RENEWAL APPLICATION
ADDENDUM L1

SITE CHARACTERIZATION

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Introduction

This addendum describes the Waste Isolation Pilot Plant (WIPP) site in terms of its geology, hydrology, climatology, air quality, ecology, and cultural and natural resources. The purpose of this addendum is to provide information on the disposal system's natural characteristics that are relevant to the assessment of the WIPP site as a potential repository for transuranic (TRU) and TRU mixed waste and to establish the favorable characteristics of the site and background environmental quality. The U.S. Department of Energy (DOE) is developing the WIPP as a deep geologic repository for disposal of TRU waste from government defense installations across the country. In order for the DOE to formulate a reasonable expectation of site conditions far into the future, the site has been characterized in detail to provide data for a variety of geologic and hydrologic parameters. The DOE uses these parameters in computational models to predict the likelihood and possible consequences of various scenarios expected to apply to the WIPP site over a 10,000-year period

The DOE located the WIPP site 26 miles (mi) (41.8 kilometers [km]) east of Carlsbad, New Mexico, in Eddy County (Figure L1-1). The region surrounding the WIPP site has been under study for many years, and exploration of both potash and hydrocarbon deposits has provided extensive knowledge of the geology of the region. Two exploratory boreholes were drilled by the federal government during 1974 at a location northeast of the present site; that location was abandoned in 1975 as a possible repository site after a well, U.S. Energy Research and Development Administration (ERDA)-6, was drilled, and unacceptable geologic structure and pressurized brine were encountered. The results of these investigations were reported by Powers et al. (1988, pp. 2-6). During late 1975 and early 1976, the ERDA identified the present site, and an initial exploratory borehole (ERDA-9) was drilled. By the time an initial phase of site characterization was completed in August 1978, 47 boreholes had been drilled or were in progress for hydrologic and various geologic purposes. Since 1978, the DOE has drilled additional boreholes to support hydrologic programs, geologic programs, and facility design. Geophysical logs, cores, basic data reports, geochemical sampling and testing, and hydrological testing and analyses are reported by the DOE and its scientific advisor, Sandia National Laboratories (SNL), in numerous documents and are maintained in reference libraries that are available to the public, such as the Sandia WIPP Central File (in Albuquerque, New Mexico). The DOE recently submitted the second Compliance Recertification Application (CRA-2009) to the U.S. Environmental Protection Agency (EPA). CRA-2009 provides a comprehensive update of recent site characterization and monitoring activities for the WIPP. Where necessary, specific references from these documents are cited to reinforce the statements being made. Additional sources of information on the various topics in this section are listed in a bibliography at the end of the chapter.

Biological studies of the site began in 1975 to gather information for the Environmental Impact Statement. Meteorological studies began in 1976, and economic studies were initiated during 1977. Baseline environmental data were initially reported in 1987 and are now updated annually by the DOE.

The DOE selected the WIPP disposal horizon to be located within a salt deposit known as the Salado Formation (hereafter referred to as the Salado) at a depth of 2,150 feet (ft) (650 meters [m]) below the ground surface. The present site was selected based on the following site selection criteria: the Salado is regionally extensive; includes continuous beds of salt without complicated structure; is deep enough for waste isolation, reducing the potential for dissolution of the rock salt by surface water or shallow groundwater; and is near enough to the surface to make access reasonable. Particular site-selection criteria narrowed the choices when the present site was located during 1975–76.

L1-1Geology

Geological data have been collected from the WIPP site and surrounding area for use in evaluating the suitability of the site as a radioactive waste repository. These data have been collected principally by the DOE and its predecessor agencies, the United States Geological Survey (USGS), the New Mexico Bureau of Mines and Mineral Resources (NMBMMR), and private organizations engaged in natural resource exploration and extraction. The DOE has analyzed the data provided in the following discussion and believes the WIPP site is suitable for the long-term isolation of radioactive waste. Numerous questions have been raised and subsequently discussed, investigated, and resolved in order for the DOE to reach the conclusion that the site is suitable. The DOE discusses these questions in the following with emphasis on the resolution of the issues.

Geological field studies designed to collect data pertinent to the conceptual models of WIPP site geology and hydrology are ongoing. The Culebra Dolomite Member (Culebra) and Magenta Dolomite Member (Magenta) are the two carbonates in the Rustler Formation (Rustler), the youngest evaporite-bearing formation in the Delaware Basin. Geologic data related to the Culebra and Magenta remains of particular interest, as these members are the most significant transmissive units at the WIPP site.

Holt (1997) provides detailed information on enhancement of the conceptual model for transport of contaminants and radionuclides in the Culebra. Holt (1997) discusses interpretation and conceptual insights obtained from field and laboratory tracer tests and core studies that support the double-porosity conceptual model of the Culebra, in which Culebra porosity is divided into advective and diffusive components.

Geological data and hydrological testing of new wells provide the basis for estimating the transmissivity field for modeling fluid flow and transport in the Culebra (Beauheim 2002). Geological data correlate strongly with Culebra transmissivity (Holt and Yarbrough 2002), and they are available from many more locations, such as industry (oil, gas, potash) drillholes, than are transmissivity data, which generally require hydrological well tests. With this correlation, Culebra properties can be inferred over a wide area, leading to an improved computational model of the spatial distribution of Culebra transmissivity. A comprehensive hydrological testing program for the Culebra and Magenta, including drilling and testing of new wells, has been performed to improve understanding of the Culebra and Magenta and to assess the causes(s) of rising water levels across the WIPP site (DOE 2009, Appendix Hydro).

L1-1a Data Sources

The geology of southeastern New Mexico has been of great interest for more than a century. The Guadalupe Mountains have become world renown for geologists because of the spectacular exposures of Permian-age reef rocks and related facies. Some historical references included in the Bibliography are Shumard (1858), Crandall (1929), Newell et al. (1953), and Dunham (1972). Because of intense interest in both hydrocarbon and potash resources in the region, there exists a large volume of data as potential background for the WIPP site, though some data are proprietary. Finally, there is the geological information developed directly and indirectly by studies sponsored by WIPP; it ranges from raw data to interpretive reports.

Elements of the geology of southeastern New Mexico have been discussed or described in professional journals or technical documents from many different sources. These types of articles are an important source of information, and where there is no contrary evidence, the information in these articles is included through reference where subject material is relevant. Implicit rules of professional conduct of research and reporting are assumed to have been applied, and journal/editorial review has been applied as well. Certain elements of the geology presented in such sources have been deemed critical to the WIPP and have been the subject of specific WIPP-sponsored studies.

Geological data have been developed by the DOE through a variety of WIPP-sponsored studies using drilling, mapping, or other direct observation; geophysical techniques; and laboratory work. Boreholes are, however, a major source of geological data for the WIPP and surrounding area. From boreholes come raw data that provide the basis for point data and interpreted data sets. These data serve as the base for computing other useful elements such as structure maps for selected stratigraphic horizons or isopachs (thickness) of selected stratigraphic intervals.

L1-1b Geologic History

This section summarizes the more important points of the geologic history within about a 200 mi (321.9 km) radius of the WIPP site, with emphasis on more recent or nearby events. Major elements of the geological history from the end of the Precambrian in the vicinity of the WIPP site were compiled in graphic form (Figure L1-3). The geologic time scale that the DOE uses for the WIPP is based on a compilation by Palmer (1983, pp. 503-504) for *The Decade of North American Geology* (DNAG). There are several compiled sources of chronologic data related to different reference sections or methods (see, for example, Harland et al. [1982] and Salvador [1985] in the bibliography). Although most of these sources show generally similar ages for chronostratigraphic boundaries, there is no consensus on either reference boundaries or most representative ages. The DNAG scale is accepted by the DOE as a standard that is useful and sufficient for WIPP purposes, as no known critical parameters require more accurate or precise dates.

The geologic history in this region can conveniently be subdivided into three general phases:

- A Precambrian period, represented by metamorphic and igneous rocks, ranging in age from about 1.5 to 1.1 billion years old

- A period principally of erosion from about 1.1 to 0.6 billion years ago, as there is no rock record from this time

- An interval from 0.6 billion years to the present; represented by a more complex deposition of mainly sedimentary rocks with shorter periods of erosion and dissolution.

This latter phase is the main subject of the DOE's detailed discussion in this text.

Precambrian crystalline rocks have been penetrated in only a few deep boreholes in the vicinity of the WIPP, and therefore relatively little petrological information is available. Foster (1974, Fig. 3) extrapolated the elevation of the Precambrian surface under the area of the WIPP site as being between 14,500 ft (4.42 km) and 15,000 ft (4.57 km) below sea level; the site surface at the WIPP is about 3,400 ft (1,036 m) above sea level. Keesey (1977, Vol. II, Exhibit No. 2) projected a depth to the top of Precambrian rocks of 18,200 ft (5.55 km) based on the geology of a nearby borehole in Section 15, T22S, R31E.

Precambrian rocks of a variety of types crop out in the following locations: the Sacramento Mountains northwest of the WIPP; around the Sierra Diablo and Baylor Mountains near Van Horn, Texas; west of the Guadalupe Mountains at Pump Station Hills; and in the Franklin Mountains near El Paso, Texas. East of the WIPP, a relatively large number of boreholes on the Central Basin Platform have penetrated the top of the Precambrian (Foster, 1974, Fig. 3). As summarized by Foster (1974, p. 10), Precambrian rocks in the area considered similar to those in the vicinity of the site range in age from about 1.35 to 1.14 billion years.

For a period of about 500 million years (1.1 to 0.6 billion years ago), there is no certain rock record in the region around the WIPP site. The most likely rock record for this period may be the Van Horn sandstone, but there is no conclusive evidence that it represents part of this time period. The region is generally interpreted to have been subject to erosion for much of the period, until the Bliss sandstone began to accumulate during the Cambrian.

L1-1c Stratigraphy and Lithology in the Vicinity of the WIPP Site

This section presents the stratigraphy and lithology of the Paleozoic and younger rocks underlying the WIPP site and vicinity (Figure L1-4), emphasizing the units nearer the surface. Details begin with the Permian (Guadalupian) Bell Canyon Formation (hereafter referred to as the Bell Canyon)—the upper unit of the Delaware Mountain Group—because this is the uppermost water-bearing formation below the evaporites. The principal stratigraphic data are the chronologic sequence, age, and extent of rock units, including some of the nearby relevant facies changes. Characteristics such as thickness and depth are summarized here from published sources for deeper rocks. The main lithologies for upper formations and members of some formations are described;

some of the major stratigraphic divisions (e.g., Jurassic) are not described because they do not occur at or near the WIPP site.

L1-1c(1) General Stratigraphy and Lithology below the Bell Canyon Formation

As stated previously, the Precambrian basement near the site is projected to be about 18,200 ft (5.55 km) below the surface (Keesey, 1977, Vol. II, Exhibit No. 2), consistent with information presented by Foster in 1974. Ages of similar rock suites in the region range from about 1.35 to 1.14 billion years.

The basal units overlying Precambrian rocks are clastic rocks commonly attributed either to the Bliss sandstone or the Ellenberger Group (Foster, 1974, p. 10*ff*), considered most likely to be Ordovician in age in this area. The Ordovician system comprises the Ellenberger, Simpson, and Montoya groups in the northern Delaware Basin. Carbonates are predominant in these groups, with sandstones and shales common in the Simpson group. Foster (1974, p. 12) reported 975 ft (297 m) of Ordovician north of the site area and extrapolated a thicker section of about 1,300 ft (396 m) at the present site (p. 17). Keesey (1977, Vol. II, Exhibit No. 2) projected a thickness of 1,200 ft (366 m) within the site boundaries.

Silurian-Devonian rocks in the Delaware Basin are not stratigraphically well defined, and there are various notions for extending nomenclature into the basin. Common drilling practice is not to differentiate, although the Upper Devonian Woodford shale at the top of the sequence is frequently distinguished from the underlying dolomite and limestone (Foster, 1974, p. 18). Foster (1974, p. 21) showed a reference thickness of 1,260 ft and 160 ft (384 m and 49 m) for the carbonates and the Woodford shale, respectively; he estimated thickness contours for the present WIPP site of about 1,150 ft (351 m) and 170 ft (52 m), respectively. Keesey (1977, Vol. II, Exhibit No. 2) projected 1,250 ft (381 m) of carbonate and showed 82 ft (25 m) of the Woodford shale.

The Mississippian system in the northern Delaware Basin is commonly attributed to "Mississippian limestone" and the overlying Barnett shale (Foster, 1974, p. 24), but the nomenclature is not well settled. At the reference well used by Foster (1974, p. 25), the limestone is 540 ft (165 m) thick and the shale is 80 ft (24 m) thick; isopachs at the WIPP are 480 ft (146 m) and less than 200 ft (61 m). Keesey (1977, Vol. II, Exhibit No. 2) indicates 511 ft (156 m) and 164 ft (50 m), respectively, within the site boundaries.

The nomenclature of the Pennsylvanian system applied within the Delaware Basin is both varied and commonly inconsistent with accepted stratigraphic rules. Chronostratigraphic, or time-stratigraphic, names are applied to these lithologic units: the Morrow, the Atoka, and the Strawn, from base to top (Foster, 1974, p. 31). Foster (1974, p. 34) extrapolated thicknesses of about 2,200 ft (671 m) for the Pennsylvanian at the WIPP site. Keesey (1977, Vol. II, Exhibit No. 2) reports 2,088 ft (636 m) for these units. The Pennsylvanian rocks in this area are mixed clastics and carbonates, with carbonates more abundant in the upper half of the sequence.

The Permian system in the northern Delaware Basin is the thickest system in the northern Delaware Basin, and it is divided into four series from the base to top: the Wolfcampian, the

Leonardian, the Guadalupian, and the Ochoan. According to Keesey (1977, Vol. II, Exhibit No. 2), the three lower series total 8,684 ft (2,647 m) near the site. Foster (1974, p. 35*ff*) indicates a total thickness for the lower three series of 7,665 ft (2,336 m) from a reference well north of WIPP. Foster's 1974 isopach maps of these series indicate about 8,500 ft (2,591 m) for the WIPP site area. The Ochoan series at the top of the Permian is considered in more detail later, because the formations host and surround the WIPP repository horizon. Its thickness at DOE-2, about 2 mi (3.2 km) north of the site center, is 3,938 ft (1,200 m) according to Mercer et al. (1987, pp. 23-24).

The Wolfcampian series is also referred to as the Wolfcamp Formation (hereafter referred to as the Wolfcamp) in the Delaware Basin. In the site area, the lower part of the Wolfcamp is dominantly shale, with carbonate and some sandstone according to Foster (1974, p. 38); carbonate increases to the north. Clastics increase to the east toward the margin of the Central Basin Platform. Keesey (1977, Vol. II, Exhibit No. 2) reports the Wolfcamp to be 1,493 ft (455 m) thick at a well near the WIPP site. The Leonardian Series is represented by the Bone Spring Formation (hereafter referred to as the Bone Spring) (erroneously called the Bone Spring Limestone in many publications). According to Foster (1974, p. 39) the lower part of the formation is commonly interbedded carbonate, sandstone, and some shale, while the upper part is dominantly carbonate. Near the site, the Bone Spring is 3,247 ft (990 m) thick according to Keesey (1977, Vol. II, Exhibit No. 2).

The Guadalupian series is represented in the general area of the site by a number of formations exhibiting complex facies relationships (Figure L1-5). The Guadalupian series is known in considerable detail west of the site from outcrops in the Guadalupe Mountains, where numerous outcrops and subsurface studies have been undertaken. (See for example P. B. King [1948], Newell et al. [1953], and Dunham [1972] in the Bibliography.) According to Garber et al. (1989, p. 36), similar facies relationships are expected from the site to the north (Figure L1-5).

Within the Delaware Basin, the Guadalupian series comprises three formations: the Brushy Canyon, the Cherry Canyon, and the Bell Canyon, from base to top. These formations are dominated by submarine channel sandstones with interbedded limestone and some shale. A limestone (Lamar) generally tops the series, immediately underneath the Castile Formation (hereafter referred to as the Castile). Around the margin of the Delaware Basin, reefs developed during the same time the Cherry Canyon and the Bell Canyon were being deposited. These massive reef limestones, the Goat Seep and Capitan limestones are equivalent in time to these basin sandstone formations but were developed much higher topographically around the basin margin. A complex set of limestone to sandstone and evaporite beds was deposited further away from the basin behind the reef limestones. The Capitan reef limestones are well known because the Carlsbad Caverns are partially developed in these rocks.

L1-1c(2) The Bell Canyon Formation

The Bell Canyon is known from outcrops on the west side of the Delaware Basin and from subsurface intercepts for oil and gas drilling. Several informal lithologic units are commonly named during such drilling. Mercer et al. (1987, p. 28) stated that DOE-2 penetrated the Lamar limestone, the Ramsey sand, the Ford shale, the Olds sand, and the Hays sand. This informal nomenclature is used for the Bell Canyon in other WIPP reports.

The Clayton Williams Badger Federal borehole near the WIPP site (Section 15, T22S, R31E) intercepted 961 ft (293 m) of the Bell Canyon, including the Lamar limestone, according to Keesey (1977, Vol. II, Exhibit No. 2). Reservoir sandstones of the Bell Canyon were deposited in channels that are straight to slightly sinuous. Density currents flowed from shelf regions, cutting channels and depositing the sands that are identified in Harms and Williamson (1988, pp. 299-317).

Within the basin, the Bell Canyon (Lamar limestone)/Castile contact is distinctive on geophysical logs because of the contrast in low natural gamma of the basal Castile anhydrite compared to the underlying limestone. Density or acoustic logs are also distinctive because of the massive and uniform lithology of the anhydrite compared to the underlying beds. In cores, the transition is sharp, as described by Mercer et al. (1987, p. 312) for DOE-2.

L1-1c(3) The Castile Formation

The Castile is the lowermost lithostratigraphic unit of the Late Permian Ochoan series (Figure L1-6). It was originally named by Richardson for outcrops in Culberson County, Texas. The Castile crops out along a lengthy area on the western side of the Delaware Basin. The two distinctive lithologic sequences, now known as the Castile and the Salado, were separated into the upper and lower Castile by Cartwright in 1930. Lang, in 1939, clarified the nomenclature by restricting the Castile to the lower unit and naming the upper unit the Salado. By defining an anhydrite resting on the marginal Capitan limestone as part of the Salado, Lang, in 1939, effectively restricted the Castile to the Delaware Basin inside the ancient reef rocks.

Through detailed studies of the Castile, Anderson et al. (1972, pp. 59-86) introduced an informal system of names that are widely used and included in many WIPP reports. They named the units, beginning at the base, as anhydrite I (A1), halite I (H1), anhydrite II (A2), etc. The informal nomenclature varies throughout the basin upwards from A3 because of the complexity of the depositional system. The Castile consists almost entirely of thick beds of two lithologies: 1) interlaminated carbonate and anhydrite, and 2) high-purity halite. The interlaminated carbonate and anhydrite are well known as possible examples of annual layering or varves.

In the eastern part of the Delaware Basin, the Castile is commonly 980 to 2,022 ft thick (299 to 616 m) (Powers et al, 1996, see also Borns and Shaffer, 1985, Figs. 9, 11, and 16 for a range based on fewer boreholes). At DOE-2, the Castile is 989 ft (301 m) thick. The Castile is thinner in the western part of the Delaware Basin, and it lacks halite units. Anderson et al. (1978) and Anderson (1978, Figs. 1, 3, 4, and 5) correlated geophysical logs, interpreting thin zones equivalent to halite units as dissolution residues. Anderson further interpreted the lack of halite in the basin as having been removed by dissolution.

For borehole DOE-2, a primary objective was to ascertain whether a series of depressions in the Salado, 2 mi (3.3 km) north of the site center, was from dissolution in the Castile as proposed by Davies in his doctoral thesis in 1984. Studies have suggested that these depressions were not due to dissolution but to halokinesis in the Castile (for example, see Borns [1987] and Chaturvedi

[1987] in the Bibliography). Robinson and Powers (1987, pp. 69-79) determined that one deformed zone in the western part of the Delaware Basin was partly due to synsedimentary, gravity-driven clastic deposition and suggested that the extent of dissolution may be overestimated. No Castile dissolution is known to be present in the immediate vicinity of the WIPP site. The process of dissolution and the resulting features are further discussed later in this addendum.

In Culberson County, Texas, the Castile hosts major native sulfur deposits. The outcrops of the Castile on the Gypsum Plain south of White's City, New Mexico, have been explored for native sulfur without success, and there is no reported indicator of native sulfur anywhere in the vicinity of the WIPP.

In a portion of the area around the WIPP, the Castile has been significantly deformed, and there are pressurized brines associated with the deformed areas; borehole ERDA-6 encountered both. WIPP-12, 1 mi (1.6 km) north of the WIPP site, revealed lesser Castile structure, but it also encountered a zone of pressurized brine within the Castile. The Castile deformation is described and discussed later in Section 1.1.5 (structural features), and pressurized brines are described in Section 1.2, which details the area's hydrology.

The Castile continues to be an object of research interest unrelated to the WIPP program as an example of evaporites supposedly deposited in "deep water." Anderson (1993, pp. 12-13) discusses alternatives and contradictory evidence. Similar discussions may eventually affect concepts of the Castile deposition and dissolution; however, this issue is largely of academic interest and bears no impact on the suitability of the Los Medaños region for the WIPP site.

L1-1c(4) <u>The Salado Formation</u>

The Salado is dominated by halite, in contrast to the underlying Castile, and extends well beyond the Delaware Basin. Lowenstein (1988, pp. 592-608) has termed the Salado a "saline giant." The Fletcher Anhydrite Member, which is deposited on the Capitan reef rocks, is defined by Lang (1939, pp. 1569-1572; 1942, pp. 63-79) as the base of the Salado. Some investigators believe the Fletcher Anhydrite Member may interfinger with anhydrites normally considered part of the Castile. The Castile/Salado contact is not uniform across the basin, and whether it is conformable is still under consideration. Around the WIPP site, the Castile/Salado contact is commonly placed at the top of a thick anhydrite informally designated as A3; the overlying halite is called the infra-Cowden salt and is included within the Salado. Bodine (1978, pp. 28-29) suggests that the clay mineralogy of the infra-Cowden in ERDA-9 cores changes at about 15 ft (4.6 m) above the lowermost Salado and that the lowermost clays are more like the Castile clays. The top of the thick anhydrite remains the local contact for differentiating the Salado from the Castile, and there is no known significance to the WIPP from these differences.

The Salado in the northern Delaware Basin is broadly divided into three informal members. (Figure L1-7 details the Salado's stratigraphy.) The middle member is known locally as the McNutt potash zone, and it includes 11 defined potash zones, 10 of which are of economic significance in the Carlsbad Potash District. The lower and upper members remain unnamed. The WIPP repository level is located below the McNutt Potash Zone in the lower member.

Within the Delaware Basin, a system is used for numbering the more significant sulfate beds in the Salado, from Marker Bed 100 (near the top of the formation) to Marker Bed 144 (near the base). The system is generally used within the Carlsbad Potash District as well as the WIPP site. The facility horizon is located between Marker Bed 139 and Marker Bed 138.

In the central and eastern part of the Delaware Basin, the Salado is at its thickest, ranging up to about 2,000 ft (about 600 m) thick and consisting mainly of interbeds of sulfate minerals and halite, with halite dominating. The thinnest portions of the Salado consist of a brecciated residue of insoluble material a few tens of feet thick that are exposed at the surface in parts of the western Delaware Basin. The common sulfate minerals are anhydrite ($CaSO_4$), gypsum ($CaSO_4 \bullet 2H_2O$) near the surface, and polyhalite ($K_2SO_4 \bullet MgSO_4 \bullet 2CaSO_4 \bullet 2H_2O$). The sulfate minerals form beds and are also found along boundaries between halite crystals.

Early investigators of the Salado recognized a repetitious vertical succession, or cycle, of beds in the Salado: clay-anhydrite-polyhalite-halite and minor polyhalite-halite. Later investigators described the cyclical units as clay-magnesite-anhydrite, polyhalite or glauberite-halite-argillaceous halite capped by mudstone. Lowenstein (1988, pp. 592-608) defined a depositional cycle (Type I) consisting of: 1) basal mixed siliciclastic and carbonate (magnesite) mudstone, 2) laminated to massive anhydrite or polyhalite, 3) halite, and 4) halite with mud. Lowenstein in 1988 also recognized repetitious sequences of halite and halite with mud as incomplete Type I cycles and termed them Type II cycles. Lowenstein (1988, pp. 592-608) interpreted the Type I cycles as having formed in a shallowing upward, desiccating basin beginning with a perennial lake or lagoon of marine origin and evaporating to saline lagoon and saltpan environments. Type II cycles are differentiated because they do not exhibit features of prolonged subaqueous deposition and also have more siliciclastic influx than do Type I cycles.

From detailed mapping of the Salado in the air intake shaft (AIS) at WIPP, Holt and Powers (1990a, pp. 2-26) interpreted depositional cycles of the Salado in terms of modern features such as those at Devil's Golf Course at Death Valley National Monument, California. The evaporative basin was desiccated, and varying amounts of insoluble residues had collected on the surface through surficial dissolution, eolian sedimentation, and some clastic sedimentation from temporary flooding caused from surrounding areas. The surface developed local relief that could be mapped in some cycles, while the action of continuing desiccation and exposure increasingly concentrated insoluble residues. Flooding, most commonly from marine sources, reset the sedimentary cycle by depositing a sulfate bed.

The details available from the shaft demonstrated the important role of syndepositional water level to water table changes that created solution pits and pipes within the halitic beds while they were at the surface. Holt and Powers (1990a, Appendix F) concluded that passive halite cements filled the pits and pipes, as well as less dramatic voids, as the water table rose. Early diagenetic to synsedimentary cements filled the porosity early and rather completely with commonly clear and coarsely crystalline halite, reducing the porosity to a very small volume according to Casas and Lowenstein (1989).

Although Holt and Powers (1990a) found no evidence for postdepositional halite dissolution in the AIS, dissolution of the upper Salado halite has occurred west of the WIPP. Effects of dissolution are visible in Nash Draw and at other localities where gypsum karst has formed, where units above the Salado such as the Rustler Formation-Dewey Lake Redbeds (Dewey Lake), and post-Permian rocks have subsided. Dissolution studies are summarized in CCA Appendix DEF, Section DEF.3. The dissolution margin of upper Salado halite, based on changes in thickness of the interval from the Culebra dolomite to the Vaca Triste Sandstone Member of the Salado, has been interpreted in detail by Powers (2002a, 2002b, 2003a), Holt and Powers (2002), and Powers et al. (2003). Powers (2002a, 2002b, 2003a) examined data from additional drillholes and noted that the upper Salado dissolution margin appears relatively narrow in many areas, and it directly underlies much of Livingston Ridge. The hydraulic properties of the Culebra correlate in part with dissolution of halite from the upper Salado (Holt and Yarbrough 2002; Powers et al. 2003.

Within the Nash Draw, Robinson and Lang (1938, pp. 2-64 to 2-67) recognized a zone equivalent to the upper Salado but lacking halite. Test wells in the southern Nash Draw produced brine from this interval, and it has become known as the brine aquifer. Robinson and Lang in 1938 considered this zone a residuum from dissolution of Salado halite. Jones et al. (1960, p. 25) remarked that the residuum should be considered part of the Salado, though geophysical log signatures may resemble the lower Rustler.

At the center of the site, Holt and Powers in their 1984 report recognized clasts of fossil fragments and mapped channeling in siltstones and mudstones above halite; they considered these beds to be a normal part of the transition from shallow evaporative lagoons and desiccated salt pans of the Salado to the saline lagoon of the lower Rustler. Although the Salado salt may have been dissolved prior to deposition of the Rustler clastics, the process is detached from the concept of subsurface removal of salt from the Salado in more recent time to develop a residuum and associated "brine aquifer."

Based on the Salado isopachs, thickness begins to change significantly near Livingston Ridge, the eastern margin of the Nash Draw. That should be the approximate eastward limit to the residuum and "brine aquifer," although the normal sedimentary sequence may yield limited fluids east of this margin.

The DOE believes the Salado is of primary importance to the containment of waste. As the principal natural barrier, many of the properties of the Salado have been characterized, and numerical codes were developed to simulate the natural processes within the Salado that affect the disposal system performance.

L1-1c(5) Rustler Formation

The Rustler is the youngest evaporite-bearing formation in the Delaware Basin. It was originally named by Richardson for outcrops in the Rustler Hills of Culberson County, Texas. Adams (1944, p. 1614) first used the names "Culebra member" and "Magenta member" to describe the two carbonates in the formation, indicating that W. B. Lang favored the names, although Lang did not use these names in his most recent publication. Vine in his 1963 work described extensively the

Rustler in the Nash Draw and proposed the four formal names and one informal term for the stratigraphic subdivisions still used for the Rustler (from the base): the Los Medaños member, the Culebra member, the Tamarisk member, the Magenta member, and the Forty-niner member (Forty-niner) (Figure L1-8).

An additional system of informal subdivisions was contributed by Holt and Powers (1988, Fig. 3.2), based on more detailed lithologic units of the noncarbonate members (Figure L1-8). These subdivisions have partially been related to hydrostratigraphic units for the Rustler.

Two studies of the Rustler since Vine's 1963 work contribute important information about the stratigraphy, sedimentology, and regional relationships while examining more local details as well. Eager (1983, pp. 273-283) reported on relationships of the Rustler observed in the southern Delaware Basin as part of sulfur exploration in the area. Holt and Powers (1988, Chapter 5.0) reported the details of sedimentologic and stratigraphic studies of WIPP shafts and cores as well as of geophysical logs from about 600 boreholes in southeastern New Mexico.

The Rustler is regionally extensive (a similar unit in the Texas panhandle is also called the Rustler). Within the area around the WIPP site, evaporite units of the Rustler are interbedded with significant siliciclastic beds and carbonates. Both the Magenta and the Culebra extend regionally beyond areas of direct interest to the WIPP. In the general area of the WIPP, both the Tamarisk and the Forty-niner have similar lithologies: lower and upper sulfate beds and a middle unit that varies principally from mudstone to halite from west to east (Figure L1-8).

