erratically distributed outcrops in collapse areas. The Culebra consists of microcrystalline gray dolomite or dolomitic limestone characterized by numerous spherical cavities 1 to 10 mm in diameter. It is conformably overlain by the Tamarisk member, named herein for exposures directly east of Tamarisk Flat. It consists of about 115 feet of massive gypsum at the surface, changing to anhydrite in the subsurface, and a bed, 5 feet thick, of siltstone near the base. Surficial deformation caused by hydration and solution are characteristic of all the outcrops. The Tamarisk member is conformably overlain by the Magenta member, about 20 feet thick and consisting of alternating wavy laminae of pale-red dolomite and pale yellowish-green anhydrite or gypsum. The top member of the Rustler formation conformably overlies the Magenta and is here named the Forty-niner member after Forty-niner Ridge, where it crops out. In surface exposures it consists of about 40 to 65 feet of broken and slumped massive gypsum and a bed of siltstone in the lower part. The siltstone beds in the Tamarisk and Forty-niner members probably represent the insoluble residue of salt beds reported from the subsurface to the east."

Overlying the Rustler formation with apparent conformity are the Pierce Canyon redbeds of Permian or Triassic age. These rocks consist of about 200 to 250 feet of laminated or minutely cross-laminated moderate reddish-brown siltstone. The contact between the Pierce Canyon redbeds and the overlying Santa Rosa sandstone is a disconformity, at least locally.

The Santa Rosa sandstone of Late Triassic age consists of pale-red sandstone and conglomerate lenses crossbedded in sets 3 to 15 feet thick separated locally by moderate reddish-brown siltstone and claystone. Only the lower 50 to 70 feet of Santa Rosa was recognized in the area.

The Gatuna formation of Pleistocene (?) age unconformably overlies all older rocks. In much of the area it consists of 3 to 5 feet of moderate reddish-orange sandstone, siltstone, and conglomerate. Locally, in karst depressions, the Gatuna attains a thickness of at least 100 feet. In some areas the lithology closely resembles the Pierce Canyon redbeds or the Santa Rosa sandstone.

Caliche forms a resistant layer at the ground surface, 5 to 10 feet thick, that protects older rocks from erosion in many areas. The caliche consists of calcareous material with a variable amount of imbedded sand grains, pebbles, and rock fragments. Caliche mounds and broken flexure ridges, 10 to 15 feet high, have formed narrow zones 50 to several hundred feet long.

Quaternary alluvium has been deposited along the sides of depressions. It is overlain by playa lake deposits, which are in turn overlain by conspicuous sand dunes as much as 100 feet high.

The regional structure is relatively simple and consists of a dip of a few feet per mile to the east and southeast.

Normally flat-lying strata are tilted, warped, and locally distorted at the surface by hydration and solution of the evaporite rocks in the subsurface. Nash Draw, a depression 4 to 6 miles wide and about 18 miles long, has resulted from the solution of salt in the Rustler and Salado formations and collapse of the overlying relatively insoluble rocks. Topography and surface structure conform in some areas with the configuration of the underlying solution surface at the top of the massive salt in the Salado formation; however, locally there is an inverse correspondence. Many circular karst features 1/10 to 1/2 mile in diameter are in the area. Some of these features are structural domes, but they contain a core of tilted or brecciated rock. These karst features result from the formation and collapse of sinkholes, differential solution at the top of the massive salt, and hydration of the anhydrite beds."

Von Hake, C., and Cloud, W.K. 1968. United States Earthquakes 1966. Coast and Geodetic Survey. U.S. Department of Commerce, Washington, D.C.

INTRODUCTION, p. 1;

" This publication, issued by the National Earthquake Information Center of the Coast and Geodetic Survey, is a summary of earthquake activity in the United States and regions under its jurisdiction for the calendar year 1966. The sources of non-instrumental information used in the compilation include the U. S. Weather Bureau whose observers prepare periodic reports on local seismic activity; telegraphic information collected by the Science Service, Washington, D.C.; bulletins of the Seismological Society of America; special reports of various institutions; newspaper clippings; and reports from interested individuals. Instrumental data used in locating earthquakes are obtained from the seismological observatories listed on page 85, and from other cooperating seismological stations located throughout the United States.

The Coast and Geodetic Survey endeavors to coordinate efforts in collecting all types of earthquake information with the special objective of correlating instrumental earthquake locations with noninstrumental reports received from the epicentral areas. This is achieved through intensive regional investigations in various states by local organizations, and by the Coast and Geodetic Survey. This information is used to map the seismic areas of the country, thereby promoting public safety through a better understanding of earthquake phenomena. Since the success of the general information service depends largely on the cooperation of local officials and citizens, all are urged to complete and return earthquake questionnaire forms."