In a general sense, halite in the Los Medaños broadly persists to the west of the WIPP site, and halite is found east of the center of the WIPP in the Tamarisk and the Forty-niner (Figure L1-9). (Additional detail on the lithologies of these members follow.)

Two different explanations have been proposed over the history of the project to account for the observed distribution of halite in the non-dolomite members of the Rustler. The earliest researchers (e.g., Bachman [1985] and Snyder [1985]) assumed that halite had originally been present in all the non-sulfate intervals of the Forty-niner, Tamarisk, and Los Medaños Members, and that its present-day absence reflected post-depositional dissolution.

An alternative interpretation was presented by Holt and Powers (1988) following detailed mapping of the Rustler exposed in the WIPP ventilation (now waste) and exhaust shafts in 1984. Fossils, sedimentological features, and bedding relationships were identified in units that had previously been interpreted from boreholes as dissolution residues. Cores from existing boreholes, outcrops, geophysical logs, and petrographic data were also reexamined to establish facies variability across the area.

As a result of these studies, the Rustler was interpreted to have formed in variable depositional environments, including lagoon and saline playas, with two major episodes of marine flooding which produced the carbonate units. Sedimentary structures were interpreted to indicate synsedimentary dissolution of halite from halitic mudstones around a saline playa and fluvial transport of more distal clastic sediments. The halite in the Rustler, by this interpretation, has a present-day distribution similar to that at the time the unit was deposited. Some localized dissolution of halite may have occurred along the depositional margins, but not over large areas. Hence, the absence of halite in Rustler members at the WIPP site more generally reflects non-deposition than dissolution.

This hypothesis was tested and refined by subsequent investigations (e.g., Powers and Holt 1990, 1999, 2000; Holt and Powers 1990a) and is now considered the accepted explanation for the present-day distribution of halite in the Rustler. Powers and Holt (1999) thoroughly described the sedimentary structures and stratigraphy of the Los Medaños as part of the procedure for naming the unit. This shows the basis for interpreting the depositional history of the member and for rejecting significant post-burial dissolution of halite in that unit. Powers and Holt (2000) further describe the lateral facies relationships in other Rustler units, especially the Tamarisk, developed on sedimentologic grounds, and rejected the concept of broad, lateral dissolution of halite from the Rustler across the WIPP site area.

The Culebra transmissivity shows about six orders of magnitude variation across the area around the site, and the changes have commonly been attributed to post-depositional dissolution of the Rustler halite. Powers and Holt (1990, 1999, and 2000) largely rule out this explanation. Variations in transmissivity of the Culebra were correlated qualitatively to the thickness of overburden above the Culebra (see discussion in Section 2.1.5.2), the amount of dissolution of the upper Salado, and the distribution of gypsum fillings in fractures in the Culebra (Beauheim and Holt 1990). Subsequently, Holt and Yarbrough (2002) and Powers et al. (2003) related the variation in Culebra transmissivity more quantitatively to overburden thickness and dissolution of upper Salado halite. The Permittees believe that variations in Culebra transmissivity are primarily caused by the relative abundance of open fractures in the unit, which may be related to each of these factors.

In the region around the WIPP, the Rustler reaches a maximum thickness of more than 500 ft (152 m) (Figure L1-10), while it is about 300 to 350 ft (91 to 107 m) thick within most of the WIPP site. Much of the difference in the Rustler thickness can be attributed to variations in the amount of halite contained in the formation from place to place. The Tamarisk accounts for a larger part of thickness changes than do either the Los Medaños or the Forty-niner. Much project-specific information about the Rustler is contained in Holt and Powers (1988). The WIPP shafts were a crucial element in their study, exposing features not previously reported. Cores were available from several WIPP boreholes, and their lithologies were matched to geophysical log signatures to extend the interpretation throughout a larger area in southeastern New Mexico.

L1-1c(5)(a) The Los Medaños Member

The Los Medaños[1] rests on the Salado with apparent conformity at the WIPP site. It consists of significant proportions of bedded and burrowed siliciclastic sedimentary rocks with cross bedding and fossil remains. These beds record the transition from strongly evaporative environments of the

[1] The Los Medaños was named by Powers and Holt in 1999. Older documents refer to this unit as the "unnamed lower member" of the Rustler.

Salado to saline lagoonal environments. The upper part of the Los Medaños includes halitic and sulfitic beds within clastics. Holt and Powers (1988, p. 9-1*ff*) interpret these as facies changes within a saline playa environment. The implied model from earlier descriptions is that the nonhalitic areas of the upper Los Medaños are dissolution residues from post-depositional dissolution.

As shown in Holt and Powers (1988, Fig. 4.7), the Los Medaños ranges in thickness from about 96 to 126 ft (29 to 38 m) within the site boundaries. The maximum thickness recorded during that study was 208 ft (63 m) southeast of the WIPP site. Halite extends west of most of the site area in this unit (see Figure L1-9 for an illustration of the halite margins). Cross sections based on geophysical log interpretations in Holt and Powers (1988) show the relationship between the thickness of the unit and the presence of halite.

L1-1c(5)(b) The Culebra Dolomite Member

The Culebra rests with apparent conformity on the Los Medaños, though the underlying unit ranges from claystone to its lateral halitic equivalent in the site area. West of the WIPP site, in the Nash Draw, the Culebra is disrupted in response to dissolution of underlying halite. Holt and Powers (1988, pp. 6-12, 6-13, 8-14*ff*) attribute this principally to dissolution of the Salado halite, noting the presence of sedimentologic features in the lower Rustler (Powers and Holt, 1999).

The Culebra was described by Robinson and Lang in 1938 as a dolomite 35 ft (11 m) in thickness; Adams (1944, p. 78) noted that oölites are present in some outcrops as well. The Culebra is generally brown, finely crystalline, locally argillaceous and arenaceous dolomite, with rare to abundant vugs with variable gypsum and anhydrite filling. Holt and Powers (1988) describe the Culebra features in detail, noting that most of the Culebra is microlaminated to thinly laminated, while some zones display no depositional fabric. Holt and Powers (1984) described an upper interval of the Culebra consisting of waxy, golden-brown carbonate, dark organic claystone, and some coarser siltstone of probable algal origin. Because of the unique organic composition of this thin layer, Holt and Powers (1984) did not include it in the Culebra for thickness computations, and this will be factored into discussions of Culebra thickness. Based on core descriptions from the WIPP Project, Holt and Powers (1988, p. 5-11) concluded that there is very little variation of depositional sedimentary features throughout the Culebra.
Vugs are an important part of Culebra porosity (additional discussion on Culebra hydrologic characteristics is given in Section L1-2a[5]). They are commonly zoned parallel to bedding. In outcrop, vugs are commonly empty. In the subsurface, vugs may be filled with anhydrite or gypsum, or they may have some clay lining. Lowenstein (1988, pp. 20-21) noted similar features. Holt and Powers (1988) attribute vugs partly to syndepositional growth as nodules and partly, later, as replacive textures. Lowenstein (1988, pp. 592-608) also described textures related to later replacement and alteration of sulfates. Vugs or pore fillings vary across the WIPP site and contribute to the porosity structure of the Culebra. Natural fractures filled with gypsum are common east of the WIPP site center and in a smaller area west of the site center (Figure L1-11).

Holt (1997) reexamined geological and hydrological data for the Culebra and developed a conceptual model for transport processes. In this document, Holt (1997) recognized several porosity types for the Culebra, and separated four Culebra units (CU) informally designated CU-1 through CU-4 from top to bottom. CU-1 differs from underlying units because it has been disrupted very little by syndepositional processes. Microvugs and interbeds provide most of the porosity, and the permeability of CU-1 is relatively limited. CU-2 and CU-3 likely contribute most of the flow in the Culebra, and the significant difference is that CU-2 includes more persistent silty dolomite interbeds. CU-2 and CU-3 include “small-scale bedding-plane fractures, networks of randomly oriented small-scale fractures and microfractures, discontinuous silty dolomite interbeds, large vugs hydraulically connected with microfractures and small-scale fractures, microvugs hydraulically connected with microfractures and intercrystalline porosity, blebs of silty dolomite interconnected with microfractures and intercrystalline porosity, and intercrystalline porosity” (Holt 1997, p. 2-19). Bedding-plane fractures dominate CU-4 at the base of the Culebra, and the unit shows some brittle deformation. CU-4 has not been isolated for hydraulic testing.

Holt (1997, p. I) also related porosity and solute transport, conceptualizing the medium “as consisting of advective porosity, where solutes are carried by the groundwater flow, and fracture-bounded zones of diffusive porosity, where solutes move through slow advection or diffusion.” Holt (1997) noted that length or time scales will govern how each porosity type will contribute to solute transport.

After dolomite, Sewards et al. (1991, p. IX-1) report that clay is the most abundant mineral of the Culebra. Clay minerals include corrensite, illite, serpentine, and chlorite. Clay occurs in bulk rock and in fracture surfaces.

In the WIPP site area, the Culebra varies in thickness. Different data sources provide varying estimates (Table L1-1). Holt and Powers (1988, pp. 4-7) considered the organic-rich layer at the Culebra/Tamarisk contact separately from the Culebra in interpreting geophysical logs.

Comparing data sets, Holt and Powers (1988) typically interpret the Culebra as being about 3 ft (about 1 m) thinner than have other sources. In general, this reflects the difference between including or excluding the unit at the Culebra/Tamarisk contact. Each data set shows areal differences in thickness of the Culebra when it is examined township by township.

LaVenue et al. (1988) calculated a mean thickness of 25 ft (7.7 m) for the Culebra based on 78 boreholes. This mean thickness has been used uniformly for the Culebra in PA calculations. Many of the boreholes represented multiple drilling locations (points) at individual hydrology drill pads H-2 through H-11. The multiple points at each drillhead normally would be considered a single location for statistical purposes. If each data point is considered to be distinct, the implication is that thickness varies significantly over the distances between these closely spaced boreholes, and it may not be consistent for calculations to use averaging thickness as a parameter. Mercer (1983, Table 1) reported a data set similar to LaVenue et al. (1988), but without statistics.

The borehole database makes it possible to defend choices of the Culebra thicknesses for the area being modeled. If repository performance is insensitive to Culebra thickness, defining the specific thickness of the Culebra is not important.

L1-1c(5)(c) The Tamarisk Member

Vine (1963, p. B15) named the Tamarisk for outcrops near Tamarisk Flat in the Nash Draw. Outcrops of the Tamarisk are distorted, and subsurface information was used to establish member characteristics. Vine reported two sulfate units separated by a siltstone, about 5 ft (1.5 m) thick, interpreted by Jones et al. (1960) as a dissolution residue.

The Tamarisk is generally conformable with the underlying Culebra. The transition is marked by an organic-rich unit interpreted as being present over most of southeastern New Mexico. The Tamarisk around the site area consists of lower and upper sulfate units separated by a unit that varies from mudstone (generally to the west) to mainly halite (to the east). Near the center of the WIPP site, the lower anhydrite was partially eroded during deposition of the middle mudstone unit, as observed by in the WIPP Waste Shaft and the WIPP Exhaust Shaft. The lower anhydrite was completely eroded at WIPP-19. Before shaft exposures were available, the lack of the lower Tamarisk anhydrite at WIPP-19 was interpreted as the result of solution, and the mudstone was considered a cave filling.

Jones et al. (1960) interpreted halite to be present east of the center of the WIPP site based on geophysical logs and drill cuttings. Based mainly on cores and cuttings records from the WIPP potash drilling program, Snyder prepared a map in 1985 showing the halitic areas of each of the noncarbonate Rustler members. A very similar map based on geophysical log characteristics was prepared independently by Powers in 1984 (see Figure L1-9).

Holt and Powers (1988) describe the mudstones and halitic facies in the middle of the Tamarisk, and they interpreted the unit as formed in a salt pan to mud-flat system. They cited sedimentary features and the lateral relationships as evidence of syndepositional dissolution of halite in the marginal mud-flat areas.

The Tamarisk thickness varies greatly in southeastern New Mexico, principally as a function of the thickness of halite in the middle unit. Within T22S, R31E, Holt and Powers (1988) show a range from 84 to 184 ft (26 to 56 m) for the entire Tamarisk and a range from 6 to 110 ft (2 to 34 m) for the interval of mudstone-halite between lower and upper anhydrites. Expanded geophysical logs with corresponding lithology illustrate some of the lateral relationships for this interval (Figure L1-12). See also Powers and Holt (2000).

L1-1c(5)(d) The Magenta Member

Adams (1944, p. 1614) attributes the name "Magenta member" to W. B. Lang, based on a feature north of Laguna Grande de la Sal named Magenta Point. According to Holt and Powers (1988, p. 5-22*ff*), the Magenta is a gypsiferous dolomite with abundant primary sedimentary structures and well-developed algal features. It does not vary greatly in sedimentary features across the site area.

Holt and Powers (1988, p. 5-22) reported that the Magenta varies from 23 to 28 ft (7.0 to 8.5 m); they did not contour the thickness because of limited changes.

L1-1c(5)(e) The Forty-niner Member

Vine (1963) named the Forty-niner for outcrops at Forty-niner Ridge in the eastern Nash Draw, but the outcrops of the Forty-niner are poorly exposed. In the subsurface around the WIPP, the Forty-niner consists of basal and upper sulfates separated by a mudstone. It is conformable with the underlying Magenta. As with other members of the Rustler, geophysical log characteristics can be correlated with core and shaft descriptions to extend geological inferences across a large area (Holt and Powers, 1988).

The Forty-niner ranges from 43 to 77 ft (13 to 23 m) thick within T22S, R31E. East and southeast of the WIPP, the Forty-niner exceeds 80 ft (24 m), and some of the geophysical logs from this area indicate halite is present in the beds between the sulfates. See also Powers and Holt (2000).

Within the Waste Shaft, the Forty-niner mudstone displays sedimentary features and bedding relationships indicating sedimentary transport. These beds have not been described in detail prior to mapping in the Waste Shaft at the WIPP. The features found in the shaft led Holt and Powers (1988, p. i, ii) to reexamine the available evidence for and interpretations of dissolution of halite in the Rustler units.

L1-1c(6) The Dewey Lake

The nomenclature for rocks included in the Dewey Lake was introduced during the 1960s to clarify relationships between these rocks assigned to the Upper Permian and the Cenozoic Gatuña Formation (Gatuña).

There are three main sources of data about the Dewey Lake in the area around the WIPP. Miller reported the petrology of the unit in 1955 and 1966. Schiel described outcrops in the Nash Draw areas and interpreted geophysical logs of the unit in southeastern New Mexico and west Texas to infer the depositional environments and stratigraphic relationships in 1988 and 1994. Holt and Powers (1990) were able to describe the Dewey Lake in detail at the AIS for the WIPP in 1990, confirming much of Schiel's information and adding data regarding the lower Dewey Lake.

The Dewey Lake overlies the Rustler conformably though local examples of the contact (e.g., the AIS described by Holt and Powers [1990]) show minor disruption by dissolution of some of the upper Rustler sulfate). The formation is predominantly reddish-brown fine sandstone to siltstone or silty claystone with greenish-gray reduction spots. Thin bedding, ripple cross-bedding, and larger channeling are common features in outcrops, and additional soft sediment deformation features and early fracturing are described from the lower part of the formation by Holt and Powers (1990). Schiel (1988; 1994, p. 5-13) attributed the Dewey Lake to deposition on "a large, arid fluvial plain subject to ephemeral flood events."

There is no direct faunal or radiometric evidence of the age of the Dewey Lake in the vicinity of the WIPP site. It is assigned to the Ochoan series considered to be late Permian in age, and it is regionally correlated with units of similar lithology and stratigraphic position. Schiel in both 1988 and 1994 reviewed the limited radiometric data from lithologically similar rocks (Quartermaster Formation) and concluded that much of the unit could be early Triassic in age. Renne et al. (1996)

resampled tephra from the Quartermaster in the Texas panhandle area and found that radiometric data support the idea that the Quartermaster is mainly Triassic in age rather than Permian. Others have begun to infer as well that the Dewey Lake in the vicinity of the WIPP may be mostly Triassic (e.g., Powers and Holt 1999). These age relationships continue to be of academic interest because of the geologic significance of the Permo-Triassic boundary, but there is no significance for waste isolation at the WIPP.

Near the center of the WIPP site, Holt and Powers (1990, Fig. 5) mapped 498 ft (152 m) of the Dewey Lake (Figure L1-13). The formation is thicker to the east (Schiel, 1994, p. 6) of the WIPP site, in part because western areas were eroded before the overlying Triassic rocks were deposited.

The Dewey Lake is extensively fractured, and both cements and fracture fillings have been further examined to ascertain the possible contributions of surface infiltration to underlying units. Holt and Powers (1990, p. 3-8*ff*) described the Dewey Lake as cemented by carbonate above 164.5 ft (50 m) in the AIS; some fractures in the lower part of this interval were also filled with carbonate, and the entire interval surface was commonly moist. Below this point, the cement is harder and more commonly anhydrite (Powers 2003b), the shaft is dry, and fractures are filled with gypsum. Powers (2002c; 2003b) reports core and geophysical log data supporting these vertical changes in natural mineral cements in the Dewey Lake over a larger region at a horizon that is believed to underlie known natural groundwater occurrences in the Dewey Lake. In areas where the Dewey Lake has been exposed to weathering after erosion of the overlying Santa Rosa, this cement boundary tends to generally parallel the eroded upper surface of the Dewey Lake, suggesting that weathering has affected the location of the boundary. Where the Dewey Lake has been protected by overlying rocks of the Santa Rosa, the cement change appears to be stratigraphically controlled but the data points are too few to be certain. Holt and Powers (1990, pp. 3-11, Fig. 16) suggested the cement change might be related to infiltration of meteoric water. They also determined that some of the gypsum-filled fractures are syndepositional. The Dewey Lake fractures include horizontal to subvertical trends, some of which were mapped in detail (Holt and Powers, 1986, Figs. 6–8).

Lambert (1991, pp. 5-65) analyzed the deuterium/hydrogen (D/H) ratios of gypsum from all of the various members of the Rustler and gypsum veins in the Dewey Lake and suggests that none of the gypsum formed from evaporitic fluid, such as Permian seawater. Rather, they last recrystallized in the presence of meteoric water. Several samples were collected from localities known or proposed as evaporitic karst features. Lambert (1991, pp. 5-66) infers that the gypsum D/H is not consistent with modern meteoric water, but it may be consistent with earlier meteoric fluids (Pleistocene or older) isotopically resembling Rustler meteoric water. There is no obvious correlation with depth indicating infiltration of modern surface-derived groundwaters or precipitation. Strontium isotope ratios ($^{87}Sr/^{86}Sr$) indicate no intermixing or homogenization of fluids between the various Rustler members and between the Rustler and the Dewey Lake, but there may be lateral movement of water within the Dewey Lake. The Dewey Lake carbonate vein material shows a broader range of strontium ratios than does surface caliche, and the ratios barely overlap. Lambert (1987) concluded, based on isotopic data, that confined Rustler groundwaters have a minimal meteoric component, and have been isolated from the atmosphere for at least 12,000 to 16,000 years. These data also suggest that the present day Rustler hydrologic system is transient rather than at steady state.

L1-1c(7) The Santa Rosa

There have been different approaches to the nomenclature of rocks of the Triassic age in southeastern New Mexico. Bachman generally described the units in 1974 as "Triassic, undivided" or as the Dockum Group. Vine in 1963 used the term "Santa Rosa Sandstone." "The Santa Rosa" has become common usage. Lucas and Anderson in 1993 imported other formation names that are unlikely to be useful for WIPP.

The Santa Rosa is disconformable over the Dewey Lake (Vine, 1963, p. B25). The rocks of the Santa Rosa have more variegated hues than the underlying uniformly colored Dewey Lake. Coarse-grained rocks, including conglomerates are common, and the formation includes a variety of cross-bedding and sedimentary features (Lucas and Anderson, 1993, pp. 231-235).

Within the WIPP site boundary, the Santa Rosa is relatively thin to absent (Figure L1-14). At the AIS, Holt and Powers (1990, Fig. 5) attributed about 2 ft (0.6 m) of rock to the Santa Rosa. The Santa Rosa is a maximum of 255 ft (78 m) thick in potash holes drilled for WIPP east of the site boundary. The Santa Rosa is thicker to the east.

The geologic data from design studies (Sergent et al. 1979) were incorporated with data from drilling to investigate shallow subsurface water in the Santa Rosa to provide structure and thickness maps of the Santa Rosa in the vicinity of the WIPP surface structures area (Powers 1997). These results are consistent with the broader regional distribution of the geologic structure of (?) the Santa Rosa.

L1-1c(8) The Gatuña Formation

Lang in Robinson and Lang (1938) named the Gatuña for outcrops in the vicinity of the Gatuña Canyon in the Clayton Basin. Rocks now attributed to the Gatuña in Pierce Canyon were once included in the "Pierce Canyon Formation," along with rocks now assigned to the Dewey Lake. The formation has been mapped from the Santa Rosa, New Mexico, area south to the vicinity of Pecos, Texas. It unconformably overlies different substrates.

Vine in 1963 and Bachman in 1974 provided some limited description of the Gatuña. The DOE's most comprehensive study of the Gatuña is based on WIPP investigations and landfill studies for Carlsbad and Eddy County. Much of the formation is colored light reddish-brown. It is broadly similar to the Dewey Lake and the Santa Rosa, though the older units have more intense hues. The formation is highly variable, ranging from coarse conglomerates to claystones with some highly gypsiferous sections. Sedimentary structures are abundant. Analysis of lithofacies indicates that the formation is dominantly fluvial in origin with areas of low-energy deposits and evaporitic minerals. It was deposited in part over areas actively subsiding in response to dissolution.

The thickness of the Gatuña is not very consistent regionally. Thicknesses range up to about 300 ft (91 m) at the Pierce Canyon, with thicker areas generally subparallel to the Pecos River. To the east, the Gatuña is thin or absent. Holt and Powers (1990) reported about 9 ft (2.7 m) of undisturbed Gatuña in the AIS at the WIPP. Powers (1997) integrated data from facility design geotechnical work (Sergent et al. 1979) and drilling to investigate shallow water to develop maps of the Gatuña in the vicinity of the WIPP surface facility. These maps are consistent with the broader regional view of the distribution of the Gatuña.

The Gatuña has been considered to be Pleistocene in age based on a volcanic glass in the upper Gatuña that has been identified as the Lava Creek B ash dated at 0.6 million years by Izett and Wilcox (1982). An additional volcanic ash from the Gatuña in Texas yields consistent K-Ar and geochemical data, indicating it is about 13 million years (Powers and Holt 1993, p. 272). Thus the Gatuña ranges in age over a period of time that may be greater than the Ogallala Formation (hereafter referred to as the Ogallala) on the High Plains east of the WIPP.

L1-1c(9) The Mescalero Caliche

The Mescalero Caliche is an informal stratigraphic unit apparently first differentiated by Bachman in 1974, though Bachman (1973, 17) described the "caliche on the Mescalero Plain." He differentiated the Mescalero from the older, widespread Ogallala caliche or caprock on the basis of textures, noting that breccia and pisolitic textures are much more common in the Ogallala caliche. The Mescalero has been noted over significant areas in the Pecos drainage, including the WIPP area, and it has been formed over a variety of substrates. Bachman described the Mescalero as a two-part unit: (1) an upper dense laminar caprock and (2) a basal, earthy-to-firm, nodular calcareous deposit. Machette (1985, 5) classified the Mescalero as having Stage V morphologies of a calcic soil (the more mature Ogallala caprock reaches Stage VI).

Bachman (1976, Figure 8) provided structure contours on the Mescalero caliche for a large area of southeastern New Mexico, including the WIPP site. From the contours and Bachman's discussion of the Mescalero as a soil, it is clear that the Mescalero is expected to be continuous over large areas. Explicit WIPP data are limited mainly to boreholes, though some borehole reports do not mention the Mescalero. The unit may be as much as 10 feet (3 meters) thick.

The Mescalero overlies the Gatuña and was interpreted by Bachman on basic stratigraphic grounds as having accumulated during the early-to-middle Pleistocene. Samples of the Mescalero from the vicinity of the WIPP were studied using uranium-trend methods. Based on early written communication from Rosholt, Bachman (1985, 20) reports that the basal Mescalero began to form about 510,000 years ago and the upper part began to form about 410,000 years ago; these ages are commonly cited in WIPP literature. The samples are interpreted by Rosholt and McKinney (1980, Table 5) in the formal report as indicating ages of 570,000 ± 110,000 years for the lower part of the Mescalero and 420,000 ± 60,000 years for the upper part.

According to Bachman (1985, 19), where the Mescalero is flat-lying and not breached by erosion, it is an indicator of stability or integrity of the land surface over the last 500,000 years.

L1-1c(10) Surficial Sediments

Soils of the region have developed mainly from Quaternary and Permian parent material. Parent material from the Quaternary system is represented by alluvial deposits of major streams, dune sand, and other surface deposits. These are mostly loamy and sandy sediments containing some coarse fragments. Parent material from the Permian system is represented by limestone, dolomite, and gypsum bedrock. Soils of the region have developed in a semiarid, continental climate with abundant sunshine, low relative humidity, erratic and low rainfall, and a wide variation in daily and seasonal temperatures. Subsoil colors normally are light brown to reddish brown but are often mixed with lime accumulations (caliche) that result from limited, erratic rainfall and insufficient leaching. A soil association is a landscape with a distinctive pattern of soil types (series). It normally consists of one or more major soils and at least one minor soil. There are three soil associations within 5 mi (8.3 km) of the WIPP site: the Kermit-Berino, the Simona-Pajarito, and the Pyote-Maljamar-Kermit. Of these three associations, only the Kermit-Berino have been mapped across the WIPP site (by Chugg et al. [1952, Sheet No. 113]). These are sandy soils developed on eolian material. The Kermit-Berino include active dune areas. The Berino soil has a sandy A horizon; the B horizons include more argillaceous material and weak to moderate soil structures. A and B horizons are described as noncalcareous, and the underlying C horizon is commonly caliche. Bachman in 1980 interpreted the Berino soil as a paleosol that is a remnant B horizon of the underlying Mescalero.

Generally, the Berino which covers about 50 percent of the site, consists of deep, noncalcareous, yellow-red to red sandy soils that developed in wind-worked material of mixed origin. These soils are described as undulating to hummocky and gently sloping (ranging from 0 to 3 percent slopes). The soils are the most extensive of the deep, sandy soils in the Eddy County area. The Berino is subject to continuing wind and water erosion. If the vegetative cover is seriously depleted, the water-erosion potential is slight, but the wind-erosion potential is very high. These soils are particularly sensitive to wind erosion in the months of March, April, and May, when rainfall is minimal and winds are highest.

The Kermit consists of deep, light-colored, noncalcareous, excessively drained loose sands, typically yellowish-red fine sand. The surface is undulating to billowy (from 0 to 3 percent slopes) and consists mostly of stabilized sand dunes. The Kermit is slightly to moderately eroded. Permeability is very high, and if vegetative cover is removed, the water-erosion potential is slight, but the wind-erosion potential is very high. In 1980, Rosholt and McKinney applied uranium-trend methods to samples of the Berino from the WIPP site area. They interpreted the age of formation of the Berino as 330,000 ± 75,000 years.

L1-1d Physiography and Geomorphology

In this section, the DOE presents a discussion of the physiography and geomorphology of the WIPP site and surrounding area.

L1-1d(1) Regional Physiography and Geomorphology

The WIPP site is in the Pecos Valley section of the southern Great Plains physiographic province (Figure L1-15), a broad highland belt sloping gently eastward from the Rocky Mountains and the

Basin and Range Province to the Central Lowlands Province. The Pecos Valley section itself is dominated by the Pecos River Valley, a long north-south trough that is from 5 to 30 mi (8.3 to 50 km) wide and as much as 1,000 ft (305 m) deep in the north. The Pecos River system has evolved from the south, cutting headward through the Ogallala sediments and becoming entrenched some time 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. The surface locally has a karst terrain containing superficial sinkholes, dolines, and solution-subsidence troughs from both surface erosion and subsurface dissolution. 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 6,000 ft (1,829 m) in the northwest to about 2,000 ft (610 m) in the south.

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 and is a poorly drained, eastward-sloping surface covered by gravels, wind-blown sand, and caliche that has developed since early to middle Pleistocene time. Few and minor topographic features are present in the High Plains section, formed when more than 500 ft (152 m) 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 Mountains 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.

L1-1d(2) Site Physiography and Geomorphology

The land surface in the area of the WIPP site is a semiarid, wind-blown plain sloping gently to the west and southwest and is hummocky with sand ridges and dunes. A hard caliche layer (Mescalero caliche) is typically present beneath the sand blanket and on the surface of the underlying Pleistocene Gatuña. Figure L1-16 is a topographic map of the area. Elevations at the site range from 3,570 ft (1,088 m) in the east to 3,250 ft (990 m) in the west. The average east-to-west slope is 50 ft per mi (9.4 m per km).

The Livingston Ridge is the most prominent physiographic feature near the site. It is a west-facing escarpment that has about 75 ft (23 m) of topographic relief and marks the eastern edge of the Nash Draw, the drainage course nearest to the site. The Nash Draw is a shallow 5-mile-wide (8-km-wide) basin, 200 to 300 ft (61 to 91 m) deep and open to the southwest. It was caused, at least in part, by subsurface dissolution and the accompanying subsidence of overlying sediments. The Livingston Ridge is the approximate boundary between terrain that has undergone erosion and/or solution collapse and terrain that has been affected very little.

About 18 mi (24 km) east of the site is the southeast-trending San Simon Swale, a depression due, at least in part, to subsurface dissolution (Figure L1-1). Between San Simon Swale and the site is a broad, low mesa named "the Divide." Lying about 6 mi (9.7 km) east of the site and about 100 ft (30 m) above the surrounding terrain, the Divide is a boundary between southwestern drainage toward the Nash Draw and southeastern drainage toward the San Simon Swale. The Divide is capped by the Ogallala and the overlying caliche, upon which have formed small, elongated depressions similar to those in the adjacent High Plains section to the east.

Surface drainage is intermittent; the nearest perennial stream is the Pecos River, 12 mi (19 km) southwest of the WIPP site boundary. The site's location near a natural divide protects it from flooding and serious erosion caused by heavy runoff. Should the climate become more humid, any perennial streams should follow the present basins, and the Nash Draw and the San Simon Swale would be the most eroded, leaving the area of the Divide relatively intact.

Dissolution-caused subsidence in the Nash Draw and elsewhere in the Delaware Basin has caused a search for geomorphic indications of subsidence near the site. One feature that has attracted some attention is a very shallow sink about 2 mi (3 km) north of the center of the site. It is very subdued, about 1,000 ft (305 m) in diameter, and about 30 ft (9 m) deep. Resistivity studies indicate a very shallow surficial fill within this sink and no disturbance of underlying beds, implying a surface, rather than subsurface, origin. Resistivity surveys in the site area showed an anomaly in Section 17 within the WIPP site boundary. It resembles the pattern over a known sink, a so-called breccia pipe, but drilling showed a normal subsurface structure without breccia, and the geophysical anomaly is assumed to be caused by low-resistivity rock in the Dewey Lake.

L1-1e Tectonic Setting and Site Structural Features

The processes and features included in this section are those more traditionally considered part of tectonics, broad-scale processes that develop the features of the earth. Salt dissolution is a different process that can develop some features resembling those of tectonics.

Broad-scale structural elements of the area around the WIPP developed over geological time, and most formed during the late Paleozoic. There is little historical or recent geological evidence of significant tectonic activity in the vicinity. More recently, the entire region has tilted, and activity related to Basin and Range tectonics formed major structures southwest of the area. Seismic activity is specifically addressed in Section L1-4.

Broad subsidence began in the area as early as the Ordovician, developing a sag called the Tabosa Basin. By late Pennsylvanian to early Permian time, the Central Basin Platform developed (Figure L1-17), separating the Tabosa Basin into two parts: the Delaware Basin to the west and the Midland Basin to the east. The Permian Basin refers to the collective set of depositional basins in the area during the Permian period. Southwest of the Delaware Basin, the Diablo Platform began developing either late in the Pennsylvanian or early Permian. The Marathon Uplift and Ouachita tectonic belt limited the southern extent of the Delaware Basin. Most of these broader scale features surrounding the Delaware Basin formed during the late Paleozoic and have remained relatively constant in their relationships since.

L1-1e(1) Basin Tilting

According to Brokaw et al. (1972, p. 30) pre-Ochoan sedimentary rocks in the Delaware Basin show evidence of gentle downwarping during deposition, while Ochoan and younger rocks do not. A relatively simple eastward tilt generally from about 75 to 100 ft per mi (14 to 19 m per km) has been superimposed on the sedimentary sequence. King (1948, p. 108) generally attributes the uplift of the Guadalupe and Delaware mountains along the west side of the Delaware Basin to later Cenozoic, though he also notes that some faults along the west margin of the Guadalupe Mountains have displaced Quaternary gravels.

King (1948, p. 144) also infers that the uplift is related to the Pliocene-age deposits of the Llano Estacado. Subsequent studies of the Ogallala of the Llano Estacado show that it ranges in age from Miocene (about 12 million years before present) to Pliocene. This is the most likely time range for uplift of the Guadalupe Mountains and broad tilting to the east of the Delaware Basin sequence.

L1-1e(2) Faulting

Fault zones are well known along the Central Basin Platform, east of the WIPP, from extensive drilling for oil and gas as reported by Hills (1984, pp. 250-267). Holt and Powers performed a more recent analysis in 1988 of geophysical logs to examine regional geology for the Rustler that showed these faults displaced, at least, the Rustler rocks of late Permian age. The overlying Dewey Lake shows marked thinning along the same trend as the fault line or zone according to Schiel (1988, Fig. 21), but the structure contours of the top of the Dewey Lake are not clearly offset. Schiel (1988) concluded that the fault was probably reactivated during Dewey Lake deposition, but movement ceased at least by the time the Santa Rosa was deposited. No surface displacement or fault has been reported along this trend, indicating movement has not been significant enough to rupture the overlying materials since Permian time.

Within the Delaware Basin, there are few examples of faults that may offset part of the evaporite section. At the northern end of the WIPP site, Snyder in Borns et al. (1983, p. 17*ff*) drew structure contours on the top of the basal A1 of the Castile for boreholes WIPP-11, WIPP-12, and WIPP-13. Northeast-southwest-trending faults were interpreted to displace this unit both north and south of WIPP-11 (Borns et al., 1983). Snyder inferred that the Bell Canyon/Castile contact is also faulted and displaced along the same trend. Barrows in Borns et al. (1983, pp. 58-60) interpreted seismic reflection data to indicate, with varying confidence, faults within Castile rocks but not in underlying units.

The faults interpreted by Snyder (Borns et al., 1983) around WIPP-11 depend on the correct identification of the basal Castile anhydrite (A1) in that borehole. The evaporite structure is complex, and some of the upper units of the Castile and the lower Salado differ from surrounding boreholes. The diagnostic Castile/Bell Canyon contact was not reached by this borehole, and the faults inferred for the Castile/Bell Canyon contact also depend on correct identification of A1 and projection of A1 thickness by Snyder (Borns et al., 1983). Inferred connections with the underlying Bell Canyon or deeper units could signify circulation of fluids to the evaporite section within the site boundaries. This is unlikely, given the Castile geology within boreholes WIPP-13 and DOE-2 near the trend of the inferred fault. The structure contour maps by Snyder were based on data obtained from WIPP-II, however, when WIPP-13 and DOE-2 were drilled much later, the projected trends by Snyder were not valid. WIPP-13 and DOE-2 did not show evidence of complex structure in the upper limits of the Castile and lower Salado. Drilling for hydrocarbon exploration has been extensive around the northern and western boundaries of the site since the mid-1980s.

Muehlberger et al. (1978, pp. 337-340) have mapped quaternary fault scarps along the Salt Basin graben west of both the Guadalupe and the Delaware Mountains. These are the nearest known Quaternary faults of tectonic origin to the WIPP. Kelley in 1971 inferred the Carlsbad and Barrera faults along the eastern escarpment of the Guadalupe Mountains based mainly on vegetative linaments. Hayes and Bachman reexamined the field evidence for these faults in 1979 and concluded that they were nonexistent.

On a national basis, Howard et al. (1971, Sheets 1-2) assessed the location and potential for activity of young faults. For the region around the WIPP site, Howard et al. (1971, Sheet 1) located faults along the western escarpment of the Delaware and the Guadalupe mountains trend. These faults were judged to be late Quaternary (approximately the last 500,000 years) or older.

In summary, there are no known Quaternary or Holocene faults of tectonic origin offsetting rocks at the surface nearer to the site than the western escarpment of the Guadalupe Mountains. A significant part of the tilt of basin rocks is attributed to a mid-Miocene to Pliocene uplift along the Guadalupe/Sacramento mountains trend that is inferred on the basis of High Plains sediments of the Ogallala. Seismic activity is low and is commonly associated with secondary oil recovery along the Central Basin Platform.

L1-1e(3) Igneous Activity

Within the Delaware Basin, only one feature of igneous origin is known to have formed since the Precambrian. An igneous dike or series of echelon dikes occurs along a linear trace about 75 mi (120 km) long from the Yeso Hills south of White's City, New Mexico, to the northeast. At its closest, the dike trend passes about 8 mi (13 km) northwest of the WIPP site center. Evidence for the extent of the dike ranges from outcroppings at Yeso Hills to subsurface intercepts in boreholes and mines to airborne magnetic responses.

An early radiometric determination by Urry (1936, pp. 35-40) for the dike yielded an age of 30 ± 1.5 million years. Work by Calzia and Hiss (1978, pp. 39-45) on dike samples are consistent with early work, indicating an age of 34.8 ± 0.8 million years. Work by Brookins et al. (1980, pp. 28-31) on dike samples in contact with polyhalite indicated an age of about 21.4 million years.

Volcanic ashes found in the Gatuña were airborne from distant sources such as Yellowstone and do not represent volcanic activity at the WIPP.

L1-1e(4) Loading and Unloading

Loading and unloading during the geological history since deposition is considered an influence on the hydrology of the Permian units because of its possible effect on the development of fractures (Powers and Holt, 1995).

The sedimentary loading, depth of total burial, and erosion events combine in a complex history reconstructed here from regional geological trends and local data. The history is presented in Figure L1-18 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 AIS (Holt and Powers, 1990).

Given the maximum local thickness of the Dewey Lake, the maximum load at the end of the Permian was no more than approximately 787 feet (240 meters). Given the present depth to the Culebra from the top of the Dewey Lake in the AIS, approximately 115 feet (35 meters) of Dewey Lake might have been eroded during the Early Triassic before additional sediments were deposited. The Triassic thickness at the AIS is approximately 26 feet (8 meters). Northeast of the WIPP site (T21S, R33E), Triassic rocks (Dockum Group) have a maximum local thickness of approximately 1,233 feet (373 meters). This thickness is a reasonable estimate of the maximum thickness also attained at the WIPP site prior to the Jurassic Period. At the end of the Triassic, the total thickness at the WIPP site may have then attained approximately 1,863 feet (586 meters) in two similar loading stages of a few million years each, over a period of approximately 50 million years.

The Jurassic outcrops nearest to the WIPP site are in the Malone Mountains of west Texas. There is no evidence that Jurassic rocks were deposited at or in the vicinity of the WIPP site. As a consequence, the Jurassic is considered a time of erosion or nondeposition at the site, though erosion is most likely.

This much erosion during the Jurassic obviously cannot be broadly inferred for the area or there would not be thick Triassic rocks still preserved. Triassic rocks of this thickness are preserved nearby, indicating either pre-Jurassic tilting or that erosion did not occur until later (but still after tilting to preserve the Triassic rocks near the WIPP site). It is also possible that the immediate site area had little Triassic deposition or erosion, but very limited Triassic deposition (that is, 26 feet [8 meters]) at the WIPP site seems unlikely.

Lang (1947) reported fossils from Lower Cretaceous rocks in the Black River Valley southwest of the WIPP site. Bachman (1980) also reported similar patches of probable Cretaceous rocks near Carlsbad and south of White's City. From these reports, it is likely that some Cretaceous rocks were deposited at the WIPP site. Approximately 70 miles (110 kilometers) south-southwest of the WIPP site, significant Cretaceous outcrops of both Early and Late Cretaceous age have a total maximum thickness of approximately 1,000 feet (300 meters). Southeast of the WIPP, the nearest Cretaceous outcrops are thinner and represent only the Lower Cretaceous. Based on outcrops, a maximum thickness of 1,000 feet (300 meters) of Cretaceous rocks could be estimated for the WIPP site. Compared to the estimate of Triassic rock thickness, it is less likely that Cretaceous rocks were this thick at the site. The uppermost lines of Figure L1-18 summarize the assumptions of maximum thickness of these units.

A more likely alternative is that virtually no Cretaceous rocks were deposited, followed by erosion of remaining Triassic rocks during the Late Cretaceous to the Late Cenozoic. Such erosion may also have taken place over an even longer period, beginning with the Jurassic Period. Ewing (1993) favors Early Cretaceous uplift and erosion for the Trans-Pecos Texas area, but he does not analyze later uplift and erosional patterns.

In the general vicinity of the WIPP site, there are outcrops of Cenozoic rock from the Late Miocene (Gatuña and Ogallala Formations). There is little reason to infer any significant Early Cenozoic sediment accumulation at the WIPP site. Erosion is the main process inferred to have occurred during this period and an average erosion rate of approximately 11 meters per million years is sufficient during the Cenozoic to erode the maximum inferred Triassic and Cretaceous thickness prior to Gatuña and Ogallala deposition. Significant thicknesses of Cretaceous rocks may not have been deposited, however, and average erosion rates could have been lower.

Maximum-known Gatuña thickness in the area around the WIPP is approximately 330 feet (100 meters); at the WIPP site the Gatuña is very thin to absent. Ogallala deposits are known from the Divide east of the WIPP site, as well as from the High Plains further east and north. On the High Plains northeast of the WIPP, the Upper Ogallala surface slopes to the southeast at a rate of approximately 20 feet per mile (4 meters per kilometer). A straight projection of the 4,100-foot (1,250-meter) contour line from this High Plains surface intersects the site area, which is at an elevation slightly above 3,400 feet (1,036 meters). This difference in elevation of 700 feet (213 meters) represents one estimate, probably near an upper bound, of possible unloading subsequent to deposition of the Ogallala Formation.

Alternatively, the loading and unloading of the Ogallala could have been closer to 330 feet (100 meters). In any case, it would have occurred as a short-lived pulse over a few million years at most.

While the above inferences about greater unit thicknesses and probable occurrence are permissible, a realistic assessment suggests a more modest loading and unloading history. It is likely that the Dewey Lake accumulated to near local maximum thickness of approximately 787 feet (240 meters) before being slightly eroded prior to the deposition of Triassic rocks. It also is most probable that the Triassic rocks accumulated at the site to near local maximum thickness. In two similar cycles of rapid loading, the Culebra was buried to a depth of approximately 2,132 feet (650 meters) by the end of the Triassic.

It also seems unlikely that a significant thickness of Cretaceous rock accumulated at the WIPP site. Erosion probably began during the Jurassic, slowed or stopped during the Early Cretaceous as the area was nearer or at base level, and then accelerated during the Cenozoic, especially in response to uplift as Basin and Range tectonics encroached on the area and the basin was tilted more. Erosional beveling of Dewey Lake and Santa Rosa suggest considerable erosion since tilting in the mid-Cenozoic. Erosion rates for this shorter period could have been relatively high, resulting in the greatest stress relief on the Culebra and surrounding units. Some filling occurred during the Late Cenozoic as the uplifted areas to the west formed an apron of Ogallala sediment across much of the area, but it is not clear how much Gatuña or Ogallala sediment was deposited in the site area. From general reconstruction of Gatuña history in the area (Powers and Holt 1993), the DOE infers that Gatuña or Ogallala deposits likely were not much thicker at the WIPP site than they are now. The loading and unloading spike (Figure L1-18) representing Ogallala thickness probably did not occur. Cutting and headward erosion by the Pecos River has created local relief and unloading by erosion. At the WIPP site, this history is little complicated by dissolution, though locally (for example, Nash Draw) the effects of erosion and dissolution are more significant. The underlying evaporites have responded to foundering of anhydrite in less dense halite beds. These have caused local uplift of the Culebra (as at ERDA 6) but little change in the overburden at the WIPP. Areas east of the WIPP site are likely to have histories similar to that of the site. West of the site, the final unloading is more complicated by dissolution and additional erosion leading to exposure of the Culebra along stretches of the Pecos River Valley.

L1-1f Nontectonic Processes and Features

Halite in evaporite sequences is relatively plastic, which can lead to the process of deformation; it is also highly soluble, which can lead to the process of dissolution. Both processes (deformation and dissolution) can develop structural features similar to those developed by tectonic processes. The features developed by dissolution and deformation can be distinguished from similar-looking tectonic features where the underlying units do not reflect the same feature as do the evaporites. Beds underlying areas of dissolved salt are not affected, but overlying units to the surface may be affected. As an example, evaporite deformation can commonly be shown not to affect the underlying Bell Canyon. The deformation also tends to die out in overlying units, and the Rustler or the Dewey Lake may show little, if any, of the effects of the deformed evaporites.

L1-1f(1) Evaporite Deformation

The most recent review of evaporite deformation in the northern Delaware Basin and original work to evaluate deformation is summarized here.

L1-1f(1)(a) Basic WIPP History of Deformation Investigations

Gravity-Driven Structure in the Castile Formation

This document describes the structural features in the Castile that are commonly attributed to gravity-driven deformation. In order to properly present this subject, the data will first be presented in a general historical overview. The known extent of deformation in the Castile, how these structures are likely to develop in the future, how well they can be predicted, and the potential impact law act of these structures on the WIPP will also be discussed. Apart from the general geological impact, the performance of the WIPP as it might be affected by such structures is not specifically assessed here.

Background Information

Parts of the Castile have been known for a number of years to be deformed. Cross sections of the basin geology through its margins have shown some evidence of deformation. Jones et al. (1973) provided a map of the isopachs of part of the Castile that clearly show much thicker portions in some of the areas along the northwestern to northern Delaware Basin, just inside the margin of the Capitan reef. Very little information was collated concerning deformation within the Delaware Basin prior to studies of the basin as a possible site for radioactive waste disposal.

Jones et al. (1973) is probably the most lucid early presentation of this information, although a dissertation by Snider (1966) and a paper by Anderson et al. (1972) also reflect thicker sections in some Castile units adjacent to the reef.

In 1975, SNL drilled a borehole, ERDA-6, at a site (Figure L1-19) that had been partially investigated by Oak Ridge National Laboratories (ORNL) during 1974. Two boreholes (AEC-7 and AEC-8) had been drilled in 1974 by ORNL. Formation boundaries and marker beds in ERDA-6 were structurally high compared to AEC-7 and AEC-8, and the degree of deformation increased downward. At about the 2,711-ft (826-m) depth, ERDA-6 began to produce pressurized brine and gas. The hole was eventually tested extensively to determine the nature and origin of the brine. Beds within the Castile were displaced structurally upward, apparently by hundreds of feet (Jones, 1981; Anderson and Powers, 1978), and some of the lower units may have actually pierced upper units (Anderson and Powers, 1978). Because of the desire for structurally uncomplicated units to simplify mining for a repository, the site under investigation at ERDA-6 was abandoned in 1975. In 1975-76 the current site was initially selected, and investigations were begun (Powers et al., 1978). As part of the selection criteria, a zone about 6 mi (10 km) wide inside the Capitan reef was avoided because it included known deformed Castile and Salado (Griswold, 1977). This is the first instance in which the site investigations were directly influenced by discovery of deformation in the Castile and the lower Salado.

The present site for the WIPP was selected and initially investigated in 1976 to determine if the desired characteristics for the preliminary site selection were present (Griswold, 1977; Powers et al.,1978). As the general criteria appeared to be met during this phase, the site and surrounding areas were characterized much more extensively and intensively beginning in 1977. Extensive new seismic reflection data were collected in 1977 and 1978 that began to reveal the deformed Castile north of the center of the site (Figure L1-20). Because the principal effect was that the good quality Castile seismic reflectors from the area south of the site center were "disturbed," the area to the north was dubbed the "disturbed zone" (DZ). It also became known as "the area of anomalous seismic reflectors," or the "zone of anomalous seismic reelection data." The boundary of the DZ was variously described as being from about 0.5 to 1 mi (0.8 to 1.6 km) north of the center of the site, depending on the criteria to define the DZ. Powers et al. (1978) generally defined the DZ as beginning about 1 mi (1.6 km) north of the site center, where the seismic reflector character was poor to uninterpretable or "anomalous" (Borns et al., 1983). About 0.5 mi (0.8 km) north of the site center, it appeared that beds within the Castile began to steepen in gradient, dipping to the south from a higher area to the north. The Environmental Evaluation Group (EEG) summarized various map limits to the DZ, including the area where the Castile dip begins to steepen (Neill et al., 1983). Borns et al. (1983) included two separate areas south of the site as part of the DZ-based seismic character.

The first new drillhole within the area encompassed by the DZ was WIPP-11, and it was located about 3 mi (5 km) north of the center of the WIPP site (Figure L1-19). Long and Associates (1977) examined proprietary petroleum company data in 1976, and they identified anomalous areas around the WIPP site, including the structural anomaly at the WIPP-11 location. Seismic reflection data acquired in 1977 indicated possible salt flowage within the Castile and a structure that could be similar to that at ERDA-6 (SNL and USGS, 1979). WIPP-11 was drilled early in 1978, demonstrating the extensive deformation within the Castile and extending upward into the Salado. WIPP-11 did not encounter any brine or gas flows.

Seismic reflection data acquired in 1977 not only showed a zone of steepened dip of the Castile north of the site center, it also showed a possible fault offsetting parts of the Salado and the Rustler. A series of five boreholes were planned to provide detailed information on the structure of the Rustler/Salado contact. Four boreholes (WIPP 18, 19, 21, and 22) were required to demonstrate that there was no detectable offset on that contact in the area interpreted from 1977 seismic reflection data (Figure L1-19). Later epochs (1978 and 1979) of seismic data in the same area, along with the drilling, continued to show generally poor resolution or uninterpretable data in the area of the DZ. These studies generally showed that the acoustic velocity of the upper section changes laterally, complicating further the interpretation of the deeper Castile structure. Through the WIPP 18-22 drilling program, the upper Salado and the Rustler were determined to be fundamentally undisturbed over the southern margin of the disturbed zone where the Castile appears to dip to the south (SNL and USGS, 1979).

The upper part of the Castile about 1 mi (1.6 km) north of the WIPP site center was interpreted to range from about 250 ft to as much as 400 ft (100 to 120 m) (SNL and D'Appolonia Consulting Engineers, 1982a) above the elevation of the top of the Castile at about the center of the WIPP site. WIPP-12 was located approximately 1 mi (1.6 km) north of the site center to test the amount the Castile was elevated (Figures L1-19 and L1-20). It was drilled late in 1978 to the top of the Castile and detected approximately 160 ft (50 m) of structural elevation compared to ERDA-9 and the center of the site (SNL and D'Appolonia Consulting Engineers, 1982a). The amount of disturbance of the Salado was not considered to be an impediment to underground development, although the underground storage facility was later reoriented away from this northern area to an area south of the site center. From drilling WIPP-12 and the WIPP 18-22 series, the southern margin of the DZ was considered to be much more gentle in structure, while the seismic character and WIPP-11 indicated much more severe deformation of the Castile further to the north.

Two additional phases of seismic reflection data were acquired in 1978 and 1979. These data mainly concerned the immediate site area (about 4 square mi [10 square km]) and the southern edge of the DZ. They indicated much the same problems and margins associated with the DZ from the 1977 data. The latest seismic data (1979) were principally acquired to facilitate construction and Site and Preliminary Design Validation (SPDV) activities. As the project moved into SPDV activities, the DZ was little investigated directly during the period from about late 1979 until mid-1981.

A microgravity survey of the site area was conducted to determine if the structure within the DZ could be partially resolved (Barrows et al., 1983; Barrows and Fett, 1985). The large differences in density of halite and anhydrite could cause detectable differences in the gravity field locally if the units were displaced and/or thickened relative to the surrounding areas. The microgravity survey covered an area of "normal" stratigraphy from south of the WIPP site center to the area of WIPP-11 (Figure L1-21). As interpreted (Barrows et al., 1983), the microgravity does not resolve the larger scale deformation within the Castile. Based on the interpretation of probable shallow disturbance of the gravity field, WIPP-14 and WIPP-34 were drilled about 2 mi (3 km) north and about 0.5 mi (0.8 km) east of the site center (Figure L1-19). These boreholes encountered normal stratigraphy within the Rustler and upper Salado (SNL and D'Appolonia Consulting Engineers, 1982b; SNL and USGS, 1981), with some slight structural depression made apparent mainly by the deformation northeast of this area around ERDA-6 (Holt and Powers, 1988). Barrows et al. (1983) attributed the gravity anomaly around WIPP-14 to decreased density within parts of the Rustler, mainly from the difference in density due to anhydrite versus gypsum in WIPP-14. The overall difference in mass was attributed to karst processes by Barrows et al. (1983) rather than to deformation of any of the units associated with the DZ.

During the mapping of the first shaft drilled at the WIPP site (the Salt Handling Shaft), Marker Bed 139 was observed to have a few inches of relief on the basal contact and 2 to 3 ft (0.6 to 0.9 m) of relief on the upper surface. Jarolimek et al. (1983) interpreted the internal structure on these high points of Marker Bed 139 as showing a radial structure due apparently to gypsum growth textures and subsequent crushing, indicating a fundamentally depositional origin to the relief rather than any structural disturbance related to the DZ. Borns and Shaffer (1985) conducted an investigation of additional cores and holes drilled through Marker Bed 139, as there was concern on the part of the EEG that the apparent structure was related to the DZ. Borns and Shaffer (1985) also concluded that the relief was not due to structural deformation, but instead, was due mainly to erosional processes that carved part of the relief found on the top of the Marker Bed. From either point of view, the difference in relief on the upper and basal contacts of Marker Bed 139, in such a thin unit, were convincing evidence that a form of tectonic deformation was not involved.

In late 1981, WIPP-12 was deepened to test for the possible presence of brine and/or pressurized gas within the structure in the Castile (D'Appolonia Consulting Engineers, 1982). The probability of producing brine/gas from WIPP-12 was considered reasonably low at the time, because most known pressurized brine/gas was associated with much more deformed units in the Castile at WIPP-12. Fractured anhydrite in the upper Castile did begin to yield pressurized brine and gas when intercepted late in 1981, and WIPP-12 and ERDA-6 were further tested. Later geophysical work (Earth Technology Corporation, 1987) suggests that the brine may underlie part of the WIPP facility, beyond the area usually included in the DZ. Though the DOE and the EEG agreed that the structure did not constitute a threat to health and safety, the proposed underground facilities were reoriented south of the site center, avoiding longer haulage and the slight structure encountered at the facility horizon. As a consequence of the deepening and testing of WIPP-12, the link between structure and pressurized brine and gas was strengthened.

The last direct investigation of the DZ was a by-product of another investigation. DOE-2 was drilled approximately 2 mi (3.2 km) north of the center of the WIPP site to investigate the origin of a modest depression on Marker Bed 124 (Griswold, 1977; Powers et al., 1978) that was detected in a core hole drilled by a potash company. DOE-2 was principally a test of the hypothesis that the depression was caused by ductile flow of halite in response to deep dissolution of halite by water from the Bell Canyon (Mercer et al., 1987). Halite layers in the lower Salado were thicker than usual, indicating that part of the sequence had not been dissolved, and the Castile was very deformed. The Castile stratigraphy was not normal; the second halite was apparently squeezed out of the area during deformation. The stratigraphy in DOE-2 is apparently the result of processes which caused the DZ and is not the result of any dissolution (Borns, 1987; Mercer et al., 1987).

The preceding paragraphs describe most of the direct investigations of the disturbed zone and place them in their historical context. In the following text, more of the specific features of the DZ will be described, interpreted, and discussed to indicate the significance of the structures and processes of formation for the WIPP.

Specific Features of the Disturbed Zone

The first specific feature of the DZ is its boundary. As discussed above, the different concepts of the boundary depend on ideas of where the Castile began to change and steepen its dip (about one-half mi [0.8 km] north of the site center) or where the seismic data became unreliable to uninterpretable. Borns et al. (1983) present one diagram (Figure L1-20) of the seismic time structure for the top of the Castile that illustrates the variously defined boundaries. The principal part of the disturbed zone is defined by a lobate area (Figure L1-20) shown as an "area of complex structure" where the seismic data are considered "ambiguous." The structurally deformed area clearly includes an area about halfway between boreholes WIPP-12 and ERDA-9, as well as a larger area to the northeast. The two-way travel time contoured on the map is a function of depth; as the seismic reflector is nearer the surface, the travel time to the reflector and back to the surface decreases. Thus, the areas enclosed with contours of smaller values should be interpreted as structurally higher. (The top of the Castile in WIPP-12 was 160 ft [50 m] higher than it is in ERDA-9.) The map was not directly converted to depth because the seismic reflection and borehole geophysical logging programs clearly demonstrate that there are also lateral velocity variations within the upper part of the rock section, especially within the Rustler and the Dewey Lake. These velocity variations cannot be extracted from the travel times adequately to permit converting the travel time to depth. Nonetheless, the map demonstrates the best general information about the extent of the DZ. The central and southern parts of the WIPP site area display relatively uniform seismic travel time structure, and nothing within the geological data contradicts that information to date.

The broad forms of the structures within the DZ are generally anticlinal and synclinal (Borns, 1987), although they are not necessarily regular shapes. The best known shape for part of the DZ is between WIPP-12 and ERDA-9, where seismic information and several drillholes constrain part of the interpretation of the stratigraphy. There the structure tends to be a gently dipping limb of an anticlinal structure. Most of the remaining shapes attributed to the Castile within the DZ or related areas are based on one drill hole or a few drill holes that somewhat constrain the interpretation of the structure. WIPP-11, WIPP-13, DOE-1, and ERDA-6 are all examples. A generalized cross section of the structure at ERDA-6 (Anderson and Powers, 1978) shows a piercement structure and a regular shape; the piercement is based on stratigraphic inferences, but the shape is fundamentally uncontrolled by closely spaced data. WIPP-11 and WIPP-12 are both believed to penetrate anticlinal forms, though the structure is only partially known from drilling and seismic reflection data. DOE-2 is believed to lie in a synclinal structure, and contacts on various units show a nested series of depressions in the upper Salado (Borns, 1987). There are too few drill holes into the Castile to reconstruct the detailed shapes of Castile structures. The seismic data are not well enough constrained to calculate depths to reflectors, and most reflectors are too "disturbed" to interpret in this area. The specific shapes of individual structures are unlikely to be defined in the near future.

Anderson and Powers (1978) contoured several structures within the Delaware Basin, including structures at Poker Lake at least grossly similar to ERDA-6. Borns and Shaffer (1985) reexamined the information from Poker Lake and concluded that the actual shape is poorly constrained. Outside of the area on the north side of the current WIPP site, the information available is too sparse to define the individual shapes of structural features on borehole data.

It is important to note that, to date, none of the structures are demonstrably associated with comparable structure on the underlying Delaware Mountain Group. Snyder (in Borns et al., 1983) does show an upthrown block (horst) through WIPP-11 on the top of the Bell Canyon that is based on his projection of the thickness of the lower Castile; WIPP-11 did not penetrate the complete Castile section. Other areas, such as the Poker Lake structures, may display some relief on the top of the Delaware Mountain Group, but Borns and Shaffer (1985) do not attribute the relief to faulting. They believe the relief existed before and during deposition of the overlying Castile units. The underlying units to the Castile are, for the most part, uninvolved in the structures displayed by the Castile.