Westinghouse Electric Corporation 1990. WIPP Final Safety Analysis Report. WP02-9. Rev. 0. Westinghouse Electric Corporation, Waste Isolation Division, Carlsbad, NM.

PREFACE

"**Background**

This Final Safety Analysis Report (FSAR) has been prepared for the Waste Isolation Pilot Plant (WIPP) in order to satisfy the commitments made in the Working Agreement for Consultation and Cooperation(Article III, Section C and Article IV, Section K, known as the Working Agreement) between the State of New Mexico and the U.S. department of energy (DOE) and the requirements of Order DOE 5481.1B,Safety Analysis and Review System.

The objectives of the Safety Analysis Preparation and Review process, as specified in Order DOE 5481.1B, ensure that:

1. Potential hazards are systematically identified;

2. Potential consequences are analyzed;

3. Reasonable measures to eliminate, control or mitigate the hazards have been taken, including, where applicable, compliance with commitments made in environmental assessments and impact statements;

4. There is documented management authorization of the DOE operation based upon an objective assessment of the safety analysis.

Specific hazards that are analyzed include credible natural hazards such as flood, weather (tornado, wind, etc.) and earthquake; and credible man made hazards such as fire, explosion, radiation, and mining hazards. Mitigating measures include facility design and construction, operational controls, and administrative limits.

This FSAR represents a statement and commitment by the DOE that the WIPP facility can be operated safely and at minimum risk, if operated in accordance with this FSAR. Consequently, this FSAR has been prepared to document that a systematic analysis of the potential hazards associated with operating the WIPP facility has been performed (objective 1 of Order DOE 5481.1B); that potential consequences have been analyzed (objective 2 of Order DOE 5481.1B); and that reasonable measures have been taken to eliminate, control, or mitigate the hazards (objective 3 of Order DOE 5481.1B). In addition, this FSAR documents the implementation of commitments made in the environmental impact statement regarding the mitigation of adverse impacts to the environment (objective 3 of Order DOE 5481.1B)."

Zoback, M.L., and Zoback, M.D. 1980. State of Stress in the Conterminous United States. Journal of Geophysical Research, Vol. 85, No. B11, pp. 6113-6156.

Southern Great Plains, p. 6134, col. 2, para. 3;

" The southern Great Plains area is characterized by a very uniform state of stress in which the least principal horizontal stress direction to NNE-SSW. The data come from two primary sources: (1) alinement of post-5 m.y. volcanic feeders in the Raton-Clayton volcanic field of northern New Mexico and (2) fracture orientations obtained from hydraulically fractured wells in the Permian basin of western Texas [*Zemanek et al.*, 1970]. An earthquake focal mechanism and in situ stress measurements in eastern Colorado show consistent orientations. Despite the similar least principal horizontal stress orientations in the southern Great Plains and in the plateau interior, the probable extensional regime (as inferred from earthquake focal mechanisms and basaltic volcanism) distinguishes the southern Great Plains from the Colorado Plateau interior and Midcontinent provinces which are dominated by compressional stress regimes. The least principal horizontal stress directions to the southern Great Plains province are generally oblique to those in the Midcontinent stress province; however, in west-central Texas the data suggest a counter-clockwise rotation of the stress field from west to east to directions more consonant with midcontinent stress orientations (Plates 1 and 2). The easternmost site of this group of data (TX-15) is a normal fault focal mechanism, suggesting that the boundary with the compression-dominated Midcontinent stress province must lie further to the east.

Two important characteristics of the stress field in the southern Great Plains province are (1) *its uniformity* ($\sim \pm 15°$, *which is within the range of estimated accuracy of the* different stress indicators) over a region with a north-south extent of at least 1100 km and (2) an abrupt transition in stress orientation in relation to the Rio Grande rift that occurs locally over a lateral distance of <50 km. this $\sim 90°$ change in least principal horizontal stress orientation along the Rio Grande rift-Great Plains boundary corresponds to a decrease in heat flow and a crustal and lithospheric thickening under the Great Plains in relation to the Rio Grande rift [*Thompson and Zoback,* 1979]. IN addition, seismic reflection profiling across the Rio Grande rift's eastern boundary [*Brown et al.*, 1979] has revealed a high-angle, narrow, linear zone defined by a lack of coherent reflections which extends from near the surface to the base of the crust. Physically, this sharp boundary may mark a zone of lateral 'decoupling' within the crust facilitating the abrupt change in stress orientation."

Zoback, M.D., and Zoback, M.L. 1991. "Tectonic Stress Field of North America and Relative Plate Motions." In Neotectonics of North America, D.B. Slemmons, E.R. Engdahl, M.D. Zoback, and D.D. Blackwell, eds., pp. 339-366. Geological Society of America, Boulder, CO.

STRESS PROVINCES OF NORTH AMERICA, p. 349, col. 1, para. 2;

" In this section we discuss the individual stress provinces shown in Figure 4 and summarized in Table 2.

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