Structure contour and isopach maps of the Salado and the Rustler over areas of the complicated Castile structure also show that the overlying units are successively less involved in the structure (e.g., Borns and Shaffer, 1985; Borns et al., 1983; Holt and Powers, 1988). Lower units that are thicker and deformed are overlain by units that are thinner and less structurally involved in the deformation. Under normal geological circumstances, e.g., dealing with a rock sequence of carbonates or siliciclastics, the deformation would be considered to be completed by the time of deposition of the lowermost undeformed rock unit. Here, within a much more plastic set of rocks, the same geological reasoning is of less value, as the rocks may compensate laterally for late deformation effects and produce the same results.

Borns (1983; 1987; Borns et al., 1983) has extensively examined the macroscopic to microscopic features from cores taken within the structurally deformed areas. These studies follow earlier, broader studies of macroscopic features from the "state line outcrop" (Kirkland and Anderson, 1970) and ERDA-6 (Anderson and Powers, 1978). Kirkland and Anderson (1970) reported that small-scale folding within the Castile outcrops is oriented consistently along the general north-south strike of beds in the Delaware Basin. From this they concluded that the deformation was related to tilt of the basin, generally believed to be Cenozoic in age (e.g., Anderson, 1978; King, 1948; Borns et al., 1983), although authors differ in opinions on when this took place by tens of millions of years. Anderson and Powers (1978) used this apparent relationship to estimate that folding at ERDA-6 took place after the tilt of the basin. Jones (1981) estimated that deformation took place before the Ogallala was deposited because that unit is undeformed at the location of ERDA-6. Bachman (1980) and Madsen and Raup (1988) are among investigators who interpret angular relationships between various formations of the Ochoan Series, beginning with the Castile/Salado contact. These relationships require tilting of the existing beds to the east, as the angular unconformities are always placed on the western side of the basin. Tilting of the basin may well have occurred through much of the time when the Ochoan Series was being deposited, as Holt and Powers (1988) present evidence that the depocenter for the Rustler was displaced eastward from the Castile and the Salado patterns and overlies part of the Capitan reef on the northeastern side of the Delaware Basin. The Delaware Basin appears to have tilted at various times from the late Permian to at least the Cenozoic, and the conditions for deformation may well have existed since the late Permian. Direct evidence of the time of affirmation has been difficult to obtain, and tilting of the basin, as a condition for the deformation, appears to have occurred at times beginning in the late Permian. Jones (1981) argues that the structure at ERDA-6 must be in part younger than Triassic because Triassic rocks are also deformed over the deformed evaporates, and that the structure must be older than late Cenozoic because the Ogallala over part of the structure is undeformed and erosionally truncates the upper part of the Triassic rocks. This may be the most conclusive age relationship demonstrated for any of these related structures. Conventional relationships with beds overlying deformed evaporites, such as that cited by Jones (1981) for the Ogallala, are suspect if the deformation ends or dies out vertically within the evaporites because of the potential for compensating deformation in evaporates (e.g., Borns, 1983).

Borns (1983, 1987) reexamined the "state line outcrop" as well as the cores from various boreholes and concluded that the styles of deformation present in these cores indicate a very complicated history, including episodes of deformation that are probably synsedimentary. The folding may, for example, display disharmonic or opposing styles that would not normally be attributed to a single episode of strain in a pervasive stress field. If the deformation all occurred in response to a single event such as the tilting of the Delaware Basin, the folds and other strain indicators should all have a common orientation. Isoclinal folding may occur very early, while asymmetric folding is often penetrative, indicating later time of origin. Fractures in more brittle units such as the Castile anhydrites are often very high-angle to vertical and are considered one of the late deformation features in cores. These fractures in the larger anticlinal structures of the DZ are apparently the proximate source of pressurized brines and gases. Borns (Borns and Shaffer, 1985; Borns, 1987) recognized that tilting of the basin, among other possible sources of stress, may have occurred at several different times and is not limited to a single Cenozoic event.

Hypotheses of Formation of Deformation in Castile

Several hypotheses have been advanced for the formation of the Castile structures in the DZ and other parts of the Delaware Basin (Borns et al., 1983). The five principal processes hypothesized as causes of the DZ are gravity foundering, dissolution, gravity sliding, gypsum dehydration, and depositional processes (Borns et al., 1983). Each of these hypotheses will be briefly summarized, though gravity foundering due to density differences between halite and anhydrite is considered the leading hypothesis (Borns, 1987).

Gravity foundering is based on the fact that anhydrite (about 181 pounds per cubic ft [lb/ft^3], or 2.9 grams per cubic centimeter [gm/cc]) is much more dense than halite (about 134 lb/ft^3 [2.15 gm/cc]). When anhydrite beds overlie halite, there is considerable potential for the anhydrite to sink and for the halite to rise. This potential exists throughout much of the Delaware Basin in the Castile. Mathematical and centrifuge models of similar systems confirm the potential for such deformation and even suggest that the rate of deformation is about 0.02 inch (in)/year (yr) (0.05 centimeters [cm]/yr) (Borns et al., 1983). At such a rate, the DZ could be inferred to have developed over about 700,000 years (Borns et al., 1983). The principal difficulty with this hypothesis is that there are large areas of the Delaware Basin that remain undeformed, though the stratigraphy is similar to that within the DZ. The potential for gravity foundering exists over most of the basin, yet only a small part actually manifests such deformation. A special condition, such as a localized higher water content or an anomalous distribution of water, is hypothesized to explain why deformation is localized despite the pervasive density inversion (Borns et al., 1983). The presence of pressurized brine and gas associated with some of these structures is at least consistent with this explanation.

Halite could potentially be removed from the evaporite section by dissolution and change the form of the evaporites. The density structure could be changed by removing salt near the surface, causing collapse and fill with sediment that is more dense than the removed salt (Anderson and Powers, 1978). Borns et al. (1983) reviewed some of the evidence that evaporites were deformed near surficial sinks and concluded that there was certainly some association but that the pattern of deformation did not match the shallow dissolution. If salt is dissolved from the lower Salado or the Castile, then overlying beds should deform in response to the removal of mass. DOE-2 was drilled to test that hypothesis. Recrystallized halite has been offered as evidence of the passage of fluids, but there appears to be no unique relationship between recrystallized halite and deformation. In addition, certain halite sections appear much overthickened, which is clearly not directly due to halite removal. These features indicate generally that the halite can be squeezed and will "move" laterally. The fact that the Rustler shows no discernable overall structural lowering over the DZ (Holt and Powers, 1988) suggests that neither the dissolution of the lower Salado nor the Castile is the origin of the deformation. The one area in which the Rustler is structurally affected is around ERDA-6, and there it is warped upward as noted by Jones (1981). Borns et al. (1983) do not believe that the Bell Canyon has been a source for brines in the Castile because of the chemistry (Lambert, 1978; 1983a) and the small volume.

Gravity sliding in the Delaware Basin could be driven by two physical situations: the general eastward dip and the dip off the Capitan reef and forereef into the basin. In contrast to the gravity foundering mechanism, where movement is dominantly vertical, gravity would result in sliding blocks moving mainly laterally as well as downslope in this mechanism. Some of the deformation is adjacent to the reef (Jones et al., 1973), lending some substance to the hypothesis that the reef-forereef slope and facies changes could cause such sliding. Some deformation is in somewhat isolated portions of the basin (e.g. Poker Lake) (Anderson and Powers, 1978; Borns and Shaffer, 1985), and these structures were originally interpreted to align along the strike of the basin

(Anderson and Powers, 1978). Borns and Shaffer (1985) conclude that the data do not uniquely support that interpretation, and these structures may or may not support the concept of gravity sliding within the basin. Borns et al. (1983) also concluded that the timing of the various structures is an important factor in evaluating this hypothesis. As discussed above, neither the age of the various structures nor the timing of the basin tilt are well constrained. If tilting of the basin is an important event in forming these structures, the various macro to microstructures should probably be consistently related. As in gravity foundering, much of the basin area has not reacted to what appears to be widespread similar stresses. Special circumstances, such as an anomalous distribution of water, may be necessary to overcome a threshold for deformation to occur.

In general, as temperature and pressure increase, gypsum dehydrates to form anhydrite and release free water. Borns et al. (1983) discuss the effects this process has in experiments that weaken the anhydrite. Borns et al. (1983) suggest, however, that a major difficulty with this hypothesis is that there should remain relics of the original gypsum within the sedimentary column; these are not observed. Borns et al. (1983) suggest that mostly anhydrite was deposited in the Castile, and as a consequence, the dehydration hypothesis has little observable support. More recently pseudomorphs after gypsum have been recorded in every major anhydrite of the Castile (Harwood and Kendall, 1988; Hovorka, 1988; Powers, unpublished data; SNL and D'Appolonia Consulting Engineers, 1982c). Gypsum certainly has been present in the Castile, though anhydrite cannot be dismissed as possibly an important primary mineral. Delicate forms of original gypsum crystals are sometimes preserved and pseudomorphed by anhydrite or halite. Each requires volume-for-volume replacement, probably through dissolution and crystallizing the replacement mineral. There are no observed fluid escape paths, and the gypsum may have been replaced very early in the sedimentary history. The additional major drawback to this hypothesis is that the process should be pervasive, while the deformation is localized. Special pleading for an additional factor is necessary in this process as in some other hypotheses.

Depositional or syndepositional processes have been invoked for some of the deformation in the Castile. Borns et al. (1983) list four main mechanisms that have been suggested: penecontemporaneous folding, resedimentation, slump blocks off of reef margins, and sedimentation on inclined surfaces. Penecontemporaneous folding requires consolidation of the units over relatively short times. Borns et al. (1983) also cite the lack of observed features that indicate the rocks were reexposed. Evaporite units in the Mediterranean contain resedimented material: turbidities, slumping, and mud flows with other clastic sediment. Borns et al. (1983) report that "the units of the WIPP area show little chaotic or clastic structures." They also apply the same argument of Kirkland and Anderson (1970) that the deformed units would have to be consolidated by the time of resedimentation.

In a more recent study of cores from the western part of the Delaware Basin, Robinson and Powers (1987) report a lobate unit of the resedimented Castile anhydrite clasts overlying both the lower anhydrite and halite of the Castile and underlying the second anhydrite. The apparently unconformable contact with both anhydrite 1 and halite 1 lies across the extension of the Huapache monocline, which appears to have been still active during the time part of the Castile was deposited. Polyclasts within some beds of this unit demonstrate that the original anhydrite was partially consolidated and that a unit of clasts was also at least partially consolidated to provide the polyclasts. These units were consolidated early between the time halite 1 was deposited and anhydrite began to be deposited.

In the rest of the basin there is no apparent interval between the end of the halite and beginning of the anhydrite deposition. The relationship clearly indicates that the western margin was an area of sulfate clast formation, deposition, and lithification over a very short interval of geologic time. Hovorka (1988) indicates that similar clastic deposits occur in cores from nearer the eastern margin of the Delaware Basin. Snider (1966) proposed much earlier that sedimentation caused anomalous thickness of Castile units near the basin margin, and Billo (1986) presented a similar conclusion. Neither reported any textural evidence to support their conclusions.

Clearly, Castile rock has been resedimented, but in the area where textural data are available, only modest deformation appears to be present (Robinson and Powers, 1987). At this time, there is little to suggest that such sedimentation resulted in the deformation in the DZ. There is also no direct evidence from the WIPP area that suggests slump blocks off of the reef margin moved into the area, causing deformation. The high inferred slopes of some of these structures argues strongly against sedimentation on inclined surfaces (Borns et al., 1983).

The concept that deformation was syndepositional or penecontemporaneous with deposition appears to mainly be driven by the fact that deformation decreases upward through successive units. Normal geologic reasoning would support penecontemporaneous deformation but does not take into account the rather plastic behavior of halite, allowing flow from over high areas to move halite into low areas. Overlying units, such as the Rustler, are made of much less plastic material and do not respond as the Salado does. The deformation appears to be compensated in overlying units through deposition.

Overall, both gravity-driven mechanisms require some special additional conditions restricting deformation to small areas though most of the basin appears to be equally susceptible. Dissolution permits a more localized effect, but there does not appear to be an overall loss of mass in these areas, and the chemistry of the fluids and hydrology of the units do not readily support the concept. Most of the syndepositional processes have no evidence to support them in the area of the DZ. The most favored hypothesis at the moment is gravity foundering, with a yet undetected anomalous distribution of fluid lowering the viscosity of halite locally to permit deformation.

Timing of Deformation

Most of the arguments about timing of deformation have already been discussed. Standard geologic arguments about relative timing, based on involvement of the overlying units, is unlikely to hold for the evaporite units. Jones (1981) notes that uplifted and arched Triassic rocks near the ERDA-6 borehole are truncated by the flat-lying, undeformed Pliocene Ogallala. This was interpreted as an indication that salt movement was complete before deposition of the Ogallala (Jones, 1981). However, he does not explain either how the Triassic structure relates to the deeper DZ or how it is distinguished from near surface dissolution effects (Borns et al., 1983). The Castile rocks may have been deformed during any time period from Permian to the present. More to the point, for some hypotheses, the general conditions thought necessary to deform the Castile and the Salado are still present, and mechanisms such as gravity foundering are potentially active (Borns et al., 1983).

An additional piece of data is relevant. Brines from ERDA-6 and WIPP-12 were analyzed, and the brines were calculated to last have moved after about 800,000 years ago (Lambert and Carter, 1984; Barr et al., 1979). One set of reasonable assumptions about brine chemistry and interactions with the rock leads to calculated residence times of about 25,000 to 50,000 years for these brines. This may relate to the last time deformation was active on this structure, although it is not uniquely an indicator of deformation. The interaction between rock and water may have been strictly hydrologically driven and may not require deformation at that time.

The second point of interest is that some modeling calculations indicate, as stated above, that the kinds of structures observed in the DZ may require periods on the order of 700,000 years to form. There is no indication when the structures formed by this calculation, but it is relevant to timing and assessing how these structures might affect the WIPP.

Importance to the WIPP

The structures interpreted from core retrieved from WIPP-12 and ERDA-6 serve as possible analogs to effects of deformation on the WIPP. The DOE and the EEG have analyzed the effects of brine and structure at WIPP-12 and the southern portion of the site and have concluded that the geologic conditions represent no threat to health and safety. In addition, both boreholes encountered brine only within the anhydrite units, and that is the experience of all other encounters of these larger brine inflows (Popielak et al., 1983). Anhydrite supports the fractures that provide porosity for the brine, and the anhydrite/halite units form an effective seal, as the pressurized brines and gas did not escape upward. The principal concern for isolation would be that the deformation, and its associated phenomena such as pressurized brine and gas could cause breaching of the repository and provide or make a pathway for the escape of the waste constituents. The period of time expected for development of the structure (700,000 years) is well beyond periods of regulatory concern. In addition, the evidence of the pressurized brine and gas occurrences is that they are confined to these Castile anhydrite layers and do not breach the lower Salado to reach the stratigraphic level of the repository. There is nothing at present to indicate that these features will form in the time period of concern or that they can directly cause a breach of the repository.

L1-1f(2) Evaporite Dissolution

Because evaporites are much more soluble than most other rocks, project investigators have considered it important to understand the dissolution processes and rates that take place within any site considered for long-term isolation. These dissolution processes and rates constitute the limiting factor in any evaluation of the site. Over the course of the WIPP Project, extensive resources have been committed to identify and study a variety of features in southeastern New Mexico interpreted to have been caused by dissolution. The subsurface distribution of halite for various units has been mapped. Several different kinds of surface features have been attributed to dissolution of salt or karst formation. The processes proposed or identified include point-source (brecciation), "deep" dissolution, "shallow" dissolution, and karst. The categories are not well defined. Nonetheless, as discussed in the following sections, dissolution is not considered a threat to isolation of waste at the WIPP.

L1-1f(2)(a) Brief History of Project Studies

Well before the WIPP Project, several geologists recognized that dissolution is an important process in southeastern New Mexico and that it contributed to the subsurface distribution of halite and to the surficial features. A number of these are listed in the Bibliography to this addendum, including Lee (1925, pp. 107-121), Maley and Huffington (1953, pp. 539-546), and Olive (1957, pp. 351-358). Robinson and Lang identified an area in 1938 under the Nash Draw where brine occurred at about the stratigraphic position of the upper Salado/basal Rustler and considered that salt had been dissolved to produce a dissolution residue. Vine mapped the Nash Draw and surrounding areas, reporting in 1963 on various dissolution features. Vine (1963) reported surficial domal structures later called "breccia pipes" and identified as deep seated dissolution and collapse features.

As the USGS and ORNL began to survey southeastern New Mexico as an area in which to locate a repository site in salt, Brokaw et al. in 1972 prepared a summary of the geology that included solution and subsidence as significant processes in creating the features of southeastern New Mexico. Brokaw et al. (1972) recognized a solution residue at the top of salt in the Salado, and the unit commonly became known as the "brine aquifer" because it yielded brine in the Nash Draw area. Brokaw et al. (1972) interpreted the east-west decrease in thickness of the Rustler to be a consequence of removal of halite and other soluble minerals from the formation by dissolution.

During the early 1970s, the basic ideas about shallow dissolution of salt (generally from higher stratigraphic units and within a few hundred feet of the surface) were set out in a series of reports by Bachman, Jones, and collaborators. Piper independently evaluated the geological survey data for ORNL. Claiborne and Gera concluded that salt was being dissolved too slowly from the near-surface units to affect a repository for several million years, at least.

By 1978, shallower drilling around the WIPP site to evaluate potash resources was interpreted by Jones (1978, p. 9), who felt the Rustler included "dissolution debris, convergence of beds, and structural evidence for subsidence." Halite in the Rustler has been reevaluated by the DOE, but there are only minor differences in distribution among the various investigators, and these investigators have different explanations about how this distribution occurred (see previous section on the Rustler stratigraphy): through dissolution of the Rustler's halite after the Rustler was deposited or through syndepositional dissolution of halite from saline mud flat environments during the Rustler deposition.

Under contract to SNL, Anderson, in work reported in 1978, reevaluated halite distribution in deeper units, especially the Castile and the Salado. He identified local anomalies proposed as features developed after dissolution of halite by water circulating upward from the underlying Bell Canyon. In response to Anderson's developing concepts, ERDA-10 was drilled south of the WIPP area during the latter part of 1977. ERDA-10 is interpreted to have intercepted a stratigraphic sequence without evidence of solution residues in the upper Castile. Anderson mapped geophysical log signatures of the Castile and interpreted lateral thinning and change from halite to nonhalite lithology as evidence of lateral dissolution of deeper units (part of "deep dissolution"). Anderson (1978) considered that deep dissolution might threaten the WIPP site.

A set of annular or ring fractures is evident in the surface around the San Simon Sink, about 18 mi (30 km) east of the WIPP site. Nicholson and Clebsch (1961, p. 14) suggested that San Simon Sink developed as a result of deep-seated collapse. WIPP-15 was drilled at about the center of the sink to a depth of 811 ft (245 m) to obtain samples for paleoclimatic data and stratigraphic data to interpret collapse. Anderson and Bachman both interpret San Simon Sink as dissolution and collapse features, and the annular fractures are not considered evidence of tectonic activity.

Following the work by Anderson, Bachman mapped surficial features in the Pecos Valley, especially at the Nash Draw, and differentiated between those surface features in the basin that were formed by karst and deep collapse features over the Capitan reef. WIPP-32, WIPP-33, and two boreholes over the Capitan reef were eventually drilled. Their data, which demonstrated the concepts proposed by Bachman, are documented in Snyder and Gard (1982, p. 65).

A final program concerning dissolution and karst was initiated following a microgravity survey of a portion of the site during 1980. Based on localized low-gravity anomalies, Barrows et al., in 1983 interpreted several areas within the site as locations of karst. WIPP-14 was drilled during 1981 at a low-gravity anomaly. It revealed normal stratigraphy through the zones previously alleged to be affected by karst. As a follow-up in 1985, Bachman also reexamined surface features around the WIPP and concluded there was no evidence for active karst within the WIPP site. The nearest karst feature is northwest of the site boundaries at WIPP-33 and is considered inactive.

L1-1f(2)(b) Extent of Dissolution

Within the Rustler, dissolution of halite is believed to have occurred only near the depositional margins.

Upper intervals of the Salado thin dramatically west and south of the WIPP site (Figures L1-22 and L1-23) compared to deeper Salado intervals (Figure L1-24). There are no cores for further consideration of possible depositional variations. As a consequence, this margin is interpreted as the edge of dissolution of the upper Salado.

General margins of halite for the Castile are well west of the WIPP site and are generally accepted. Although Robinson and Powers (1987, pp. 69-79) question the volume of salt that may have been dissolved from the Castile, the general boundaries are not disputed.

L1-1f(2)(c) Timing of Dissolution

The dissolution of Ochoan-Epoch evaporites through the near-surface processes of weathering and groundwater recharge has been studied extensively (Anderson, 1981, pp. 133-145; Lambert, 1983a; Lambert, 1983b, pp. 291-298; Bachman, 1984, pp. 1-22; see also Holt and Powers, 1988). The work of Lambert (1983a) was specifically mandated by the DOE's agreement with the State of

New Mexico in order to evaluate, in detail, the conceptual models of evaporite dissolution proposed by Anderson (1981, pp. 133-145). There was no clear consensus of the volume of rock salt removed. Hence, estimates of the instantaneous rate of dissolution vary significantly. Dissolution may have taken place as early as the Ochoan, during or shortly after deposition. For the Delaware Basin as a whole, Anderson (1981, pp. 133-145) proposed that up to 40 percent of the rock salt in the Castile and the Salado was dissolved during the past 600 thousand years ago (ka). Lambert (1983b, pp. 291-298) suggested that in many places the variations in salt-bed thicknesses inferred from borehole geophysical logs that were the basis for Anderson's (1981) calculation were depositional in origin, compensated by thickening of adjacent nonhalite beds, and were not associated with the characteristic dissolution residues. Borns and Shaffer also suggested in 1985 a depositional origin for many apparent structural features attributed to dissolution.

Snyder (1985, pp. 85-229), as do earlier workers (e.g., Vine, 1963; Lambert, 1983b, pp. 291-298; Bachman, 1984, pp. 1-22), attributes the variations in thickness in the Rustler, which crops out in the Nash Draw, to post-depositional evaporite dissolution. Holt and Powers (1988, pp. 7-1 to 7-27) have challenged this view and attribute the east-to-west thinning of salt beds in the Rustler to depositional facies variability rather than post-depositional dissolution. Bachman (1974, pp. 74-194; 1976, pp. 135-144; 1980, pp. 80-109) envisioned several episodes of dissolution since the Triassic, each dominated by greater degrees of evaporite exhumation and a wetter climate, interspersed with episodes of evaporite burial and/or a drier climate. Evidence for dissolution after deposition of the Salado and before deposition of the Rustler along the western part of the Basin was cited by Adams (1944, pp. 1596-1625). Others have argued that the evaporites in the Delaware Basin were above sea level and therefore subject to dissolution during the Triassic, Jurassic, Tertiary, and Quaternary periods. Because of discontinuous deposition, not all of these times are separable in the geological record of southeastern New Mexico. Bachman (1984) contends that dissolution was episodic during the past 225 million years as a function of regional base level, climate, and overburden.

Some investigators have reasoned that wetter climate accelerated the dissolution. Various estimates of middle Pleistocene climatic conditions have indicated that climate was more moist during the time of the Gatuña than during the Holocene. An example of evidence of mass loss from dissolution since Mescalero time (approximately 500 ka) is found in displacements of the Mescalero caliche as large as 180 ft (55 m) in collapse features in the Nash Draw. However, given the variations in Pleistocene climate, it is unrealistic to apply a calculated average rate of dissolution, determined over 500 ka, to shorter periods, much less extrapolate such a rate into the geological future.

There have been several attempts to estimate the rates of dissolution in the basin. Bachman provided initial estimates of dissolution rates in 1974 based on a reconstruction of the Nash Draw relationships. Although these rates do not pose a threat to the WIPP, Bachman later reconsidered the Nash Draw relationships and concluded that pre-Cenozoic dissolution had also contributed to salt removal. Thus the initial estimated rates were too high. Anderson concluded in 1978 that the integrity of the WIPP to isolate radioactive waste would not be jeopardized by dissolution within about 1 million years. Anderson and Kirkland (1980, pp. 66-69) expanded on the concept of brine-density flow proposed by Anderson in 1978 as a means of dissolving evaporites at a point by circulating water from the underlying Bell Canyon. Wood et al. (1982) examined the mechanism and concluded that, while it was physically feasible, it would not be effective enough in removing salt to threaten the ability of the WIPP to isolate TRU waste.

There is local evidence of Cenozoic dissolution taking place at the same time that part of the Gatuña was being deposited in the Pierce Canyon area. Nonetheless, there is no indicator that the rates of dissolution in the Delaware Basin are sufficient to affect the ability of the WIPP to isolate TRU waste.

L1-1f(2)(d) Features Related to Dissolution

Bachman (1980, p. 97) separated breccia pipes, formed over the Capitan reef by dissolution and collapse of a cylindrical mass of rock, from evaporite karst features that appear similar to breccia pipes. There are surficial features, including sinks and caves, in large areas of the basin. The Nash Draw is the result of combined dissolution and erosion. Within the site boundaries, there are no known surficial features due to dissolution or karst.

The subsurface structure of the Culebra is shown in Figure L1-25. South of the WIPP site, an antiformal structure informally called the “Remuda Basin anticline” has been created by dissolution of salt from the underlying Salado to the southwest of the anticline. Beds generally dip to the east, and salt removed to the west created the other limb of the structure. Units below the evaporites apparently do not show the same structure.

L1-2 Surface-Water and Groundwater Hydrology

The DOE believes the hydrological characteristics of the disposal system require evaluation to determine if contaminant transport via fluid flow is a pathway of concern. At the WIPP site, one of the DOE's selection criteria was to choose a location that would minimize fluid-related impacts. This was accomplished when the DOE selected: 1) a disposal medium that contains very small quantities of groundwater, 2) a location where the effects of groundwater circulation on the disposal system are limited and reasonably predictable, 3) an area where groundwater use is very limited, 4) an area where there are no surface waters, 5) an area where future groundwater use is unlikely, and 6) a repository host rock that will not likely be affected by anticipated long-term climate changes possible within 10,000 years.

The following discussion summarizes the characteristics of the groundwater and surface water at and around the WIPP site. This summary is based on data-collection programs that were initiated at the inception of the WIPP program and which continue to some extent today. These programs have several purposes as follows:

- To provide sufficient information to develop predictive models of the groundwater movement within the vicinity of the WIPP site

- To collect data to evaluate the predictive models and to adapt them to the specific conditions of the WIPP site

- To develop an understanding of the surface water characteristics and the interaction between surface waters and groundwater

- To develop predictive models of the interaction between surface water and groundwater during reasonably expected climate changes.

In order to provide a comprehensive understanding of the impact of groundwater and surface water on the disposal system, the following relevant factors have been evaluated:

- Groundwater

  - General flow direction
  - Flow type
  - Horizontal and vertical flow velocities
  - Hydraulic interconnectivity between rock units
  - General groundwater use
  - Chemistry (including, but not limited to, salinity, mineralization, age, Eh, and pH)

- Surface Water

  - Regional precipitation and evapotranspiration rates
  - Location and size of surface-water bodies
  - Water volume, flow rate, and direction
  - Drainage network
  - Hydraulic connection with groundwater
  - Soil hydraulic properties (infiltration)
  - General water chemistry and use

For the purposes of groundwater modeling, the hydrological system is divided into three segments. These are 1) the Salado, which for the most part concerns the undisturbed performance of the disposal system; 2) the non-Salado rock units, which essentially are impacted by the disturbed (human intrusion) performance of the disposal system; and 3) the surface waters, which are impacted by the natural variability of the climate.

The WIPP site lies within the Pecos River drainage area (Figure L1-26). The climate is semiarid, with a mean annual precipitation of about 12 in. (0.3 m), a mean annual runoff of from 0.1 to 0.2 in. (2.5 to 5 millimeters [mm]), and a mean annual pan evaporation of more than 100 in. (2.5 m). Brackish water with total dissolved solids (TDS) concentrations of more than 3,000 parts per million (ppm) is common in the shallow wells near the WIPP site. Surface waters (Section 1.2.2) typically have high TDS concentrations, particularly of chloride, sulfate, sodium, magnesium, and calcium (Appendix D4).

At the WIPP site, the DOE obtains hydrologic data from conventional and special-purpose test configurations in multiple surface and underground boreholes. (Figure L1-2 is a map of surface borehole locations.) Geophysical logging of the surface boreholes has provided hydrologic information on the rock strata intercepted. Pressure measurements, fluid samples, and ranges of rock permeability have been obtained for selected formations through the use of standard and modified drill-stem and packer tests. Slug injection or withdrawal and tracer tests have provided additional data to aid in the estimation of transmissivity and storage of several water-bearing units. Also, the hydraulic head of groundwaters within many water-bearing zones in the region has been mapped from measured depths to water and fluid pressure measurements in the surface boreholes.

Historically, the DOE has obtained hydrological data principally from a conventional well-monitoring network comprising 71 wells located on 45 separate well pads (DOE 2003). Most of the 71 wells are completed only to a single hydrologic unit; however, six are multiple-completions to allow monitoring of two or more units in the same well. Hydrologic information (such as hydraulic head) is obtained at 80 completion intervals within the 71 wells. The focus of the hydrological monitoring is the Rustler (comprising 72 of the 80 monitored intervals) because this formation contains two of the most transmissive saturated units, the Culebra and Magenta, which are important to the modeling of releases during various human intrusion scenarios. Limited hydrological monitoring of the Bell Canyon, Dewey Lake, and Santa Rosa also occurs.

L1-2a Groundwater Hydrology

Rock units that are important to WIPP hydrology are the Bell Canyon of the Delaware Mountain Group, the Castile, the Salado, the Rustler, the Dewey Lake, and the Santa Rosa (or Dockum Group) (Figures L1-27 and L1-28). Of these rock units, the Castile and the Salado are defined as aquitards (nonwater-transmitting layers of rock that bound an aquifer).

The Bell Canyon is of interest to the DOE because it is the first regionally continuous water-bearing unit beneath the WIPP. The Castile provides a hydrologic barrier underlying the Salado, though it may contain isolated occurrences of pressurized brine.

The Culebra is the first laterally continuous unit located above the WIPP underground facility to display hydraulic conductivity sufficient to warrant concern over lateral contaminant transport. Barring a direct breach to the surface, the Culebra provides the most direct pathway between the WIPP underground and the accessible environment. The hydrology and fluid geochemistry of the Culebra are very complex and, as a result, have received a great deal of study in WIPP site characterization. (See for example LaVenue et al. (1988), Haug et al. (1987), and Siegel et al. (1991) in the Bibliography.)

At the site, the Dewey Lake is 60 ft (18 m) below the surface and about 490 ft (149 m) thick. These units appear to be mostly unsaturated hydrologically in the vicinity of the WIPP shafts and over the waste emplacement panels. However, since 1995, routine inspections of the WIPP exhaust shaft have revealed water entering the shaft at a depth of approximately 80 ft (24 m) at a location where no water had been observed during construction. The quantity and quality of water in the Dewey Lake is also monitored in a deeper fractured zone in the Dewey Lake at well WQSP-6a.

The Santa Rosa is shallow and unsaturated at the site (with the exception of a perched water table directly below the WIPP surface structures), and apparently receives recharge only through infiltration.

At the WIPP site, the DOE recognizes the Culebra and the Magenta of the Rustler as the most significant water-bearing units. The DOE's sampling and analysis of groundwater has focused on these two rock units, and the hydrologic background presented here is more detailed than for other rock units. The hydrologic properties of the interface between the Rustler and the Salado will also be discussed. Table L1-2 provides an overview of the hydrologic characteristics of the rock units of interest at the WIPP site and the Rustler/Salado contact zone.

L1-2a(1) Conceptual Models of Groundwater Flow

The DOE addresses issues related to groundwater flow within the context of a conceptual model of how the natural hydrologic system works on a large scale. The conceptual model of regional flow around the WIPP that is presented here is based on widely accepted concepts of regional groundwater flow in groundwater basins (see, for example, Hubbert 1940, Tóth 1963, and Freeze and Witherspoon 1967).

An idealized groundwater basin is a three-dimensional closed hydrologic unit bounded on the bottom by an impermeable rock unit (units with much smaller permeability than the units above), on the top by the ground surface, and on the sides by groundwater divides. The water table is the upper boundary of the region of saturated liquid flow. All rocks in the basin are expected to have finite permeability; in other words, hydraulic continuity exists throughout the basin. This means that the potential for liquid flow from any unit to any other units exists, although the existence of any particular flow path is dependent on a number of conditions related to gradients and permeabilities. All recharge to the basin is by infiltration of precipitation to the water table and all discharge from the basin is by flow across the water table to the land surface.

Differences in elevation of the water table across an idealized basin provide the driving force for groundwater flow. The pattern of groundwater flow depends on the lateral extent of the basin, the shape of the water table, and the heterogeneity of the permeability of the rocks in the basin. Water flows along gradients of hydraulic head from regions of high head to regions of low head. The highest and lowest heads in the basin occur at the water table at its highest and lowest points, respectively. Therefore, groundwater flows from the elevated regions of the water table, downward across confining layers (layers with relatively small permeability), then laterally along more conductive layers, and finally upward to exit the basin in regions where the water table (and by association, the land surface) is at low elevations. Recharge is necessary to maintain relief on the water table, without which flow does not occur.

Groundwater divides are boundaries across which it is assumed that no groundwater flow occurs. In general, these are located in areas where groundwater flow is dominantly downward (recharge areas) or where groundwater flow is upward (discharge areas). Topography and surface-water drainage patterns provide clues to the location of groundwater divides. Ridges between creeks and valleys may serve as recharge-type divides, and rivers, lakes, or topographic depressions may serve as discharge-type divides.

In the groundwater basin model, rocks can be classified into hydrostratigraphic units. A hydrostratigraphic unit is a continuous region of rock across which hydraulic properties are similar or vary within described or stated limits. The definition of hydrostratigraphic units is a practical exercise to separate rock regions with similar hydrologic characteristics from rock regions with dissimilar hydrologic characteristics. Although hydrostratigraphic units often are defined to be similar to stratigraphic units, this need not be the case. Hydrostratigraphic unit boundaries can reflect changes in hydraulic properties related to differences in composition, fracturing, dissolution, or a variety of other factors that may not be reflected in the definition of stratigraphic formations.

Confining layers in a groundwater basin model can be characterized as allowing vertical flow only. The amount of vertical flow occurring in a confining layer generally decreases in relation to the depth of the layer. Flow in conductive units is more complicated. In general, flow will be lateral through conductive units. The magnitude (in other words, volume flux) of lateral flow is related to the thickness, conductivity, and gradient present in the unit. Gradients generally decrease in deeper units. The direction of flow is generally related to the distance the unit is from the land surface. Near the land surface, flow directions are influenced primarily by the local slope of the land surface. In deeper conductive units, flow directions are generally oriented parallel to the direction between the highest and lowest points in a groundwater basin. Thus, flow rates, volumes, and directions in conductive units in a groundwater basin are generally not expected to be the same.

In the WIPP region, the Salado provides an extremely low-permeability layer that forms the base for a regional groundwater-flow basin in the overlying rocks of the Rustler, Dewey Lake, and Santa Rosa. The Castile and Salado together form their own groundwater system, and they separate flow in units above them from that in units below. Because of the plastic nature of halite and the resulting low permeability, fluid pressures in the evaporites are more related to lithostatic stress than to the shape of the water table in the overlying units, and regionally neither vertical nor horizontal flow will occur as a result of natural pressure gradients in time scales relevant to the disposal system. (On a repository scale, however, the excavations themselves create pressure gradients that may induce flow near the excavated region.) Consistent with the recognition of the Salado as the base of the groundwater basin of primary interest, the following discussion is divided into three sections: hydrology of units below the Salado, hydrology of the Salado, and hydrology of the units above the Salado.

L1-2a(2) Units Below the Salado

Units of interest to the WIPP project below the Salado are the Bell Canyon and the Castile. These units have quite different hydrologic characteristics. Because of its potential to contain brine reservoirs below the repository, the hydrology of the Castile is regarded as having the most potential of all units below the Salado to impact the performance of the disposal system.

L1-2a(2)(a) Hydrology of the Bell Canyon Formation

The Bell Canyon is considered for the purposes of regional groundwater flow to form a single hydrostratigraphic unit about 1,000 feet (300 meters) thick. Tests at five boreholes (AEC-7, AEC-8, ERDA-10, DOE-2, and Cabin Baby) indicate a range of hydraulic conductivities for the Bell Canyon from 5 x 10^{-2} feet per day to 1 x 10^{-6} feet per day (1.7 x 10^{-7} to 3.5 x 10^{-12} meters per second). The pressure measured in the Bell Canyon at the DOE-2 and Cabin Baby boreholes ranges from 12.6 to 13.3 megapascals (Mercer 1983, 29-31; DOE 1983, 4-9 to 4-12; Beauheim 1986, 61-71).

After recovery from well work in 1999, the Bell Canyon water levels at CB-1 have remained steady for more than three years at 919 m (3,015 ft) above mean sea level (SNL 2003a). In contrast, since the beginning of 1994, the Bell Canyon water levels at AEC-8 have steadily risen by more than 32 m (106 ft) at a rate of approximately 0.5 m/month (1.6 ft/month) and stood at over 933.4 m (3,062 ft) above mean sea level (SNL 2003a) at the end of 2002. This water-level rise is hypothesized to be the result of deterioration of the well and not a response to actual Bell Canyon hydrologic conditions at this location.

Fluid flow in the Bell Canyon is markedly influenced by the presence of the extremely low-permeability Castile and Salado above it, which effectively isolate it from interaction with overlying units except where the Castile is absent because of erosion or nondeposition, such as in the Guadalupe Mountains, or where the Capitan Reef is the overlying unit (Figures L1-27 and L1-28). Because of the isolating nature of the Castile and Salado, fluid flow directions in the Bell Canyon are sensitive only to gradients established over very long distances. At the WIPP, the brines in the Bell Canyon flow northeasterly under an estimated hydraulic gradient of 25 to 40 feet per mile (4.7 to 7.6 meters per kilometer) and discharge into the Capitan aquifer. Velocities are on the order of tenths of feet per year, and groundwater yields from wells in the Bell Canyon are 0.6 to 1.5 gallons (2.3 to 5.8 liters) per minute. The fact that flow directions in the Bell Canyon under the WIPP are inferred to be almost opposite to the flow directions in units above the Salado is not of concern because the presence of the Castile and Salado makes the flow in the Bell Canyon sensitive to gradients established over long distances, whereas flow in the units above the Salado is sensitive to gradients established by more local variations in water table elevation.

L1-2a(2)(b) Castile Hydrology

The Castile is dominated by low-permeability anhydrite and halite zones. However, fracturing in the upper anhydrite has generated isolated regions with much greater permeability than the surrounding intact anhydrite. These regions are located in the area of structural deformation. The higher-permeability regions of the Castile contain brine at pressures greater than hydrostatic and have been referred to as brine reservoirs. The fluid pressure measured by Popielak et al. in 1983 in the WIPP-12 borehole (12.7 [MPa]) is greater than the nominal hydrostatic pressure for a column of equivalent brine at that depth (11.1 MPa). Therefore, under open-hole conditions, brine could flow upward to the surface through a borehole.

Results of hydraulic tests performed in the ERDA-6 and WIPP-12 boreholes suggest that the extent of the highly permeable portions of the Castile is limited. The vast majority of brine is thought to be stored in low-permeability microfractures; about 5 percent of the overall brine volume is stored in large open fractures. The volumes of the ERDA-6 and WIPP-12 brine reservoirs were estimated by Popielak et al. in 1983 to be 3.5 x 10^6 cubic feet (100,000 cubic meters) and 9.5 x 10^6 cubic feet (270,000 cubic meters), respectively.

The origin of brine in the Castile has been investigated geochemically. Popielak et al. (1983, 5) concluded that the ratios of major and minor element concentrations in the brines indicate that these fluids originated from ancient seawater and that no evidence exist for fluid contribution from present meteoric waters. The Castile brine chemistries from the ERDA-6 and WIPP-12 reservoirs are distinctly different from each other and from local groundwaters. These geochemical data indicate that brine in reservoirs has not mixed to any significant extent with other waters and has not circulated. The brines are saturated, or nearly so, with respect to halite and, consequently, have little potential to dissolve halite.

L1-2a(2)(c) Hydrology of the Salado

The Salado consists mainly of halite and anhydrite. A considerable amount of information about the hydraulic properties of these rocks has been collected through field and laboratory experiments. Appendix D16 summarizes this information.

Hydraulic testing in the Salado in the WIPP underground provided quantitative estimates of the hydraulic properties controlling brine flow through the Salado. The tests are interpreted by Beauheim et al. in 1991 and 1993 using models based on potentiometric flow. The tests influence rock as far as 10 meters distant from the test zone and are not thought to significantly alter the pre-test conditions of the rock. The stratigraphic intervals tested include both pure and impure halite. Because tests close to the repository are within the disturbed rock zone (DRZ) that surrounds the excavated regions, it is reasonable to use the results of the tests farthest from the repository as most representative of undisturbed conditions.

Fifty-nine intervals were isolated and monitored and/or tested in 27 boreholes. Thirty-five of the intervals isolated halite beds, and 24 isolated anhydrite beds. Permeability estimates were obtained from 14 of the halite intervals and 16 of the anhydrite intervals. Interpreted permeabilities using a Darcy-flow model vary from 2×10^{-23} to 3×10^{-16} m^2 for impure halite intervals, with the lower values representing halite with few impurities and the higher values representing intervals within the DRZ of the excavations. Interpreted formation pore pressures vary from atmospheric to 9.8 megapascals (MPa) for impure halite, with the lower pressures believed to show effects of the DRZ. Tests in pure halite show no observable response, indicating either extremely low permeability ($<10^{-23}$ square meters), or no flow whatsoever, even though appreciable pressures are applied to the test interval. Appendix D16 contains a summary of the results of field permeability tests to date.

Interpreted permeabilities using a Darcy-flow model vary from 2 x 10^{-20} to 9 x 10^{-18} square meters for anhydrite intervals. Interpreted formation pore pressures vary from atmospheric to 14.8 MPa for anhydrite intervals (Beauheim and Roberts, 2002). Lower values are caused by depressurization near the excavation. The difference in maximum pressure between anhydrite and halite intervals is explained later in this section.

As discussed in Beauheim and Roberts (2002), permeabilities of some tested intervals have been found to be dependent on the pressures at which the tests were conducted, which is interpreted as the result of fracture apertures changing in response to changes in effective stress. Flow dimensions inferred from most test responses are subradial, meaning that flow to/from the test boreholes is not radially symmetric but is derived from a subset of the rock volume. The subradial flow dimensions are believed to reflect channeling of flow through fracture networks, or portions of fractures, that occupy a diminishing proportion of the radially available space, or through percolation networks that are not "saturated" (that is, fully interconnected). This is probably related to the directional nature of the permeability created or enhanced by excavation effects. Other test responses indicate flow dimensions between radial and spherical, which may reflect propagation of pressure transients above or below the plane of the test interval or into regions of increased permeability (e.g., closer to an excavation). The variable stress and pore-pressure fields around the WIPP excavations probably contribute to the observed non-radial flow dimensions.

The properties of anhydrite interbeds have also been investigated in the laboratory. Tests were performed on three groups of core samples from MB 139 as part of the Salado Two-Phase Flow Laboratory Program. The laboratory experiments provided porosity, intrinsic permeability, and capillary pressure data. Preliminary analysis of capillary pressure test results indicate a threshold pressure of less than 1 MPa. The laboratory-measured effective porosity and intrinsic permeability data are shown in Appendix D16.

Fluid pressure above hydrostatic is a hydrologic characteristic of the Salado (and the Castile) that plays a potentially important role in the repository behavior. It is difficult to accurately measure natural pressures in these formations because the boreholes or repository excavations required to access the rocks decrease the stress in the region measured. Stress released instantaneously decreases fluid pressure in the pores of the rock, so measured pressures must be considered as a lower bound of the natural pressures. Stress effects related to test location and the difficulty of making long-duration tests in lower-permeability rocks result in higher pore pressures observed to date in anhydrites. The highest observed pore pressure in halite-rich units, near Room Q, is on the order of 9 MPa, whereas the highest pore pressures observed in anhydrite are 12 MPa (Beauheim and Roberts, 2002). It is expected that the far-field pore pressures in halite-rich and anhydrite beds in the Salado at the repository level are similar because the anhydrites are too thin and of too low permeabilities to have liquid pressures much different than those of the surrounding salt. For comparison, the hydrostatic pressure for a column of brine at the depth of the repository is about 7 MPa, and the lithostatic pressure calculated from density measurements in ERDA-9 is about 15 MPa.

Fluid pressure in sedimentary basins that are much higher or much lower than hydrostatic are referred to as abnormal pressures by the petroleum industry, where they have received considerable attention. In the case of the Delaware Basin evaporites, the high pressures are almost certainly maintained because of the large compressibility and plastic nature of the halite and, to a lesser extent, the anhydrite. The lithostatic pressure at a particular horizon must be supported by a combination of the stress felt by both the rock matrix and the pore fluid. In highly deformable rocks, the portion of the stress that must be borne by the fluid exceeds hydrostatic pressure but cannot exceed lithostatic pressure.

Brine content within the Salado is estimated at 1 to 2 percent by weight, although the thin clay seams have been inferred by Deal et al. (1993) to contain up to 25 percent brine by weight. Brine in the Salado is likely Late Permian. This brine may move toward areas of low pressure, such as a borehole or mined section of the Salado.

Observation of the response of pore fluids in the Salado to changes in pressure boundary conditions at walls in the repository, in boreholes without packers, in packer-sealed boreholes, or in laboratory experiments is complicated by low permeability and low porosity. Qualitative data on brine flow to underground workings and exploratory boreholes have been collected routinely between 1985 and 1993 under the Brine Sampling and Evaluation Program (BSEP) and have been documented in a series of reports (Deal and Case 1987; Deal et al. 1987, 1989, 1991a, 1991b, 1993, and 1995). Additional data on brine inflow are available from the Large-Scale Brine Inflow Test (Room Q). Flow has been observed to move to walls in the repository, to boreholes without packers, and to packer-sealed boreholes. In certain cases, evidence for flow is no longer observed where it once was; in others, flow has begun where it once was not observed. In many cases, observations and experiments must last for months or years to obtain useful results. In part because of design requirements such as duration (the experimental period is short relative to the time required for the geological materials to fully respond), few quantitative data have been obtained for brine flow into the excavated region at atmospheric pressure. For performance assessment modeling, brine flow is a calculated term dependent on local pressure gradients and hydraulic properties of the Salado units. Data on pore pressure and permeability of halite and anhydrite layers are available from the Room Q test and other borehole tests (as summarized in Beauheim and Roberts, 2002), and these data form the basis for the quantification of the material properties used in the performance assessment. See Appendix D16 for additional discussions of the properties of the Salado.

L1-2a(3) Units Above the Salado

In evaluating groundwater flow above the Salado, the DOE considers the Rustler, Dewey Lake, Santa Rosa, and overlying units to form a groundwater basin with boundaries coinciding with selected groundwater divides as discussed in Section L1-2a(i). The boundary follows Nash Draw and the Pecos River valley to the west and south and the San Simon Swale to the east (Figure L1-29). The boundary continues up drainages and dissects topographic highs along its northern part. It is assumed that these boundaries represent groundwater divides whose positions remain fixed over the past several thousand years and 10,000 years into the future. For reasons described in Section L1-2a(1), the lower boundary of the groundwater basin is the upper surface of the Salado.

Nash Draw and the Pecos River are areas where discharge to the surface occurs. Hunter in 1985 described discharge at Surprise Spring and into saline lakes in Nash Draw. She reported groundwater discharge into the Pecos River between Avalon Dam north of Carlsbad and a point south of Malaga Bend as approximately 32.5 cubic feet per second (0.92 cubic meter per second), mostly in the region near Malaga Bend.

Within this groundwater basin, hydrostratigraphic units with relatively high permeability are called conductive units, and those with relatively low permeability are called confining layers. The confining layers consist of halite and anhydrite and are perhaps five orders of magnitude less permeable than conductive units.

In a groundwater basin, the position of the water table moves up and down in response to changes in recharge. The amount of recharge is generally a very small fraction of the amount of rainfall; this condition is expected for the WIPP. The water table would stabilize at a particular position if the pattern of recharge remained constant for a long time. The equilibrated position depends, in part, on the distribution of hydraulic conductivity in all hydrostratigraphic units in the groundwater basin. However, the position of the water table depends mainly on the topography and geometry of the groundwater basin and the hydraulic conductivity of the uppermost strata. The position of the water table adjusts to changes in recharge. Consequently, the water table can be at a position that is very much different from its equilibrium position at any given time. Generally, the water table drops very slowly in response to decreasing recharge but might rise rapidly in times of increasing recharge.

The asymmetry of response occurs because the rate at which the water table drops is limited by the rate at which water flows through the entire basin. In contrast, the rate at which the water table rises depends mainly on the recharge rate and the porosity of the uppermost strata. From groundwater basin modeling, the head distribution in the groundwater basin appears to equilibrate rapidly with the position of the water table.

The groundwater basin conceptual model described above has been implemented as a numerical model used to simulate the interactive nature of flow through conductive layers and confining units for a variety of possible rock properties and climate futures. Thus, this model has allowed insight into the magnitude of flow through various units.

One conclusion from the regional groundwater basin modeling is pertinent here. In general, vertical leakage through confining layers is directed downward over all of the area within the WIPP Site Boundary. This downward leakage uniformly over the WIPP site is the result of a well-developed discharge area, Nash Draw and the Pecos River, along the western and southern boundaries of the groundwater basin. This area acts as a drain for the laterally conductive units in the groundwater basin, causing most vertical leakage in the groundwater basin to occur in a downward direction. This conclusion is important in numerical modeling simplifications related to the relative importance of lateral flow in the Magenta versus the Culebra.

Public concern was expressed in 2004 as part of the WIPP recertification effort that groundwater flow to the spring supplying brine to Laguna Grande de la Sal could be related to the presence of karst features. Lorenz (2006a and 2006b) reviewed historical data and arguments on karst at the WIPP. Lorenz (2006b, p. 243) concludes that most of the geological evidence offered for the presence of karst in the subsurface at the WIPP site "has been used uncritically and out of context, and does not form a mutually supporting, scientifically defensible framework. . . . The remaining evidence is more readily interpreted as primary sedimentary features." Powers et al. (2006) provide new details on the gypsum karst present in the Rustler of Nash Draw. Powers (2006a) studies some of the natural brine lakes in Nash Draw, finding some of them to be fed by a shallow gypsum karst system with enough storage to sustain year-round flow, while others were fed by the potash-processing effluent discharged by Mosaic Potash Carlsbad into Laguna Uno. Powers (2006b) also maps closed catchment basins in the SW arm of Nash Draw that drain internally to karst features.

L1-2a(3)(a) Hydrology of the Rustler Formation

The Rustler is of particular importance for WIPP because it contains the most transmissive units above the repository. Fluid flow in the Rustler is characterized by very slow rates of vertical leakage through confining layers and faster lateral flow in conductive units. To illustrate this point, regional modeling with the groundwater basin model indicates that lateral specific discharges in the Culebra, for example, are perhaps two to three orders of magnitude greater than the vertical specific discharges across the top of the Culebra.

Because of its importance, the Rustler continues to be the focus of studies to understand better the complex relationship between hydrologic properties and geology, particularly in view of water-level rises observed in the Culebra and Magenta (e.g., SNL 2003a). An example of the complex nature of Rustler hydrology is the variation in Culebra transmissivity (T). Culebra T varies over three orders of magnitude on the WIPP site itself and over six orders of magnitude on the scale of the regional groundwater basin model with lower T east of the site and higher T west of the site in Nash Draw (e.g., Beauheim and Ruskauff 1998). As discussed below, site investigations and studies (e.g., Holt and Powers 1988; Beauheim and Holt 1990; Powers and Holt 1995; Holt 1997; Holt and Yarbrough 2002; Powers et al. 2003) suggest that the variability in Culebra T can be explained largely by the thickness of Culebra overburden, the location and extent of upper Salado dissolution, and the occurrence of halite in the mudstone units bounding the Culebra.

L1-2a(3)(a)(i) Los Medaños

The Los Medaños makes up a single hydrostratigraphic unit in WIPP models of the Rustler, although its composition varies somewhat. Overall, it acts as a confining layer. The basal interval of the Los Medaños, approximately 64 feet (20 m) thick, is composed of siltstone, mudstone, and claystone and contains the water-producing zones of the lowermost Rustler. Transmissivities of 2.7×10^{-4} square feet per day (2.9×10^{-10} square meters per second) and 2.2×10^{-4} square feet per day (2.4×10^{-10} square meters per second) were reported by Beauheim (1987a, 50) from tests at well H-16 that included this interval. The porosity of the Los Medaños was measured in 1995 as part of testing at the H-19 hydropad. Two claystone samples had effective porosities of 26.8 and 27.3 percent. One anhydrite sample had an effective porosity of 0.2 percent. These transmissivity values correspond to hydraulic conductivities of 4.2 x 10^{-6} feet per day (1.5 x 10^{-11} meters per second) and 3.4 x 10^{-6} feet per day (1.2 x 10^{-11} meters per second). Hydraulic conductivity in the lower portion of the Los Medaños is believed by the DOE to increase to the west in and near Nash Draw, where dissolution at the underlying Rustler-Salado contact has caused subsidence and fracturing of the sandstone and siltstone.

The remainder of the Los Medaños contains mudstones, anhydrite, and variable amounts of halite. The hydraulic conductivity of these lithologies is extremely low; tests of mudstones and claystones in the waste-handling shaft gave hydraulic conductivity values varying from 2 x 10^{-9} feet per day (6 x 10^{-15} meters per second) to 3 x 10^{-8} feet per day (1 x 10^{-13} meters per second) according to Saulnier and Avis (1988, 6–11).

The Los Medaños contains two mudstone layers: one in the middle of the Los Medaños and one immediately below the Culebra. An anhydrite layer separates the two mudstones. The lower and upper Los Medaños mudstones have been given the designations M1/H1 and M2/H2, respectively, by Holt and Powers (1988). This naming convention is used to indicate the presence of halite in the mudstone at some locations at and near the WIPP site. Powers (2002a) has mapped the margins delineating the occurrence of halite in both mudstone layers. Whereas early researchers (e.g., Snyder 1985) interpreted the absence of halite west of these margins as evidence of dissolution, Holt and Powers (1988) interpreted it as reflecting changes in the depositional environment, not dissolution. However, Holt and Powers (1988) concluded that dissolution of Rustler halite may have occurred along the present-day margins. The presence of halite in the Los Medaños mudstones is likely to affect the conductivity of the mudstones, but its greater importance is the implications it has for the conductivity of the Culebra. Culebra transmissivity in locations where halite is present in M2/H2 and M3/H3 (a mudstone in the lower Tamarisk Member of the Rustler) is assumed to be an order of magnitude lower than where halite does not occur (Holt and Yarbrough 2002).

Fluid pressures in the Los Medaños have been continuously measured at well H-16 since 1987. During this period, the fluid pressure has remained relatively constant at between 190 and 195 psi or a head of approximately 450 ft (137 m). Given the location of the pressure transducer, the current elevation of the Los Medaños water level at H-16 is approximately 949 m amsl. No other wells in the WIPP monitoring network are completed to the Los Medaños. Thus, H-16 provides the only current head information for this member.

L1-2a(3)(a)(ii) The Culebra

The Culebra is of interest because it is the most transmissive unit at the WIPP site, and hydrologic research has been concentrated on the unit for over a decade. Although it is relatively thin, it is an entire hydrostratigraphic unit in the WIPP hydrological conceptual model, and it is the most important conductive unit in this model.

The two primary types of field tests that are being used to characterize the flow and transport characteristics of the Culebra are hydraulic tests and tracer tests.

The hydraulic testing consists of pumping, injection, and slug testing of wells across the study area (e.g., Beauheim 1987a). The most detailed hydraulic test data exist for the WIPP hydropads (e.g., H-19). The hydropads generally comprise a network of three or more wells located within a few tens of meters of each other. Long-term pumping tests have been conducted at hydropads H-3, H-11, and H-19 and at well WIPP-13 (Beauheim 1987b, 1987c; Beauheim et al. 1995, Meigs et al, 2000). These pumping tests provided transient pressure data at the hydropad and over a much larger area. Tests often included use of automated data-acquisition systems, providing high-resolution (in both space and time) data sets. In addition to long-term pumping tests, slug tests and short-term pumping tests have been conducted at individual wells to provide pressure data that can be used to interpret the transmissivity at that well (Beauheim 1987a). (Additional short-term pumping tests have been conducted in the WQSP wells [Beauheim and Ruskauff, 1998]). Detailed cross-hole hydraulic testing has recently been conducted at the H-19 hydropad (Beauheim, 2000).

The hydraulic tests are designed to yield pressure data for the interpretation of such characteristics as transmissivity, permeability, and storativity. The pressure data from long-term pumping tests and the interpreted transmissivity values for individual wells are used for the generation of transmissivity fields in flow modeling. Some of the hydraulic test data and interpretations are also important for the interpretation of transport characteristics. For instance, the permeability values interpreted from the hydraulic tests at a given hydropad are needed for interpretations of tracer test data at that hydropad.

To evaluate transport properties of the Culebra, a series of tracer tests were conducted at six locations (the H-2, H-3, H-4, H-6, H-11, and H-19 hydropads) near the WIPP site. The first five of these tests consisted of both two-well dipole tests and multi-well convergent flow tests and are described in detail in Jones et al. (1992). A 1995 to 1996 tracer test program consists of single-well injection-withdrawal tests and multi-well convergent flow tests (Meigs and Beauheim, 2001). Unique features of this testing program include the injection of tracers into seven wells and the injection of tracer into an upper and a lower zone of Culebra at the H-19 hydropad, repeated injections under different convergent-flow pumping rates, and the use of tracers with different free-water diffusion coefficients at both the H-19 and H-11 hydropads. The 1995 to 1996 tracer tests were specifically designed to evaluate the importance of heterogeneity and diffusion on transport processes.

The Culebra is a fractured dolomite with nonuniform properties both horizontally and vertically. There are multiple scales of porosity (and permeability) within the Culebra, including fractures ranging from microscale to potentially large, vuggy zones, and inter-particle and intercrystalline porosity (Holt, 1997). Flow occurs within fractures, vuggy zones and probably to some extent in intergranular porosity. (In other words, flow occurs in response to hydraulic gradients in all places that are permeable). When the permeability contrast is large between different scales of connected porosity, transport processes can be distinguished as those occurring within advective porosity φ_a (typically referred to as fracture porosity) and those occurring within diffusional porosity φ_d (typically referred to as matrix porosity). Matrix porosity traditionally refers to inter- and intragranular porosity.

Diffusional (matrix) porosity in the Culebra may include other features such as microfractures and/or vugs. In some regions, the effective advective porosity of the Culebra is limited because a portion of the porosity has been partially or even almost totally filled by gypsum.

For the Culebra in the vicinity of the WIPP site, defining advective porosity is not a simple matter. Three regions with different types of advective porosity may be present: (1) regions with no open fractures, where matrix flow dominates and φ_a would refer to the connected matrix porosity; (2) regions with some open fractures, where advective flow occurs through matrix and fractures having permeabilities of similar magnitudes, where φ_a refers to some combination of the connected matrix porosity and the connected fracture porosity; and (3) regions with some large-aperture, open fractures with most advective flow in the fractures, where φ_a refers to the connected fracture porosity. It is thought that the dominant mode of advective transport may vary from location to location within the Culebra at the WIPP site.

The major physical transport processes that affect actinide transport through the Culebra include advection (through fractures and possibly other permeable porosity), matrix diffusion (between fractures and matrices [the matrix may include vugs and small fractures] or, more generally, diffusion between adjacent regions with large permeability contrasts), and dispersive spreading due to heterogeneity. For locations with advective transport occurring primarily within large-aperture fractures, the Culebra can most likely be considered to behave as a double-porosity medium (i.e., φ_a and φ_d are present).

Fluid flow in the Culebra is dominantly lateral and southward except in discharge areas along the west or south boundaries of the basin. Where transmissive fractures exist, flow is dominated by fractures but may also occur in vuggy zones and to some extent in intergranular porous regions. Regions where flow is dominantly through vuggy zones or intergranular porosity have been inferred from pumping tests and tracer tests. Flow in the Culebra may be concentrated along zones that are thinner than the total thickness of the Culebra. In general, the upper portion of the Culebra is massive dolomite with a few fractures and vugs, and appears to have low permeability. The lower portion of the Culebra appears to have many more vuggy and fractured zones and to have a significantly higher permeability.

There is strong evidence that the permeability of the Culebra varies spatially and varies sufficiently that it cannot be characterized with a uniform value or range over the region of interest to the WIPP. The transmissivity of the Culebra varies spatially over six orders of magnitude from east to west in the vicinity of the WIPP (Figure L1-30). Over the site, Culebra transmissivity varies over three to four orders of magnitude. Figure L1-30 shows variation in transmissivity in the Culebra in the WIPP region. Transmissivities are from 1×10^{-3} square feet per day (1×10^{-9} square meters per second) at well P-18 east of the WIPP site to 1×10^{3} square feet per day (1×10^{-3} square meters per second) at well H-7 in Nash Draw.

Transmissivity variations in the Culebra are believed to be controlled by the relative abundance of open fractures rather than by primary (that is, depositional) features of the unit. Lateral variations in depositional environments were small within the mapped region, and primary features of the

Culebra show little map-scale spatial variability, according to Holt and Powers 1988. Direct measurements of the density of open fractures are not available from core samples because of incomplete recovery and fracturing during drilling, but observation of the relatively unfractured exposures in the WIPP shafts suggests that the density of open fractures in the Culebra decreases to the east.

Recent investigations have made a significant contribution to the understanding of the large variability observed for Culebra transmissivity (e.g., Holt and Powers 1988; Beauheim and Holt 1990; Powers and Holt 1995; Holt 1997; Holt and Yarbrough 2002; Powers et al. 2003). The spatial distribution of Culebra transmissivity is believed to be due strictly to deterministic post-depositional processes and geologic controls (Holt and Yarbrough 2002). The important geologic controls include Culebra overburden thickness, dissolution of the upper Salado, and the occurrence of halite in the mudstone Rustler units (M2/H2 and M3/H3) above and below the Culebra (Holt and Yarbrough 2002). Culebra transmissivity is inversely related to thickness of overburden because stress relief associated with erosion of overburden leads to fracturing and opening of preexisting fractures. Culebra transmissivity is high where dissolution of the upper Salado has occurred and the Culebra has subsided and fractured. Culebra transmissivity is observed to be low where halite is present in overlying and/or underlying mudstones. Presumably, high Culebra transmissivity leads to dissolution of nearby halite (if any). Hence, the presence of halite in mudstones above and/or below the Culebra can be taken as an indicator for low Culebra transmissivity.

Geochemical and radioisotope characteristics of the Culebra have been studied. There is considerable variation in groundwater geochemistry in the Culebra. The variation has been described in terms of different hydrogeochemical facies that can be mapped in the Culebra. A halite-rich hydrogeochemical facies exists in the region of the WIPP site and to the east, approximately corresponding to the regions in which halite exists in units above and below the Culebra, and in which a large portion of the Culebra fractures are gypsum filled. An anhydrite-rich hydrogeochemical facies exists west and south of the WIPP site, where there is relatively less halite in adjacent strata and where there are fewer gypsum-filled fractures. Radiogenic isotopic signatures suggest that the age of the groundwater in the Culebra is on the order of 10,000 years or more (see, for example, Lambert 1987, Lambert and Carter 1987, and Lambert and Harvey 1987).

The Culebra groundwater geochemistry studies continue. Culebra water quality is evaluated semiannually at six wells, three north (WQSP-1, WQSP-2, and WQSP-3) and three south (WQSP-4, WQSP-5, and WQSP-6) (WIPP MOC 1995) of the surface structures area (see Figure 2-3 for well locations). Five rounds of semiannual sampling of water quality completed before the first receipt of waste at the WIPP were used to establish the initial Culebra water-quality baseline for major ion species including Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{2-}, and HCO_3^{2-} (Crawley and Nagy 1998). In 2000, this baseline was expanded to include five additional rounds of sampling that were completed before first receipt of RCRA-regulated waste (IT Corporation 2000). Culebra water quality is extremely variable among the six sampling wells, For example, the Cl^- concentrations range from approximately 6,000 mg/L at WQSP-6 to 130,000 mg/L at WQSP-3

The radiogenic ages of the Culebra groundwater and the geochemical differences provide information potentially relevant to the groundwater flow directions and groundwater interaction with other units and are important constraints on conceptual models of groundwater flow. Previous conceptual models of the Culebra (see for example, Chapman 1986, Chapman 1988, LaVenue et al. 1990, and Siegel et al. 1991) have not been able to consistently relate the hydrogeochemical facies, radiogenic ages, and flow constraints (that is, transmissivity, boundary conditions, etc.) in the Culebra.

The groundwater basin modeling that has been conducted, although it did not model solute transport processes, provides flow fields that reasonably explain observed hydrogeochemical facies and radiogenic ages. The groundwater basin model combines and tests three fundamental processes: (1) it calculates vertical leakage, which may carry solutes into the Culebra; (2) it calculates lateral fluxes in the Culebra (directions as well as rates); and (3) it calculates a range of possible effects of climate change. The presence of the halite facies is explained by vertical leakage of solutes into the Culebra from the overlying halite-containing Tamarisk by advective or diffusive processes. Because lateral flow rates here are low, even slow rates of solute transport into the Culebra can result in high solute concentration. Vertical leakage occurs slowly over the entire model region, and thus the age of groundwater in the Culebra is old, consistent with radiogenic information. Lateral fluxes within the anhydrite zone are larger because of higher transmissivity, and where the halite and anhydrite facies regions converge, the halite facies signature is lost by dilution with relatively large quantities of anhydrite facies groundwater.

Groundwater levels in the Culebra in the WIPP region have been measured continuously in numerous wells. Water-level rises have been observed in the WIPP region and are attributed to causes discussed below. The extent of water-level rise observed at a particular well depends on several factors, but the proximity of the observation point to the cause of the water-level rise appears to be a primary factor. Beginning in 1989, a general long-term rise has been observed in both Culebra and Magenta water levels (Figure 2-36) over a broad area of the WIPP site including Nash Draw (SNL 2003a). This long-term rise was recognized, but was thought (outside of Nash Draw) to represent recovery from the accumulation of hydraulic tests that had occurred since the late 1970s and the effects of grouting around the WIPP shafts to limit leakage. Water levels in Nash Draw were thought to respond to changes in the volumes of potash mill effluent discharged into the draw (Silva 1996); however, correlation of these water levels with potash mine discharge cannot be proven because sufficient data on the timing and volumes of discharge are not available.

Hydrological investigations conducted from 2003 through 2007 provided a wealth of new information, some of it confirming long-held assumptions and others offering new insight into the hydrological system around the WIPP site. A Culebra monitoring-network optimization study was completed by McKenna (2004) to identify locations where new Culebra monitoring wells would be of greatest value and to identify wells that could be removed from the network with little loss of information. Eighteen new wells were completed, guided by the optimization study, geologic considerations, and/or unique opportunities. Seventeen wells were plugged and abandoned, and two others were transferred to the U.S. Bureau of Land Management.

The WIPP groundwater monitoring program has augmented monthly water-level measurements with continuous (nominally hourly) fluid-pressure measurements using downhole programmable TROLL® pressure gauges in all Culebra wells except for the Water Quality Sampling Program wells. The most significant new finding arising from the continuous measurements has been the observation of Culebra water-level responses to rainfall in Nash Draw. The Culebra has long been suspected of being unconfined in at least portions of Nash Draw because of dissolution of the upper Salado, subsidence and collapse of the overlying Rustler, and karst in Rustler gypsum units (Beauheim and Holt 1990). However, continuous monitoring with TROLL® gauges has provided the first direct evidence of Culebra water levels responding to rainfall. Furthermore, the rainfall-induced head changes originating in Nash Draw are now observed to propagate under Livingston Ridge and across the WIPP site over periods of days to months (Hillesheim, Hillesheim, and Toll 2007), explaining some of the changes in Culebra water levels. Other water-level changes that appear to occur quite suddenly can now be conclusively related to drilling of nearby oil and gas wells.

Extensive hydraulic testing has been performed in the new wells. This testing has involved both single-well tests, which provide information on local transmissivity and heterogeneity, and long-term (19 to 32 days) pumping tests that have created observable responses in wells up to 9.5 km (5.9 mi) away. The transmissivity values inferred from the single-well tests (Roberts 2006 and 2007) support the correlation between geologic conditions and Culebra transmissivity developed by Holt and Yarbrough (2002) and elucidated by Holt, Beauheim, and Powers (2005). The types of heterogeneities indicated by the diagnostic plots of the pumping-test data are consistent with the known spatial distribution of transmissivity in the Culebra. Mapping diffusivity values obtained from analysis of observation-well responses to pumping tests shows areas north, west, and south of the WIPP site connected by fractures, and also a wide area that includes a NE-to-SW swath across the middle part of the WIPP site where hydraulically significant fractures are absent (Beauheim 2007). This mapping, combined with the responses observed to the long-term SNL-14 pumping test, has confirmed the presence of a high-transmissivity (high-T) area extending from the SE quadrant of the WIPP site to at least 10 km (6 mi) to the south.

Combining the Culebra monitoring data with catchment basin mapping in southwestern Nash Draw and groundwater geochemistry data provides insight into Culebra recharge. While some of the water entering gypsum karst in Nash Draw discharges into brine ponds such as Laguna Cinco, some portion of it must come into hydraulic communication with the Culebra, at least locally, because Culebra wells in Nash Draw show water-level responses to major rainfall events. However, these responses do not mean that the precipitation reached the Culebra. Rather, they indicate that the Culebra cannot be completely confined, but must be in hydraulic communication with a water table in a higher unit that does receive direct recharge from precipitation. Some of this water must eventually reach the Culebra, where it is recognized as the low ionic strength, $CaSO_4$-dominated hydrochemical facies B, but it must first have spent a considerable period in the Rustler gypsum beds to have as high a total dissolved solids (TDS) as it does. As a further indication of the recharge's indirect nature, the water from SNL-16 (which is located within a small catchment basin in Nash Draw) does not fall in the domain of facies B, but is instead in the higher ionic strength facies C, even though SNL-16 shows a clear pressure response to major rainfall events. This shows conclusively that rainfall is not rapidly flushing the Culebra in this area (Domski and Beauheim 2008).

Lowry and Beauheim (2004 and 2005) conclude from two modeling studies that leakage from units above the Culebra through poorly plugged and abandoned boreholes is a plausible explanation for the long-term rise in water levels observed at and near the WIPP site. The Intrepid East tailings pile may well be the primary source of leaking water north of the WIPP site, while natural recharge where the Culebra is unconfined southwest of the site could provide the leaking water ascribed to a southern borehole by Lowry and Beauheim (2005). The studies showed that a physically reasonable amount of leakage through unconfirmed but realistic pathways is consistent with the observed rising water levels

Although Culebra heads have been rising, the head distribution in the Culebra (Figure L1-31) is consistent with groundwater basin modeling results indicating that the generalized directional flow of groundwater is north to south. However, caution should be used when making assumptions based on groundwater-level data alone. Studies in the Culebra have shown that fluid density variations in the Culebra can affect flow direction. One should also be aware that the fractured nature of the Culebra, coupled with variable fluid densities, can also cause localized flow patterns to differ from general flow patterns.

Inferences about vertical flow directions in the Culebra have been made from well data collected by the DOE. Beauheim (1987a) reported flow directions towards the Culebra from both the Los Medaños and the Magenta over the WIPP site, indicating that the Culebra acts as a drain for the units around it. This indication is consistent with results of groundwater basin modeling.

The conceptual model, referred to as the groundwater basin model, offers a three-dimensional approach to treatment of supra-Salado rock units, and assumes that vertical leakage (albeit very slow) occurs between rock units of the Rustler (where hydraulic gradients exist). Flow in the Culebra is considered transient, but is not expected to change significantly over the next 10,000 years. This differs from previous interpretations, wherein no flow was assumed between the Rustler units.

L1-2(a)(3)(a)(iii) The Tamarisk

The Tamarisk acts as a confining layer in the groundwater basin model. Attempts were made in two wells, H-14 and H-16, to test a 7.9-foot (2.4-meter) sequence of the Tamarisk that consists of claystone, mudstone, and siltstone overlain and underlain by anhydrite. Permeability was too low to measure in either well within the time allowed for testing; consequently, Beauheim (1987a, 108–110) estimated the transmissivity of the claystone sequence to be one or more orders of magnitude less than that of the tested interval in the Los Medaños (that is, less than approximately 2.5×10^{-5} square feet per day [2.7×10^{-11} square meters per second]). The porosity of the Tamarisk was measured in 1995 as part of testing at the H-19 hydropad. Two claystone samples had an effective porosity of 21.3 to 21.7 percent. Five anhydrite samples had effective porosities of 0.2 to 1.0 percent.

Fluid pressures in the Tamarisk have been measured continuously at well H-16 since 1987. From 1998 through 2002, the pressures increased approximately 20 psi, from 80 to 100 psi (185 to 230 ft of water), probably in a continuing recovery response to shaft grouting conducted in 1993 to reduce leakage. Given the location of the pressure transducer, the elevation of Tamarisk water level has increased from 2,950 to 2,995 ft amsl (899 to 913 m amsl) during this period. Currently, no other wells in the WIPP monitoring network are completed to the Tamarisk. Thus, H-16 provides the only information on Tamarisk head levels.

Similar to the Los Medaños, the Tamarisk includes a mudstone layer (M3/H3) that contains halite in some locations at and around the WIPP site. This layer is considered to be important because of the effect it has on the spatial distribution of transmissivity of the Culebra.

L1-2(a)(3)(a)(iv) The Magenta

The Magenta is a conductive hydrostratigraphic unit about 19 feet (6 meters) thick at the WIPP. The Magenta is saturated except near outcrops along Nash Draw, and hydraulic data are available from 22 wells, including seven wells recompleted to the Magenta between 1995 and 2002 (SNL, 2003a). According to Mercer (1983), transmissivity ranges over five orders of magnitude from 1×10^{-3} to 4×10^{2} square feet per day (1×10^{-9} to 4×10^{-4} square meters per second). A slug test performed in H-9c, a recompleted Magenta well, yielded a transmissivity of 0.56 ft^2/day (6×10^{-7} m^2/s), which is consistent with Mercer's findings (SNL 2003a). The porosity of the Magenta was measured in 1995 as part of testing at the H-19 hydropad (TerraTek, 1996). Four samples had effective porosities ranging from 2.7 to 25.2 percent.

The hydraulic transmissivities of the Magenta, based on sparse data, show a decrease from west to east, with slight indentations of the contours north and south of the WIPP that correspond to the topographic expression of Nash Draw. In most locations, the hydraulic conductivity of the Magenta is one to two orders of magnitude less than that of the Culebra. The Magenta does not have hydraulically significant fractures in the vicinity of the WIPP.

Based on Magenta water levels measured in the 1980s (Lappin et al, 1989) when a wide network of Magenta monitoring wells were used, the hydraulic gradient in the Magenta varies from 16 to 20 feet per mile (3 to 4 meters per kilometer) on the eastern side, steepening to about 32 feet per mile (6 meters per kilometer) along the western side near Nash Draw (see Figure L1-32).

Regional modeling using the groundwater basin model indicates that leakage occurs into the Magenta from the overlying Forty-niner and out of the Magenta downwards into the Tamarisk. Regional modeling also indicates that flow directions in the Magenta are dominantly westward, similar to the slope of the land surface in the immediate area of the WIPP. This flow direction is different than the dominant flow direction in the next underlying conductive unit, the Culebra. This difference is consistent with the groundwater basin conceptual model, in that flow in shallower units is expected to be more sensitive to local topography.

Inferences about vertical flow directions in the Magenta have been made from well data collected by the DOE. Beauheim (1987a, 137) reported flow directions downwards out of the Magenta over the WIPP site, consistent with results of groundwater basin modeling. However, Beauheim concluded that flow directions between the Forty-niner and Magenta would be upward in the three boreholes from which reliable pressure data are available for the Forty-niner (H-3, H-14, and H-16), which is not consistent with the results of groundwater modeling. This inconsistency may be the result of local heterogeneity in rock properties that affect flow on a scale that cannot be duplicated in regional modeling.

As is the case for the Culebra, groundwater elevations in the Magenta have changed over the period of observation. The pattern of changes is similar to that observed for the Culebra.

L1-2a(3)(a)(v) The Forty-niner

The Forty-niner is a confining hydrostratigraphic layer about 66 feet (20 meters) thick throughout the WIPP area and consists of low-permeability anhydrite and siltstone. Tests by Beauheim (1987a, pages 119-123) in H-14 and H-16 yielded transmissivities of about 3×10^{-2} to 7×10^{-2} square feet per day (3×10^{-8} to 8×10^{-6} square meters per second) and 5×10^{-3} to 6×10^{-3} square feet per day (3×10^{-9} to 6×10^{-9} square meters per second), respectively for the medial siltstone unit of the Forty-niner. Tests of the siltstone in H-3d provided transmissivity estimates of 3.8×10^{-9} to 4.8×10^{-9} m^2/s (3.5×10^{-3} to 4.5×10^{-3} ft^2/day) (Beauheim et al. 1991b, Table 5-1). The porosity of the Forty-niner was measured as part of testing at the H-19 hydropad (TerraTek 1996). Three claystone samples had effective porosities ranging from 9.1 to 24.0 percent. Four anhydrite samples had effective porosities ranging from 0.0 to 0.4 percent.

Fluid pressures in the Forty-niner have been measured continuously at well H-16,-approximately 13.9 m (45.6 ft) from the well of the Air Intake Shaft (AIS), since 1987. The pressures cycle in a sinusoidal fashion on an annual basis. These cycles correlate with cycles observed in rock bolt loads in the WIPP shafts (DOE 2002c), and presumably reflect seasonal temperature changes causing the rock around the shafts to expand and contract. From 1998 through 2002, the pressures have cycled between 40 and 70 psi (90 and 160 ft of fresh water). Given the location of the pressure transducer, the elevation of Forty-niner water level has varied between 2,950 to 3,020 ft (899 to 920 m) amsl during this period. Through April 2002, Forty-niner water levels were also measured monthly at H-3d as part of the WIPP groundwater monitoring program. Measurements were discontinued after April 2002 because of an obstruction in the well. The April 2002 Forty-niner water level elevation determined at H-3d was 3,092 ft (942 m) amsl. Differences in Forty-niner water levels at H-16 and H-3d are probably due, in part, to differences in the densities of the fluids in the wells. No other wells in the WIPP monitoring network are completed to the Forty-niner.

L1-2a(3)(b) Hydrology of the Dewey Lake and the Santa Rosa

The Dewey Lake and the Santa Rosa, and surficial soils, overlie the Rustler and are the uppermost hydrostratigraphic units considered by the DOE. The Dewey Lake and overlying rocks are more permeable than the anhydrites at the top of the Rustler. Consequently, basin modeling indicates that most (probably more than 70%) of the water that recharges the groundwater basin (that is, percolates into the Dewey Lake from surface water) flows only in the rocks above the Rustler. As modeled, the rest leaks vertically through the upper anhydrites of the Rustler and into the Magenta or continues downward to the Culebra. More flow occurs into the Rustler units at times of greater recharge. Even though it carries most of the recharge because of its low permeability in most areas, lateral flow in the Dewey Lake is slow.

A saturated, perched-water zone has been identified in the lower Santa Rosa directly below the operational area of the WIPP (DOE 1999; INTERA 1997a; INTERA 1997b; DES 1997). The zone occurred at a location that previously had been dry or only partially saturated.

L1-2a(3)(b)(i) The Dewey Lake

The Dewey Lake contains a productive zone of saturation, probably under water-table conditions, in the southwestern to south-central portion of the WIPP site and south of the site. Several wells operated by the J.C. Mills Ranch south of the WIPP site produce sufficient quantities of water from the Dewey Lake to supply livestock. Short-term production rates of 25 to 30 gallons per minute (5.7 to 6.8 cubic meters per hour) were observed in boreholes P-9 (Jones 1978, Vol. 1., 167 and 168), WQSP-6, and WQSP-6a. Based on a single hydraulic test conducted at WQSP-6a, Beauheim and Ruskauff (1998) estimated the transmissivity of a 24 ft (7 m) fractured section of the Dewey Lake at 360 ft^2/day (3.9 x 10^{-4} m^2/s).The productive zone is typically found in the middle of the Dewey Lake, 180 to 265 feet (55 to 81 meters) below ground surface and appears to derive much of its transmissivity from open fractures. Where present, the saturated zone may be perched or simply underlain by less transmissive rock. Fractures below the productive zone tend to be completely filled with gypsum. Open fractures and/or moist (but not fully saturated) conditions have been observed at similar depths north of the zone of saturation, at the H-1, H-2, and H-3 boreholes (Mercer 1983).

Under the groundwater monitoring program, water levels are measured in two Dewey Lake wells, WQSP-6a and H-3d, located south of the WIPP site center. Water levels in these two wells are currently 3,198 and 3,075 ft (975 and 937 m) amsl, respectively. Water levels at WQSP-6a remain relatively constant. Over the past several years, water levels at H-3d have risen about 1 ft/yr. Similar to the six Culebra WQSP wells (WQSP-1 through WQSP-6), Dewey Lake water quality is determined semiannually at WQSP-6a. Baseline concentrations for major ion species have also been determined from ten rounds of sampling. Major ion concentrations have been stable within the baseline for all rounds of sampling conducted through May 2009.

Powers (1997) suggests that what distinguishes the low-transmissivity lower Dewey Lake from the high-transmissivity upper Dewey Lake is a change in natural cements from carbonate (above) to sulfate (below). Resistivity logs correlate with this cement change and show a drop in porosity across the cement-change boundary. Similarly, porosity measurements made on eight core samples from the Dewey Lake from well H-19b4 showed a range from 14.9 to 24.8 percent for the four samples from above the cement change, and a range from 3.5 to 11.6 percent for the four samples from below the cement change (TerraTek 1996). In the vicinity of the surface structures area of the WIPP, Powers (1997) proposed the surface of the cement change is at a depth of approximately 50 to 55 m (165 to 180 ft), is irregular, and trends downward stratigraphically to the south and west of the site center.

During site characterization and initial construction of the WIPP shafts, ~~T~~ the Dewey Lake ~~has~~ did not produce~~d~~ water within the WIPP shafts or in boreholes in the immediate vicinity of the panels. However, since 1995, water has been observed leaking into the exhaust shaft at a depth of approximately 80 ft at the location of the Dewey Lake/ Santa Rosa contact (INTERA 1997a; INTERA 1997b). The water is interpreted to be from an anthropogenic source, including infiltration from WIPP rainfall-runoff retention ponds and the WIPP salt storage area and evaporation pond located at the surface. At the site center, thin cemented zones in the upper Dewey Lake retard, at least temporarily, downward infiltration of modern waters.

Saturation of the uppermost Dewey Lake was observed for the first time in 2001 as well C-2737 was being drilled (Powers 2002c). Well C-2811 was then installed nearby to monitor this zone (Powers and Stensrud 2003). Because of the proximity of these two wells to the WIPP surface structures area, and the absence of water at this horizon when earlier wells were drilled, the saturation is assumed to be an extension of the anthropogenic waters described in the following section.

Infiltration control measures installed since 2005 appear to be affecting the recharge in this zone (DBS 2008). For modeling purposes, the hydraulic conductivity of the Dewey Lake, assuming saturation, is estimated to be 10^{-8} m/sec (3×10^{-3} ft/day), corresponding to the hydraulic conductivity of fine-grained sandstone and siltstone (Davies 1989, p. 110). The porosity of the Dewey Lake was measured as part of testing at the H-19 hydropad. Four samples taken above the gypsum-sealed region had measured effective porosities of 14.9 to 24.8 percent. Four samples taken from within the gypsum-sealed region had porosities from 3.5 to 11.6 percent.

The groundwater basin conceptual model relies on gradients established from the position of the water table for the driving force for flow. The DOE has estimated the position of the water table in the southern half of the WIPP site from an analysis of drillers' logs from three potash exploration boreholes and five hydraulic test holes. These logs record the elevation of the first moist cuttings recovered during drilling. Assuming that the first recovery of moist cuttings indicates a minimum elevation of the water table, an estimate of the water table elevation can be made, and the estimated water table surface can be contoured. This method indicates that the elevation of the water table over the WIPP waste panels may be about 980 meters above sea level, as shown in Figure L1-33.

L1-2a(3)(b)(ii) <u>The Santa Rosa</u>

The Santa Rosa ranges from 0 to about 300 feet (0 to 91 meters) thick and is present over the eastern half of the WIPP site. It is absent over the western portion of the site. It crops out northeast of Nash Draw. The Santa Rosa near the WIPP site may have a saturated thickness of limited extent. It has a porosity of about 13 percent and a specific capacity of 0.14 to 0.20 gallons per minute per foot (0.029 to 0.041 liters per second per meter) of drawdown, where it yields water in the WIPP region.

In May 1995, a scheduled video inspection of the WIPP exhaust shaft revealed water emanating from cracks in the concrete liner at a depth of approximately 80 ft below the shaft collar. Because little or no groundwater had been encountered at this depth interval previously (Bechtel

1979; DOE 1983; Holt and Powers 1984, 1986), the DOE implemented a program in early 1996 to investigate the source and extent of the water. The program included installation of wells and piezometers, hydraulic testing (pumping tests), water-quality sampling and analysis, and water-level and precipitation monitoring (DOE 1999; INTERA 1997a; DES 1997; INTERA 1997b).

In the initial phases of the investigation, three wells (C-2505, C-2506, and C-2507) and 12 piezometers (PZ-1 through PZ-12) were installed within the surface structures area of the WIPP site (Figure L1-AA). The three wells were located near the exhaust shaft and completed to the Santa Rosa/Dewey Lake contact (approximately 50 ft below ground surface). Similarly, the piezometers were also completed to the Santa Rosa/Dewey Lake contact (approximately 55 to 75 ft below ground surface). All wells and piezometers, with the exception of PZ-8, encountered a saturated zone just above the Santa Rosa/Dewey Lake contact, but water did not appear to have percolated significantly into the Dewey Lake. PZ-8, the piezometer located farthest to the east in the study area, was a dry hole.

Subsequent to the well and piezometer installations, water-level, water-quality, and rainfall data were collected. In addition, hydraulic tests were performed to estimate hydrologic properties and water production rates. These data suggest that the water present in the Santa Rosa below the WIPP surface structures area represents an unconfined, water-bearing horizon perched on top of the Dewey Lake (DES 1997). Pressure data collected from instruments located in the exhaust shaft show no apparent hydrologic communication between the Santa Rosa and other formations located stratigraphically below the Santa Rosa.

A water-level-surface map of the Santa Rosa in the vicinity of the WIPP surface structures area indicates that a potentiometric high is located near the salt water evaporation pond and PZ-7 (Figure L1-AB). The water level at PZ-7 is approximately 1 m (3.3 ft) higher than the water levels in any other wells or piezometers. Water is presumed to move radially from this potentiometric high. The areal extent of the water is larger than the 80-acre investigative area shown in Figure 2-39 (DES 1997) as evidenced by drilling records of C-2737 (Powers 2002c) located outside of and south of the WIPP surface structures area that indicate a Santa Rosa/Dewey Lake perched-water horizon at a depth of approximately 18 m (60 ft). The study of this water is ongoing.

Water-quality data for the perched Santa Rosa waters are highly variable and appear to be dominated by two anthropogenic sources: (1) runoff of rainfall into and infiltration from the retention ponds located to the south of the WIPP surface facilities, and (2) infiltration of saline waters from the salt storage area, the salt storage evaporation pond, and perhaps remnants of the drilling and tailings pit used during the construction of the WIPP salt shaft. The total dissolved solids (TDS) in the perched water range from less than 3,000 mg/L at PZ-10 to more than 160,000 mg/L at PZ-3 (DES 1997). Concentration contours are known to shift with time. For example, the high-TDS zone centered at PZ-3 moved observably to the northeast toward PZ-9 between February 1997 and October 2000 (DOE 2002b).

Hydraulic tests (INTERA 1997a; DES 1997) conducted in the three wells and 12 piezometers indicate that the Santa Rosa behaves as a low-permeability, unconfined aquifer perched on the

Dewey Lake. Hydraulic conductivity ranges from 7.4×10^{-3} to 16 ft/day (2.6×10^{-8} to 5.5×10^{-5} m/s). The wells are capable of producing at rates of about 0.3 to 1.0 gpm. The estimated storativity value for the Santa Rosa is 1×10^{-2}.

L1-2a(4) Hydrology of Other Groundwater Zones of Regional Importance

The groundwater regimes in the Capitan Limestone, which is generally regarded as the northern boundary of the Delaware Basin, and Nash Draw have been evaluated by the DOE as part of the WIPP project because of their importance in some processes, notably dissolution features, that the DOE has determined to be of low probability at the WIPP site.

L1-2a(4)(a) The Capitan Limestone

The Capitan, which outcrops in the southern end of the Guadalupe Mountains, is a massive limestone unit that grades basinward into recemented, partly dolomitized reef breccia and shelfward into bedded carbonates and evaporites. A deeply incised submarine canyon near the Eddy-Lea county line has been identified. This canyon is filled with sediments of lower permeability than the Capitan and, according to Hiss (1976) restricts fluid flow. The hydraulic conductivity of the Capitan ranges from 1 to 25 feet per day (3×10^{-6} to 9×10^{-5} meters per second) in southern Lea County and is 5 feet per day (1.7×10^{-5} meters per second) east of the Pecos River at Carlsbad. Hiss reported in 1976 that average transmissivities around the northern and eastern margins of the Delaware Basin are 10,000 square feet per day (0.01 square meters per second) in thick sections and 500 square feet per day (5.4×10^{-4} square meters per second) in incised submarine canyons. Water table conditions are found in the Capitan aquifer southwest of the Pecos River at Carlsbad; however, artesian conditions exist to the north and east. The hydraulic gradient to the southeast of the submarine canyon near the Eddy-Lea county line has been affected by large oil field withdrawals. The Capitan limestone is recharged by percolation through the northern shelf aquifers, by flow from the south and west from underlying basin aquifers and by direct infiltration at its outcrop in the Guadalupe Mountains. The Capitan is important in the regional hydrology because breccia pipes in the Salado have formed over it, most likely in response to the effects of dissolution by groundwater flowing in the Castile along the base of the Salado (see Davies 1984).

L1-2a(4)(b) Hydrology of the Rustler-Salado Contact Zone in Nash Draw

In Nash Draw the contact between the Rustler and the Salado is an unstructured residuum of gypsum, clay, and sandstone created by the dissolution of halite and has been known as the brine aquifer, Rustler-Salado residuum, and residuum. The residuum is absent under the WIPP site. It is clear that dissolution in Nash Draw occurred after deposition of the Rustler. As described previously, the topographic low formed by Nash Draw is a groundwater divide in the groundwater basin conceptual model of the units above the Salado. The brine aquifer is shown in Figure L1-34.

Robinson and Lang described the brine aquifer in 1938 and suggested that the structural conditions that caused the development of Nash Draw might control the occurrence of the brine; thus, the brine aquifer boundary may coincide with the topographic surface expression of Nash Draw. Their studies show brine concentrated along a strip from 2 to 8 miles (3.3 to 13 kilometers) wide and about 26 miles (43 kilometers) long. Data from the test holes that Robinson and Lang drilled indicate that the residuum (containing the brine) ranges in thickness from 10 to 60 feet (3 to 18 meters) and averages about 24 feet (7 meters).

In 1954, hydraulic properties were determined by Hale et al., primarily for the area between Malaga Bend on the Pecos River and Laguna Grande de la Sal. They calculated a transmissivity value of 8,000 square feet per day (8.6×10^{-3} square meters per second) and estimated the potentiometric gradient to be 1.4 feet per mile (0.27 meter per kilometer). In this area, the Rustler-Salado residuum apparently is part of a continuous hydrologic system, as evidenced by the coincident fluctuation of water levels in the test holes (as far away as Laguna Grande de la Sal) with pumping rates in irrigation wells along the Pecos River.

In the northern half of Nash Draw, the approximate outline of the brine aquifer as described by Robinson and Lang in 1938 has been supported by drilling associated with the WIPP hydrogeologic studies. These studies also indicate that the main differences in areal extent occur along the eastern side where the boundary is very irregular and, in places (test holes P-14 and H-07), extends farther east than previously indicated by Robinson and Lang.

Other differences from the earlier studies include the variability in thickness of residuum present in test holes WIPP-25 through WIPP-29. These holes indicate thicknesses ranging from 11 feet (3.3 meters) in WIPP-25 to 108 feet (33 meters) in WIPP-29 in Nash Draw, compared to 8 feet (2.4 meters) in test hole P-14, east of Nash Draw. The specific geohydrologic mechanism that has caused dissolution to be greater in one area than in another is not apparent, although a general increase in chloride concentration in water from the north to the south may indicate the effects of movement down the natural hydraulic gradient in Nash Draw.

The average hydraulic gradient within the residuum in Nash Draw is about 10 feet per mile (1.9 meters per kilometer); in contrast, the average gradient at the WIPP site is 39 feet per mile (7.4 meters per kilometer). This difference reflects the changes in transmissivity, which are as much as five orders of magnitude greater in Nash Draw. The transmissivity determined from aquifer tests in test holes completed in the Rustler-Salado contact residuum of Nash Draw ranges from 2×10^{-4} square feet per day (2.1×10^{-10} square meters per second) at WIPP-27 to 8 square feet per day (8.6×10^{-6} square meters per second) at WIPP-29. This is in contrast to the WIPP site proper, where transmissivities range from 3×10^{-5} square feet per day (3.2×10^{-11} square meters per second) at test holes P-18 and H-5c to 5×10^{-2} square feet per day (5.4×10^{-8} square meters per second) at test hole P-14. Locations and estimated hydraulic heads of these wells are illustrated in Figure L1-35.

Hale et al. (1954) believed the Rustler-Salado contact residuum discharges to the alluvium near Malaga Bend on the Pecos River. Because the confining beds in this area are probably fractured because of dissolution and collapse of the evaporites, the brine (under artesian head) moves up through these fractures into the overlying alluvium and then discharges into the Pecos River.

According to Mercer (1983, 55), water in the Rustler-Salado contact residuum in Nash Draw contains the largest concentrations of dissolved solids in the WIPP area, ranging from 41,500 milligrams per liter in borehole H-1 to 412,000 milligrams per liter in borehole H-5c. These waters are classified as brines. The dissolved mineral constituents in the brine consist mostly of sulfates and chlorides of calcium, magnesium, sodium, and potassium; the major constituents are sodium and chloride. Concentrations of the other major ions vary according to the spatial location of the sample, are probably directly related to the interaction of the brine and the host rocks, and reflect residence time within the rocks. Residence time of the brine depends upon the transmissivity of the rock. For example, the presence of large concentrations of potassium and magnesium in water is correlated with minimal permeability and a relatively undeveloped flow system.

L1-2b Surface-Water Hydrology

The WIPP site is in the Pecos River basin, which contains about 50 percent of the drainage area of the Rio Grande Water Resources Region. The Pecos River headwaters are west of Las Vegas, New Mexico, and the river flows to the south through eastern New Mexico and western Texas to the Rio Grande. The Pecos River has an overall length of about 500 mi (805 km), a maximum basin width of about 130 mi (209 km), and a total drainage area of about 44,535 mi^2 (115,301 km^2) (about 20,500 mi^2 [53,075 mi^2] contained within the basin have no external surface drainage and their surface waters do not contribute to Pecos River flows). Figure L1-36 shows the Pecos River drainage area.

The Pecos River is generally perennial, except in the reach below Anton Chico, where the low flows percolate into the stream bed. The main stem of the Pecos River and its major tributaries have low flows, and the streams are frequently dry. About 75 percent of the total annual precipitation and 60 percent of the annual flow result from intense local thunderstorms between April and September. The principal tributaries of the Pecos River in New Mexico, in downstream order, are the Gallinas River, Salt Creek, the Rio Hondo, the Rio Felix, the Eagle Creek, the Rio Peñasco, the Black River, and the Delaware River.

There are no perennial streams at the WIPP site. At its nearest point, the Pecos River is about 12 mi (19 km) southwest of the WIPP site boundary. The drainage area of the Pecos River at this location is 19,000 mi^2 (47,500 km^2). A few small creeks and draws are the only westward-flowing tributaries of the Pecos River within 20 mi (32 km) 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 mi^2 (10 km^2) with an average channel slope of 1 to 100, and drainage westward into the 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 ft (ft^3) per sec (0.057 cubic meters [m^3] per sec).

Potash mining operations in and near Nash Draw likely contribute to the flow in Nash Draw. For example, the Mississippi Potash Inc. East operation located 7 to 8 mi due north of the WIPP site disposes of mine tailings and refining-process effluent on its property and has done so since 1965. Records obtained from the New Mexico Office of the State Engineer show that since 1973, an average of 2,400 acre-feet of water per year has been pumped from local aquifers (Ogallala and Capitan) for use in the potash-refining process at that location (SNL 2003b). Based on knowledge of the potash refining process, approximately 90 percent of the pumped water is estimated to be discharged to the tailings pile. Geohydrology Associates (1978) estimated that approximately half of the brine discharged onto potash tailings piles in Nash Draw seeps into the ground annually, while the remainder evaporates.

The Black River (drainage area: 400 mi^2 [1,035 km^2]) joins the Pecos from the west about 16 mi (25 km) southwest of the site. The Delaware River (drainage area: 700 mi^2 [1,812 km^2] and a number of small creeks and draws also join the Pecos River along this reach. The flow in the Pecos River below Fort Sumner is regulated by storage in Sumner Lake, Brantley Reservoir, Lake Avalon, and several other smaller irrigation dams.

Five major reservoirs are located in the Pecos River basin: Santa Rosa Lake, Sumner Lake, Brantley Reservoir, Lake Avalon, and Red Bluff Reservoir, the last located just over the border in Texas (Figure L1-36). The storage capacities of these reservoirs and other Pecos River reservoirs adjacent to the Pecos River basin are shown in Table L1-3.

With regards to surface drainage onto and off of the WIPP site, there are no major lakes or ponds within 5 mi (8 km) of the site. The Laguna Gatuña, Laguna Tonto, Laguna Plata, and Laguna Toston are playas more than 10 mi (16 km) north of the site and are at elevations of 3,450 ft (1050 m) or higher. Thus, surface runoff from the site (elevation 3,310 ft [1010 m] above sea level) would not flow toward any of them. To the north, west, and northwest, Red Lake, Lindsey Lake, the Laguna Grande de la Sal, and a few unnamed stock tanks are more than 10 mi (16 km) from the site, at elevations of from 3,000 to 3,300 ft (914 to 1,006 m).

The mean annual precipitation in the region is about 12 in. (0.3 m), and the mean annual runoff is 0.1 to 0.2 in. (2.5 to 5 mm). The maximum recorded 24-hour precipitation at Carlsbad was 5.12 in. (130 mm) in August 1916. The predicted maximum 6-hour, 100-year precipitation event for the site is 3.6 in. (91 mm) and is most likely to occur during the summer.

The maximum recorded flood on the Pecos River occurred near the town of Malaga, New Mexico, on August 23, 1966, with a discharge of 120,000 ft^3 (3,396 m^3) per sec and a stage elevation of about 2,938 ft (895 m) above mean sea level. The minimum surface elevation of the WIPP site is over 500 ft (152 m) above the river bed and over 400 ft (122 m) above the elevation of this maximum historical flood elevation (DOE, 1980, §7.4.1).

More than 90 percent of the mean annual precipitation at the site is lost by evapotranspiration. On a mean monthly basis, evapotranspiration at the site greatly exceeds the available rainfall; however, intense local thunderstorms may produce runoff and percolation.

Water quality in the Pecos River basin is affected by mineral pollution from natural sources and from irrigation return flows. At Santa Rosa, New Mexico, the average suspended-sediment discharge of the river is about 1,650 tons (1,819 metric tons [1,000 kg]) per day. Large amounts of chlorides from Salt Creek and Bitter Creek enter the river near Roswell. River inflow in the Hagerman area contributes increased amounts of calcium, magnesium, and sulfate; and waters entering the river near Lake Arthur are high in chloride. Below Brantley Reservoir, springs flowing into the river are usually submerged and difficult to sample; springs that could be sampled had TDS concentrations of from 3,350 to 4,000 ppm (3,350 to 4,000 mg/L). Concentrated brine entering at Malaga Bend adds an estimated 70 tons per day of chloride to the Pecos River.

L1-2c <u>Groundwater Discharge and Recharge</u>

The only documented points of naturally occurring groundwater discharge in the vicinity of the WIPP are the saline lakes in the Nash Draw and the Pecos River, primarily near Malaga Bend. Although this is local flow associated with the Nash Draw and unrelated to groundwater flow at the WIPP site, it is presented here for completeness. Discharge into one of the lakes from Surprise Spring (see Figure L1-1) was measured by Hunter in 1985 at a rate of less than 0.35 ft^3 (0.01 m^3) per second in 1942. Hunter also estimated total groundwater discharge into the lakes is 24 ft^3 (0.67 m^3) per second. According to Mercer (1983) discharge from the spring comes from fractured and more transmissive portions of the Tamarisk of the Rustler, and the lakes are hydraulically isolated from the Culebra and lower units.

Groundwater discharge into the Pecos River is greater than discharge into the saline lakes. Groundwater discharge into the Pecos River between Avalon Dam north of Carlsbad and a point south of Malaga Bend was no more than approximately 32.5 ft^3 (0.92 m^3) per sec . Most of this gain in stream flow occurs near Malaga Bend (see Figure L1-1) and is the result of groundwater discharge from the residuum at the Rustler/Salado contact zone.

The only documented point of groundwater recharge is also near Malaga Bend, where an almost immediate water-level rise has been reported by Hale et al. in 1954 in a Rustler-Salado well following a heavy rainstorm. This location is hydraulically downgradient from the repository, and recharge here has little relevance to flow near the WIPP. Examination of the potentiometric surface map for the Rustler/Salado contact zone indicates that some inflow may occur north of the WIPP, where freshwater equivalent heads are highest. Additional inflow to the contact zone may occur as leakage from overlying units, particularly where the units are close to the surface and under water-table conditions.

No direct evidence exists for the location of either recharge to or discharge from the Culebra. The freshwater-head surface map (Figure L1-31) implies inflow from the north and outflow to the south. Recharge from the surface probably occurs 9 to 19 mi (15 to 30 km) northwest of the WIPP in and north of Clayton Basin where the Rustler crops out. An undetermined amount of inflow may also occur as leakage from overlying units throughout the region.

The freshwater-head contour map (Figure L1-31) indicates that flow in the Culebra is toward the south. Some of this southerly flow may enter the Rustler/Salado contact zone under water table conditions near Malaga Bend and may ultimately discharge into the Pecos River. Additional flow may discharge directly into the Pecos River or into alluvium in the Balmorhea/Loving Trough to the south.

Recharge to the Magenta may also occur north of the WIPP in Bear Grass Draw and Clayton Basin. The potentiometric surface map indicates that discharge is toward the west in the vicinity of the WIPP, probably into the Tamarisk and the Culebra near the Nash Draw. Some discharge from the Magenta may ultimately reach the saline lakes in the Nash Draw. According to Brinster in 1991, additional discharge probably reaches the Pecos River at Malaga Bend or the alluvium in the Balmorhea/Loving Trough.

Isotopic data from groundwater samples suggest that groundwater travel time from the surface to the Dewey Lake and the Rustler is long and rates of flow are extremely slow. Based on observations by Lambert and Harvey reported in 1987, low tritium levels in all WIPP-area samples indicate minimal contributions from the atmosphere since 1950. Lambert in 1987 indicated four modeled radiocarbon ages from the Rustler and the Dewey Lake groundwater are between 12,000 and 16,000 years. The uranium isotope activity ratios observed require a conservative minimum residence time in the Culebra of several thousands of years and more probably reflect minimum ages of from 10,000 to 30,000 years.

Potentiometric data from four wells support the conclusion that little infiltration from the surface reaches the transmissive units of the Rustler. Hydraulic head data are available for a claystone in the Forty-niner from wells DOE-2, H-3, H-4, H-5, and H-6. Beauheim, in 1987, compared these heads to heads in the surrounding Magenta wells and showed that flow between the units at all four wells may be upward. This observation offers no insight into the possibility of infiltration reaching the Forty-niner, but it rules out the possibility of infiltration reaching the Magenta or any deeper units at these locations.

L1-2d Water Quality

This section presents a discussion of the quality of groundwater and surface water in the WIPP area.

L1-2d(1) Groundwater Quality

Based on the major solute compositions described by Siegel et al. in 1991, four hydrochemical facies are delineated for the Culebra.

Zone A. Sodium-chloride brine (approximately 3.0 molar) with magnesium/calcium (Mg/Ca) mole ratios between 1.2 and 2.0. Zone A water is found in the eastern third of the WIPP site. The zone is roughly coincident with the region of low transmissivity described by LaVenue et al. in 1988.

On the western side of the zone, halite in the Rustler has been found only in the Los Medaños. In the eastern portion of the zone, halite has been observed throughout the Rustler.

Zone B. A dilute calcium-sulfate-rich water (ionic strength <0.1 molar) occurs in the southern part of the site. The Mg/Ca mole ratios are uniformly low (0.0 to 0.5). This zone is coincident with a high-transmissivity region, and halite is not found in the Rustler in this zone.

Zone C. Waters of variable composition with low to moderate ionic strength (0.3 to 1.6 molar) occur in the western part of the WIPP site and along the eastern side of the Nash Draw. Mg/Ca mole ratios range from 0.5 to 1.2. This zone is coincident with a region of variable transmissivity. In the eastern part of this zone, halite is present in the lower member of the Rustler. Halite is not observed in the formation on the western side of the zone. The most sodium-chloride-rich water is found in the eastern edge of the zone, close to core locations where halite is observed in the Tamarisk.

Zone D. A fourth zone can be defined based on inferred contamination related to potash-refining operations in the area. Waters from these wells have anomalously high solute concentrations (3 to 6 molar) and potassium/sodium (K/Na) weight ratios (0.22) compared to waters from other zones (K/Na = 0.01 to 0.09). In the extreme southwestern part of this zone, the composition of the Culebra well water has changed over the course of a seven-year monitoring period. The Mg/Ca mole ratio at WIPP-29 is anomalously high, ranging from 10 to 30 during the monitoring period.

This zonation is consistent with that described by Ramey in 1985, who defined three zones. The fourth zone (D) was added by Siegel et al. in 1991 to account for the local potash contamination. Together, the variations in solutes and the distribution of halite in the Rustler exhibit a mutual interdependence. Concentrations of solutes are lowest where Rustler halite is less abundant, consistent with the hypothesis that solutes in Rustler groundwaters are derived locally by dissolution of minerals (e.g., halite, gypsum, and dolomite) in adjacent strata.

The TDS in the Magenta groundwater ranges in concentration from 5,460 to 270,000 mg/L. This water is considered saline to briny. The transmissivity in areas of lower TDS concentrations is very low, thus greatly decreasing its usability, and the Magenta is not considered as a water supply. In general, the chemistry of Magenta water is variable. Groundwater types range from a predominantly sodium-chloride type to a calcium-magnesium-sodium-sulfate-type chemistry. The water chemistry may indicate a general overall increase in TDS concentrations to the south and southwest, away from the WIPP site, and a potential change to a predominantly sodium-chloride water in that area.

In the WIPP area, the water quality of the Magenta is better than that of the Culebra. However, water from the Magenta is not used anywhere in the vicinity of the WIPP.

L1-2d(2) <u>Surface-Water Quality</u>

The Pecos River is the nearest permanent water source to the WIPP site. Natural brine springs, representing outfalls of the brine aquifers in the Rustler, feed the Pecos River at Malaga Bend, 12 mi (19 km) southwest of the site. This natural saline inflow adds approximately 70 tons of chloride per day to the Pecos River. Return flow from irrigated areas above Malaga Bend further contributes to the salinity. The concentrations of potassium, mercury, nickel, silver, selenium, zinc, lead, manganese, cadmium, and barium also show significant elevations at Malaga Bend but tend to decrease downstream. The metals presumably are rapidly adsorbed onto the river sediments. Natural levels of certain heavy metals in the Pecos River below Malaga Bend exceed the water quality standards of the World Health Organization, the U.S. Environmental Protection Agency, and the State of New Mexico. For example, the water quality standards specify a maximum level for lead is 50 parts per billion (ppb); however, levels of up to 400 ppb have been measured.

As it flows into Texas south of Carlsbad, the Pecos River is a major source of dissolved salt in the west Texas portion of the Rio Grande Basin. Natural discharge of highly saline groundwater into the Pecos River in New Mexico keeps TDS levels in the water in and above the Red Bluff Reservoir very high. The TDS levels in this interval exceed 7,500 mg/L 50 percent of the time and, during low flows, can exceed 15,000 mg/L . Additional inflow from saline water-bearing aquifers below the Red Bluff Reservoir, irrigation return flows, and runoff from oil fields continues to degrade water quality between the reservoir and northern Pecos County in Texas. Annual discharge-weighted average TDS concentrations exceed 15,000 mg/L . Water use is varied in the southwest Texas portion of the Pecos River drainage basin. For the most part, water use is restricted to irrigation, mineral production and refining, and livestock watering. In many instances, surface-water supplies are supplemented by groundwaters that are being depleted and are increasing in salinity.

L1-3 Resources

The topic of resources is used to broadly define both economic (mineral and nonmineral) and cultural resources associated with the WIPP site. These resources are important since they 1) provide evidence of past uses of the area, and 2) indicate potential future use of the area with the possibility that such use could lead to disruption of the closed repository. Because of the depth of the disposal horizon, it is believed that only the mineral resources are of significance in predicting the long-term performance of the disposal system. However, the nonmineral and cultural resources are presented for completeness.

This section refers to the significance of specific natural resources that lie beneath the WIPP site. Resources are minerals or hydrocarbons that are potentially of economic value. Reserves are the portion of resources that are economic at today's market prices and with existing technology.

For hydrocarbons, proven reserves can be expected to be recovered from new wells on undrilled acreage or from existing wells where a relatively major expenditure is required to establish production. Probable reserves refer to reserves of hydrocarbons suspected of existing in certain locations based on favorable engineering and/or geologic data. Possible reserves are based on conditions where limited engineering and/or geologic data support recoverable potential.

Mineral resource discussions are focused principally on hydrocarbons and potassium salts, both of which have long histories of development in the region and both of which could be disruptive to the disposal system. The information regarding the mineral resources concentrates on the following factors:

- Number, location, depth, and present state of development including penetrations through the disposal horizon
- Type of resource
- Accessibility, quality, and demand
- Mineral ownership in the area

In addition to extractable resources, this section includes cultural and economic resources. These are focused on a description of past and present land uses unrelated to the development of minerals. The archaeological record supports the observation that changes on land use are principally associated with climate and the availability of forage for wild and domestic animals. In no case does it appear that past or present land use has had an impact on the subsurface beyond the development of shallow groundwater wells for watering livestock.

L1-3a Extractable Resources

The geologic studies of the WIPP site have included the investigation of potential natural resources to evaluate the impact of denying access to these resources and other consequences of their occurrence. This study was completed in support of the *Final Environmental Impact Statement* (FEIS) (DOE, 1980) to ensure knowledge of natural resources once the impacts of their denial was included in the decision-making process for the WIPP. Of the natural resources expected to occur beneath the site, five are of practical concern: first, the two potassium salts sylvite and langbeinite, which occur in strata above the repository salt horizon, and , the three hydrocarbons crude oil, natural gas, and distillate liquids associated with natural gas, which occur in strata below the repository horizon. Other mineral resources beneath the site are caliche, salt, gypsum, and lithium; enormous deposits of these minerals near the site and elsewhere in the country are more than adequate (and more economically attractive) to meet future requirements for these materials. In 1995 the NMBMMR performed a reevaluation of the mineral resources at and within 1 mi (1.6 km) around the WIPP site.

L1-3a(1) Potash Resources at the WIPP Site

Throughout the Carlsbad Potash District, commercial quantities of potassium salts are restricted to the middle portion, locally called the McNutt Potash Member of the Salado. A total of 11 horizons, or orebeds, have been recognized in the McNutt Potash Member. Horizon Number 1 is at the base, and Number 11 is at the top. The 11th ore zone is not mined.

The USGS uses three established standard grades: ―low, lease, and high― to quantify the potash resources at the site. The USGS assumes that the "lease" and "high" grades comprise reserves because some lease-grade ore is mined in the Carlsbad Potash District. Most of the potash that is mined, however, is better typified by the high grade. Even the high-grade resources may not be reserves if their properties make processing uneconomic.

The 1995 study contains a comprehensive summary of all previous evaluations.

Griswold (in NMBMMR, 1995, Chapter VII) used 40 existing boreholes drilled on and around the WIPP site to perform a reevaluation of potash resources. Holes were drilled using brine so that the dissolution of potassium salts was inhibited. The results of the chemical analyses of the ore-bearing intervals were adjusted to calculate the percentage equivalent as individual natural mineral species. Only the K_2O (potassium oxide) percentages as either sylvite or langbeinite were used to compute ore reserves. The conclusion reached by Griswold is that only the 4th and 10th ore zones contain economic potash reserves. The quantities are summarized in Table L1-4.

L1-3a(2) Hydrocarbon Resources at the WIPP Site

In 1974 the NMBMMR conducted a hydrocarbon resource study in southeastern New Mexico under contract to ORNL. The study included an area of 1,512 mi^2 (3,914 km^2). At the time of that study, the proposed repository site was about 5 mi (8 km) northeast of the current site. The NMBMMR 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. The NMBMMR hydrocarbon resources study is presented in more detail in the FEIS (DOE, 1980, §9.2.3.5). The reader is referred to the FEIS or the original study (Foster, 1974) for additional information.

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 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 was 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. A 1995 mineral resource reevaluation by the NMBMMR contains a comprehensive summary of this and other previous evaluations.

Broadhead et al. (NMBMMR, 1995, Chapter XI) provided a reassessment of hydrocarbon resources within the WIPP site boundary and within the first mile adjacent to the boundary. Calculations were made for resources that are extensions of known, currently productive oil and gas resources that are thought to extend beneath the study area with reasonable certainty (called probable resources in the report). Qualitative estimates are also made concerning the likelihood that oil and gas may be present in undiscovered pools and fields in the area (referred to as possible resources). Possible resources were not quantified in the study. The results of the study are shown in Tables L1-5 and L1-6.

L1-3b Cultural and Economic Resources

L1-3b(1) Demographics

The WIPP facility is located 26 mi (42 km) east of Carlsbad in Eddy County in southeastern New Mexico and includes an area of 10,240 acres (ac) (4,143 hectares [ha]). The facility is located in a sparsely populated area with fewer than 30 permanent residents living within a 10-mi (16-km) radius of the facility. The area surrounding the facility is used primarily for grazing, potash mining, and hydrocarbon production. No resource development that would affect WIPP facility operations or the long-term integrity of the facility is allowed within the 10,240 ac (4,143 ha) that have been set aside for the WIPP Project.

The community nearest to the WIPP site is the town of Loving, New Mexico, 18 mi (29 km) west-southwest of the site center. The population of Loving increased from 1 1,243 in 1990 to 1,326 in 2000. The nearest population center is the city of Carlsbad, New Mexico, 26 mi (42 km) west of the site. The population of Carlsbad has increased from 24,896 in 1990 to 26,870 in 2000. Hobbs, New Mexico, 36 mi (58 km) to the east of the site had a population decrease from 29,115 in 1990 to 28,657 in 2000. Eunice, New Mexico, 40 mi (64 km) east of the site, had a 1990 population of 2,731 and a 2000 population of 2,562. Jal, New Mexico, 45 mi (72 km) southeast of the site, had a population of 2,153 in 1990 and 1,996 in 2000.

The WIPP site is located in Eddy County near the border to Lea County, New Mexico. The Eddy County population increased from 48,605 in 1990 to 51,658 in 2000. The Lea County population decreased from 55,765 in 1990 to 55,511 in 2000.

L1-3b(2) Land Use

At present, land within 10 mi (16 km) of the site is used for potash mining operations, active oil and gas wells, and grazing. This pattern is expected to change little in the future.

The WIPP Land Withdrawal Act of 1992 (LWA) provided for the transfer of the WIPP site lands from the Department of the Interior to the DOE and effectively withdraws the lands, subject to existing rights, from entry, sale, or disposition; appropriation under mining laws; and operation of the mineral and geothermal leasing laws. The LWA directed the Secretary of Energy to produce a management plan to provide for grazing, hunting and trapping, wildlife habitat, mining, and the disposal of salt tailings.

There are no producing hydrocarbon wells within the volumetric boundary defined by the land withdrawal area? Boundary? (T22S, R31E, S15-22, 27-34). One active well, referred to as James Ranch 13, was drilled in 1982 to tap gas resources beneath Section 31. This well was initiated in Section 6, outside the WIPP site boundary. The well enters Section 31 below a depth of 6,000 ft (1.82 km) beneath ground level.

Grazing leases have been issued for all land sections immediately surrounding the WIPP facility. Grazing within the WIPP site lands operates within the authorization of the Taylor Grazing Act of 1934, the Federal Land Policy and Management Act, the Public Rangelands Improvement Act of 1978, and the Bankhead-Jones Farm Tenant Act of 1973. The responsibilities of the DOE include supervision of ancillary activities associated with grazing (e.g., wildlife access to livestock water development); tracking of water developments inside WIPP lands to ensure that they are configured according to the regulatory requirements; and ongoing coordination with respective allottees. Administration of grazing rights is in cooperation with the Bureau of Land Management (BLM) according to the Memorandum of Understanding and the coinciding Statement of Work through guidance established in the East Roswell Grazing Environmental Impact Statement. The WIPP site is composed of two grazing allotments administered by the BLM: the Livingston Ridge (No. 77027) and the Antelope Ridge (No. 77032).

L1-3b(3) History and Archaeology

The WIPP site boundary consists of a 10,240-ac (16-m^2) area located in southeastern New Mexico. From about 10,000 B. C. to the late 1800s, this region was inhabited by nomadic aboriginal hunters and gatherers who subsisted on various wild plants and animals. From about A. D.. 600 onward, as trade networks were established with Puebloan peoples to the west, domesticated plant foods and materials were acquired in exchange for dried meat, hides, and other products from the Pecos Valley and Plains. In the mid-1500s, the Spanish Conquistadors encountered Jumano and Apachean peoples in the region practicing hunting and gathering and engaging in trade with Puebloans. After the Jumanos abandoned the southern Plains region, the Comanches became the major population of the area. Neighboring populations, with whom the Comanches maintained relationships ranging from mutual trade to open warfare, included the Lipan, or Southern Plains Apache; several Puebloan groups; Spaniards; and the Mescalero Apaches.

The best documented indigenous culture in the WIPP region is that of the Mescalaro Apaches, who lived west of the Pecos. The lifestyle of the Mescalaro Apaches represents a transition between the full sedentism of the Pueblos and the nomadic hunting and gathering of the Jumanos and the Sumas. In 1763 the San Saba expedition encountered and camped with a group of Mescaleros in Los Medaños. Expedition records indicate the presence of both Lipan and Mescalero Apaches in the region.

A peace accord reached between the Comanches and the Spaniards in 1768 resulted in two historically important economic developments: 1) organized buffalo hunting by Hispanic and Puebloan "ciboleros," and 2) renewal and expansion of the earlier extensive trade networks by Comancheros. These events placed eastern New Mexico in a position to receive a wide array of both physical and ideological input from the Plains culture area to the east and north and from Spanish-dominated regions to the west and south. Comanchero trade began to mesh with the Southwest American trade influence in the early nineteenth century. However, by the late 1860s the importance of Comanchero trade was cut short by Texan influence.

The first cattle trail in the area was established along the Pecos River in 1866 by Charles Goodnight and Oliver Loving. By 1868, Texan John Chisolm dominated much of the area by controlling key springs along the river. Overgrazing, drought, and dropping beef prices led to the demise of open range cattle ranching by the late 1880s.

Following the demise of open-range livestock production, ranching developed using fenced grazing areas and production of hay crops for winter use. Herd-grazing patterns were influenced by the availability of water supplies as well as by the storage of summer grasses as hay for winter use.

The town now called Carlsbad was founded as "Eddy" in 1889 as a health spa. In addition to ranching, the twentieth century brought the development of the potash, oil, and gas industries that have increased the population eightfold in the last 50 years.

Although technological change has altered some of the aspects, ranching remains an important economic activity in the WIPP region. This relationship between people and the land is still an important issue in the area. Ranch-related sites that date to the 1940s and 1950s are common in parts of the WIPP area. These will be considered historical properties within the next several years and thus will be treated as such under current law.

The National Historic Preservation Act (NHPA) (16 USC 470 et seq.) was enacted to protect the nation's cultural resources in conjunction with the states, local governments, Indian tribes, and private organizations and individuals. The policy of the federal government includes: 1) providing leadership in preserving the prehistoric and historic resources of the nation; 2) administering federally owned, administered, or controlled prehistoric resources for the benefit of present and future generations; 3) contributing to the preservation of nonfederally owned prehistoric and historic resources; and 4) assisting state and local governments and the national trust for historic preservation in expanding and accelerating their historic preservation programs and activities. The act also established the National Register of Historic Places ("National Register"). At the state level, the State Historic Preservation Officer (SHPO) coordinates the state's participation in implementing the NHPA. The NHPA has been amended by two acts: the Archaeological and Historic Preservation Act (16 USC 469 et seq.), and the Archaeological Resource Protection Act (16 USC 470aa et seq.).

In order to protect and preserve cultural resources found within the WIPP site boundary, the WIPP submitted a mitigation plan to the New Mexico SHPO describing the steps to be taken to either avoid or excavate archaeological sites. A "site" was defined as a place used and occupied by prehistoric people. In May 1980, the SHPO made a determination of "no adverse effect from WIPP facility activities" on cultural resources. The National Advisory Council on Historic Preservation concurred that the WIPP Mitigation Plan is appropriate to protect cultural resources.

Known historical sites (more than 50 years old) in southeastern New Mexico consist primarily of early twentieth century homesteads that failed or isolated features from late nineteenth century and early twentieth century cattle or sheep ranching and military activities. To date, no Spanish or Mexican conquest or settlement sites have been identified. Historic components are rare but are occasionally noted in the WIPP area. These include features and debris related to ranching.

Since 1976, cultural resource investigations have recorded 98 archaeological sites and numerous isolated artifacts within the 16-mi^2 (41.5-km^2) area enclosed by the WIPP site boundary. In the central 4-mi^2 (10.4-km^2) area, 33 sites were determined to be eligible for inclusion on the National Register as an archaeological district. Investigations since 1980 have recorded an additional 14 individual sites outside the central 4-mi^2 (10.4-km^2) area that are considered eligible for inclusion on the National Register. The major cultural resource investigations to date are broken out in the following. Additional information can be found in the bibliography.

1977 The first survey of the area was conducted in 1977 by Nielson of the Agency for Conservation Archaeology (ACA) for SNL. This survey resulted in the location of 33 sites and 64 isolated artifacts.

1979 MacLennan and Schermer of ACA performed the next survey in 1979. It was conducted for access roads and a railroad right-of-way for Bechtel, Inc. The survey encountered 2 sites and 12 isolated artifacts.

1980 Schermer performed another survey in 1980 to relocate the sites originally recorded by Nielson. This survey redescribed 28 of the original 33 sites.

1981 Hicks directed the excavation of nine sites in the WIPP core-area in 1981.

1982 Bradley in 1985 recorded one site and four isolated artifacts in an archaeological survey for a proposed water pipeline.

1985 Lord and Reynolds examined three sites in 1985 within the WIPP core area. These sites consisted of two plant-collecting and processing sites and one base camp used between 1000 B. C. and A. D. 1400. The artifacts recovered from the excavations have been placed in the Laboratory of Anthropology at the Museum of New Mexico in Santa Fe.

1987 Mariah Associates, Inc., identified 40 sites and 75 isolates in 1987 in an inventory of 2,460 ac in 15 quarter-section units surrounding the WIPP site. In this investigation, 19 of the sites were located within the WIPP site's boundary. Sites encountered in this investigation tended to lack evident or intact features. Of the 40 new sites defined, 14 were considered eligible for inclusion in the National Register, 24 were identified as having insufficient data to determine eligibility, and 2 were determined to be ineligible for inclusion. The eligible and potentially eligible sites have been mapped and are being avoided by the DOE in its current activities at the WIPP site. Figure L1-37 maps out the 40 archaeological sites identified by the Mariah study.

1988-1992 Several archaeological clearance reports have been prepared for seismic testing lines on public lands in Eddy County, New Mexico, during this period.

No artifacts were encountered during cultural resource surveys performed from 1992 until present. The following list provides examples of WIPP projects that required cultural resource surveys. All investigations were performed and reported in accordance with requirements established by the New Mexico Office of Cultural Affairs (OCA) and administered by the SHPO.

- SPDV site investigation into status of a previously recorded site (#LA 33175) to determine potential impacts from nearby reclamation activity. Assessment included minor surface excavation.
- WIPP well bore C-2737. Cultural resource investigation for well pad and access road.
- WIPP well bores WQSP 1-6 and 6a. Individual cultural resource investigations conducted for construction of each respective well pad and access road.
- WIPP well bores SNL 1, 2, 3, 9 and 12. Cultural resource investigations conducted for construction of each respective well pad and access road.
- WIPP well bore WTS 4. Cultural resource investigation conducted in support of siting and constructing reserve pits for well drilling and development.
- North Salt Pile Expansion. Cultural resource investigation conducted in support of the expansion of the North Salt Pile, a project designed to mitigate surface water infiltration.

The Delaware Basin has been used in the past for an isolated nuclear test. This test, Project Gnome, took place in 1961 at a location approximately 8 mi (13 km) southwest of the WIPP. The primary objective of Project Gnome was to study the effects of an underground nuclear explosion in salt. The Gnome experiment involved the detonation of a 3.1-kiloton nuclear device at a depth of 1,200 ft (361 m) in the bedded salt of the Salado. The explosion created a cavity of approximately 1,000,000 ft^3 (27,000 m^3), and caused surface displacements over an area of about a 1,200-ft (360-m) radius. Fracturing and faulting caused measurable changes in rock permeability and porosity at distances up to approximately 330 ft (100 m) from the cavity. No earth tremors were reported at distances over 25 mi (40 km) from the explosion. Project Gnome was decommissioned in 1979.

L1-4 Seismicity

Seismic data are presented in two time frames, before and after the time when seismographic 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 since 1961. Various records have been examined to determine the seismic history of the area within 180 mi (288 km) of the site. With the exception of a weak shock in 1926 at Hope, New Mexico, and shocks in 1936 and 1949 felt at Carlsbad, all known shocks before 1961 occurred to the west and southwest of the site more than 100 mi (160 km) away.

The strongest earthquake on record within 180 mi (288 km) of the site was the Valentine, Texas, earthquake of August 16, 1931. It has been estimated to have been of magnitude 6.4 on the Richter scale (Modified Mercalli Intensity of VIII). The Valentine earthquake was 130 mi (208 km) south-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 mi (536 km) 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. Its magnitude was estimated to have been 7.8 (VIII to IX in Modified Mercalli Intensity). It was felt over an area of 0.5 million mi^2 (1.3 million km^2) (as far as Santa Fe to the north and Mexico City to the south); fault displacements near the epicenter were as large as 26 ft (18 m).

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 mi (288 km) of the site between 1961 and 1979 are shown in Figure L1-38. The distribution of these earthquakes 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. The 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 operating for 10 months at Fort Stockton, Texas, indicated many small shocks from the Central Basin Platform (See Figure L1-38). Activity was observed at the time the station opened on June 21, 1964. This activity may be related to the injection of water underground for oil recovery. In the Ward-Estes North oilfield, operated by the Gulf Oil Corporation, the cumulative total of water injected up to 1970 was over 1 billion barrels. Accounting for 42 percent 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 during the same period. Water injection has not been used in the region of the WIPP site to stimulate gas production. The nearest oil fields in the Delaware Basin, where any recovery might be attempted, are adjacent to the WIPP site boundary in the Delaware Formations. The source of this seismicity is insignificant because the seismic design basis uses the observed seismicity regardless of its cause.

A recent earthquake felt at the WIPP site occurred in January 1992 and is referred to as the Rattlesnake Canyon Earthquake.[2] It occurred 60 mi (100 km) east-southeast of the WIPP site. The earthquake was assigned a magnitude of 5.0. This event had no effect on any of the structures at the WIPP as documented by post-event inspections by the WIPP staff and the New Mexico Environment Department. This event was within the parameters used to develop the seismic risk assessment of the WIPP facility for the purposes of construction and operation.

The Rattlesnake Canyon event likely was tectonic in origin based on a 7 ± 1 mi (12 ± 2 km) depth. This suggests some uncertainty regarding the origin of earthquakes associated with the Central Basin Platform.

L1-5 Rock Geochemistry

An understanding of the mineralogy/geochemistry of the host repository rock is considered critical to predicting the long-term waste isolation capability of the repository. Chemical composition of the different minerals and any impurities are important to understand and predict waste-rock compatibility of the Salado. This section emphasizes the following topics:

- Mineral content and composition
- Fluid inclusions
- Fracture fillings.

The Salado is dominated by various evaporite salts; the dominant mineral is halite (NaCl) of varying purity and accessory minerals. The major accessory minerals are anhydrite ($CaSO_4$), clays, polyhalite ($K_2MgCa_2(SO_4)_4 \bullet 2H_2O$), and gypsum ($CaSO_4 \bullet 2H_2O$). In the vicinity of the repository, authigenic quartz (SiO_2) and magnesite ($MgCO_3$) are also present as accessory minerals. The marker beds in the salt are described as anhydrite with seams of clay. The clays within the Salado are enriched in magnesium and depleted in aluminum. The magnesium enrichment probably reflects the intimate contact of the clays with brines derived from evaporating sea water, which are relatively high in magnesium.

A partial list of minerals found in the Delaware Basin evaporites, together with their chemical formulas, is given in Table L1-7. The table also indicates the relative abundances of the minerals in the evaporite rocks of the Castile, the Salado, and the Rustler. Minerals found either only at depth, removed from influence of weathering, or only near the surface, as weathering products, are also identified. Although the most common Delaware Basin evaporite mineral is halite, the presence of less soluble interbeds (dominantly anhydrite, polyhalite, and claystone) and more soluble admixtures (e.g., sylvite, glauberite, and kainite) has resulted in chemical and physical properties significantly different from those of pure NaCl. In particular, the McNutt Potash

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[2] An earthquake occurred on April 13, 1995, near the town of Alpine, Texas. This earthquake has been assigned a local magnitude of M = 5.5. Details of the earthquake have not yet been published. The Alpine earthquake was felt at the WIPP site; however, no damage to WIPP facilities occurred as the result of this earthquake.

Member, between Marker Beds 116 and Marker Bed 126, is locally explored and mined for K-bearing minerals of economic interest. Under differential stress, brittle interbeds (anhydrite, polyhalite, magnesite, and dolomite) may fracture while, under the same stress regime, pure NaCl would undergo plastic deformation. Fracturing of brittle interbeds, for example, has locally enhanced the permeability, allowing otherwise nonporous rock to carry groundwater (e.g., fractured dolomite beds in the Rustler). Some soluble minerals incorporated in the rock salt (e.g., polyhalite, sylvite, leonite, and langbeinite) can be radiometrically dated, their longevity marking the time of most recent water-incursion into the evaporite section. The survival of such minerals is significant, in that such dating is impossible in pure NaCl or calcium sulfate.

Liquids were collected from fluid inclusions and from seeps and boreholes within the WIPP drifts. Analysis of these samples indicated that there is compositional variability of the fluids showing the effects of various phase transformations on brine composition. The fluid inclusions belong to a different chemical population than do the fluids emanating from the walls. It was concluded that much of the brine is completely immobilized within the salt and that the free liquid emanating from the walls is present as a fluid film along intergranular boundaries mainly in clays and in fractures in anhydrites.

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TABLES

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TABLE L1-1
CULEBRA THICKNESS DATA SETS

Source	Data Set Location								
	T22S, R31E			T21-23S, R30-32E			Entire Set		
	n	ave	st dev	n	ave	st dev	n	ave	st dev
Richey (1989)	7	7.5 m	1.04 m	115	7.9 m	1.45 m	633	7.7 m	1.65 m
Holt and Powers (1988)	35	6.4 m	0.59 m	122	7.0 m	1.26 m	508	6.5 m	1.89 m
LaVenue et al. (1988)							78	7.7 m	
WIPP Potash Drillholes									
Jones (1978)				21	7.5 m	0.70 m			
Holt and Powers (1988)				21	6.3 m	0.50 m			

Key: n = Number of boreholes or data points
ave = Average or mean
st dev = Standard deviation

TABLE L1-2
HYDROLOGIC CHARACTERISTICS OF ROCK UNITS AT THE WIPP SITE

Member Name	Thickness (m)		Hydraulic Conductivity (m/s)		Porosity	
	max	min	max	min	max	min
Forty-niner	20	−	5.0x10-9	5.0x10-10	−	−
Magenta	8	4	5.0x10-5	5.0x10-10	−	−
Tamarisk	84	8	−	−	−	−
Culebra	11.6	4	1x10-4	2x10-10	0.30	0.03
Unnamed	36	−	1x10-11	6x10-15	−	−
Rustler/ Salado Contact Zone	33	2.4	1x10-6	1x10-12	0.33	0.15

m = meters
m/s = meters per
max = maximum
min = minimum

TABLE L1-3
CAPACITIES OF RESERVOIRS IN THE PECOS RIVER DRAINAGE

Reservoir	River	Total Storage Capacity[a] (acre-feet)	Use[b]
Los Esteros	Pecos	282,000	FC
Sumner	Pecos	122,100	IR, R
Brantley	Pecos	42,000	IR, R, FC
Avalon	Pecos	5,000	IR
Red Bluff	Pecos	310,000	IR
Two Rivers	Rio Hondo	167,900	FC

[a]Capacity below the lowest uncontrolled outlet or spillway.
[b]Key:
FC=Flood control
IR=Irrigation
R=Recreation

TABLE L1-4
CURRENT ESTIMATES OF POTASH RESOURCES AT THE WIPP SITE

Mining Unit	Product	Recoverable Ore (106 tons)	
		Within the WIPP site	Outside the WIPP site
4th Ore Zone	Langbeinite	40.5 @ 6.99%	126.0 @ 7.30%
10th Ore Zone	Sylvite	52.3 @ 13.99%	105.0 @ 14.96%

Source: NMBMMR, 1995, Chapter VII

TABLE L1-5
IN-PLACE OIL WITHIN STUDY AREA

Formation	Within WIPP site (106 bbl)	Outside WIPP site (106bbl)	Total (106 bbl)
Delaware	10.33	20.8	31.13
Bone Spring	0.44	0.8	1.25
Strawn	0.4	0.4	0.8
Atoka	1.1	0.1	0.2
Total	12.3	22.9	35.3

Source: NMBMMR 1995, Chapter XI.

TABLE L1-6
IN-PLACE GAS WITHIN STUDY AREA

Formation	Gas Reserves	
	Within WIPP Site Boundary (mcf)	Adjacent to WIPP Site Boundary (mcf)
Delaware	18,176	32,873
Bone Springs	956	1,749
Strawn	9,600	9,875
Atoka	123,336	94,410
Morrow	32,000	28,780

Source: NMBMMR, 1995, Chapter XI

TABLE L1-7
CHEMICAL FORMULAS, DISTRIBUTIONS, AND RELATIVE ABUNDANCES OF MINERALS IN DELAWARE BASIN EVAPORITES

Mineral	Formula	Occurrence/Abundance
Amesite	(Mg4Al2)(Si2Al2)O10(OH)8	S,R
Anhydrite	CaSO4	CCC,SSS,RRR; rarely near surface
Calcite	CaCO3	S,RR
Carnallite	KMgCl3 • 6H2O	SS
Chlorite	(Mg,Al,Fe)12(Si,Al)8O20(OH)16	S,R
Corrensite	mixed-layer chlorite/smectite	S,R
Dolomite	CaMg(CO3)2	RR
Feldspar	(K,Na,Ca)(Si,Al)4O8	C,S,R
Glauberite	Na2Ca(SO4)2	C,S (never near surface)
Gypsum	CaSO4 • 2H2O	CCC (only near surface),S,RRR
Halite	NaCl	CCC,SSS,RRR; rarely near surface)
Illite	K1-1.5Al4[Si7-6.5Al1-1.5O20](OH)4	S,R
Kainite	KMgClSO4 • 3H2O	SS
Kieserite	MgSO4 H2O	SS
Langbeinite	K2Mg2(SO4)3	S
Magnesite	MgCO3	C,S,R
Polyhalite	K2Ca2Mg(SO4)4 • 2H2O	SS,R (never near surface)
Pyrite	FeS2	C,S,R
Quartz	SiO2	C,S,R
Serpentine	Mg3Si2O5(OH)4	S,R
Smectite	(Ca1/2,Na)0.7(Al,Mg,Fe)4(Si,Al)8O20 (OH)4 • nH2O	S,R
Sylvite	KCl	SS

Key to Occurrence/Abundance notations:
C = Castile Formation; S = Salado Formation; R = Rustler Formation
3 letters = abundant; 2 letters = common; 1 letter= rare or accessory

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FIGURES

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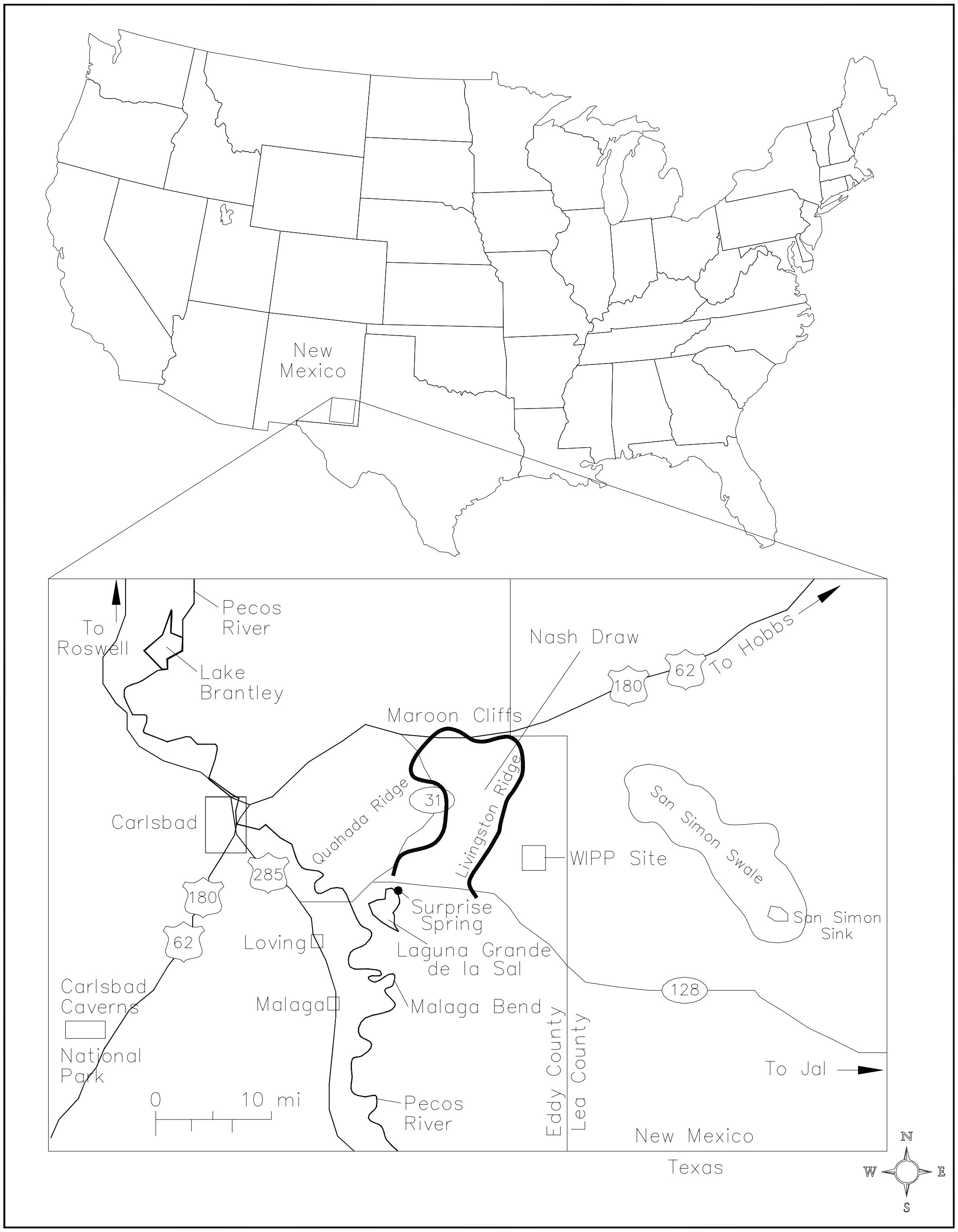


Figure L1-1
WIPP Site Location in Southeastern New Mexico

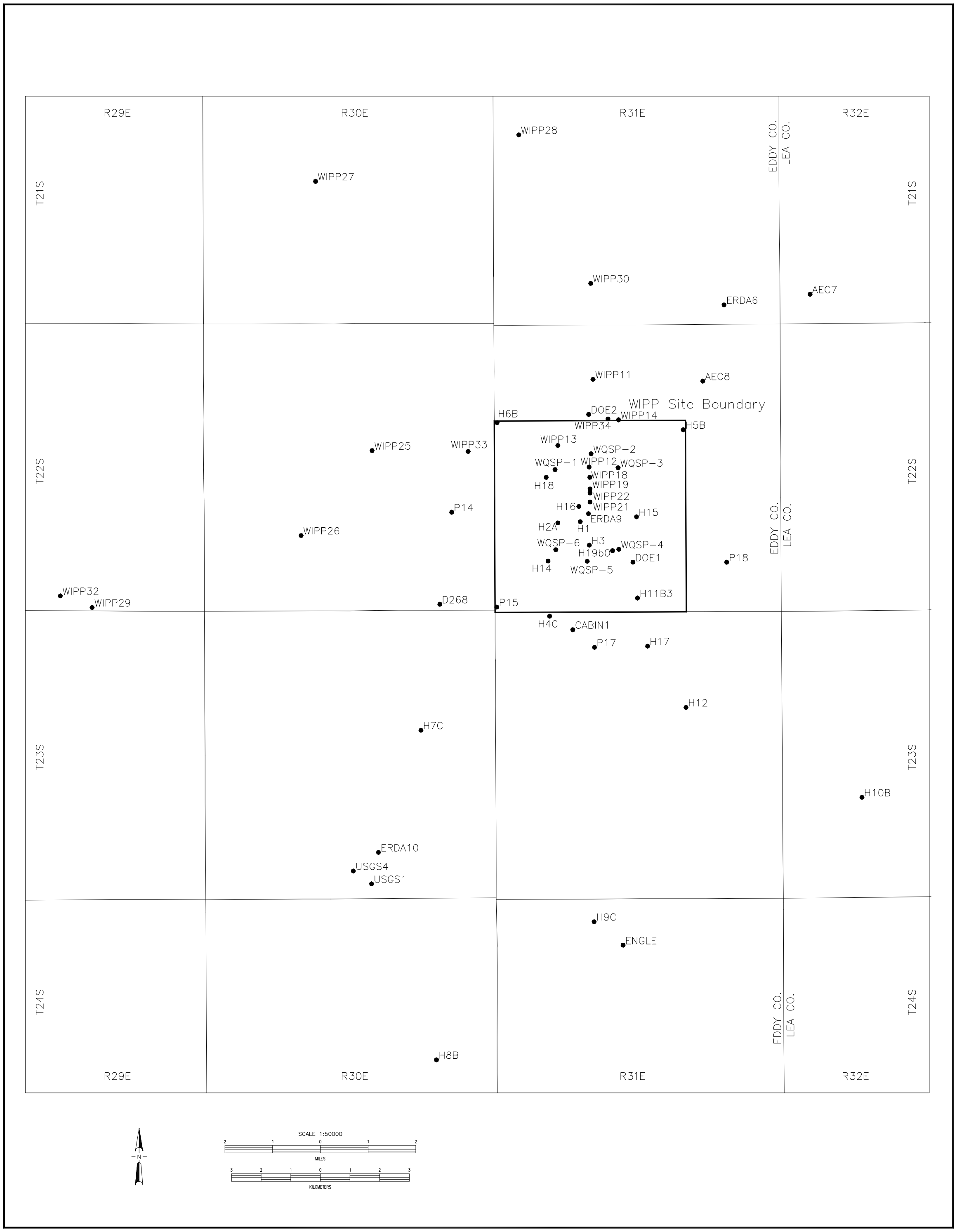


Figure L1-2
Borehole Location Map

ERA	PERIOD	EPOCH	YEARS DURATION	YEARS BEFORE PRESENT	MAJOR GEOLOGICAL EVENTS – SOUTHEAST NEW MEXICO REGION
CENOZOIC	Quartenary	Holocene	10,000		Eolian and erosion/solution activity. Development of present landscape.
		Pleistocene	1,590,000	1,600,000	
	Tertiary	Pliocene	3,700,000		Deposition of Gatuna fan sediments. Formation of caliche caprock.
		Miocene	18,400,000		Regional uplift and east–southeastward tilting; Basin–Range uplift of Sacramento and Guadalupe–Delaware Mountains.
		Oligocene	12,900,000		Erosian dominant. No Early to Mid–Tertiary rocks present.
		Eocene	21,200,000		
		Paleocene	8,600,000	66,400,000	Laramide "revolution" Uplift of Rocky Mountains. Mid tectonism and igneous activity to west and north.
MESOZOIC	Cretaceous		77,600,000	144,000,000	Submergence intermittent shallow seas. Thin lime–stone and clastics deposited.
	Jurassic		64,000,000	208,000,000	Emergent conditions. Erosion, formation of rolling terrain. Deposition of fluvial clastics.
	Triassic		37,000,000	245,000,000	Erosion. Broad flood plain develops.
PALEOZOIC	Permian		41,000,000	286,000,000	Deposition of evaporite sequence followed by continental red beds. Sedimentation continuous in Delaware, Midland, Val Verde basins and shelf areas.
	Pennsylvanian		34,000,000	320,000,000	Massive deposition of clastics. Shelf, margin, basin pattern of deposition develops.
	Mississippian		40,000,000	360,000,000	Regional tectonic activity accelerates, folding up Central Basin platform. Matador arch, ancestral Rockies. Regional erosion. Deep, broad basins to east and west of platform develop.
	Devonian		48,000,000	408,000,000	Renewed submergence. Shallow sea retreats from New Mexico; erosion. Mild epeirogenic movements. Tobosa basin subsiding. Pedernal landmass and Texas Penninsula emergent until Middle Mississippian.
	Silurian		30,000,000	438,000,000	
	Ordovician		67,000,000	505,000,000	Marathon–Quachita geosyncline, to south, begins subsiding. Deepening of Tobosa basin area; shelf deposition of clastics, derived partly from ancestral Central Basin platform and carbonates.
	Cambrian		65,000,000	570,000,000	Clastic sedimentation – Bliss sandstone.
	PRECAMBRIAN				Erosion to a nearly level plain. Mountain building, igneous activity, metamorphism, erosional cycles.

Source: Powers, et al., 1978; Palmer, 1983.

Figure L1-3
Major Geological Events – Southeast New Mexico Region

<table>
<tr><th>SYSTEM</th><th>SERIES</th><th>GROUP</th><th>FORMATION</th><th>MEMBER</th></tr>
<tr><td>RECENT</td><td>RECENT</td><td rowspan="3"></td><td>SURFICIAL DEPOSITS</td><td rowspan="3"></td></tr>
<tr><td rowspan="2">QUATERNARY</td><td rowspan="2">PLEISTOCENE</td><td>MESCALERO CALICHE</td></tr>
<tr><td>GATUNA</td></tr>
<tr><td>TERTIARY</td><td>MID-PLIOCENE</td><td></td><td>OGALLALA</td><td></td></tr>
<tr><td>TRIASSIC</td><td></td><td>DOCKUM</td><td>SANTA ROSA</td><td></td></tr>
<tr><td rowspan="13">PERMIAN</td><td rowspan="10">OCHOAN</td><td rowspan="10"></td><td>DEWEY LAKE</td><td></td></tr>
<tr><td rowspan="5">RUSTLER</td><td>Forty-niner</td></tr>
<tr><td>Magenta</td></tr>
<tr><td>Tamarisk</td></tr>
<tr><td>Culebra</td></tr>
<tr><td>Unnamed</td></tr>
<tr><td rowspan="3">SALADO</td><td>Upper</td></tr>
<tr><td>McNutt Potash</td></tr>
<tr><td>Lower</td></tr>
<tr><td>CASTILE</td><td></td></tr>
<tr><td rowspan="3">GUADALUPIAN</td><td rowspan="3">DELAWARE MOUNTAIN</td><td>BELL CANYON</td><td></td></tr>
<tr><td>CHERRY CANYON</td><td></td></tr>
<tr><td>BRUSHY CANYON</td><td></td></tr>
</table>

Figure L1-4
Site Geologic Column

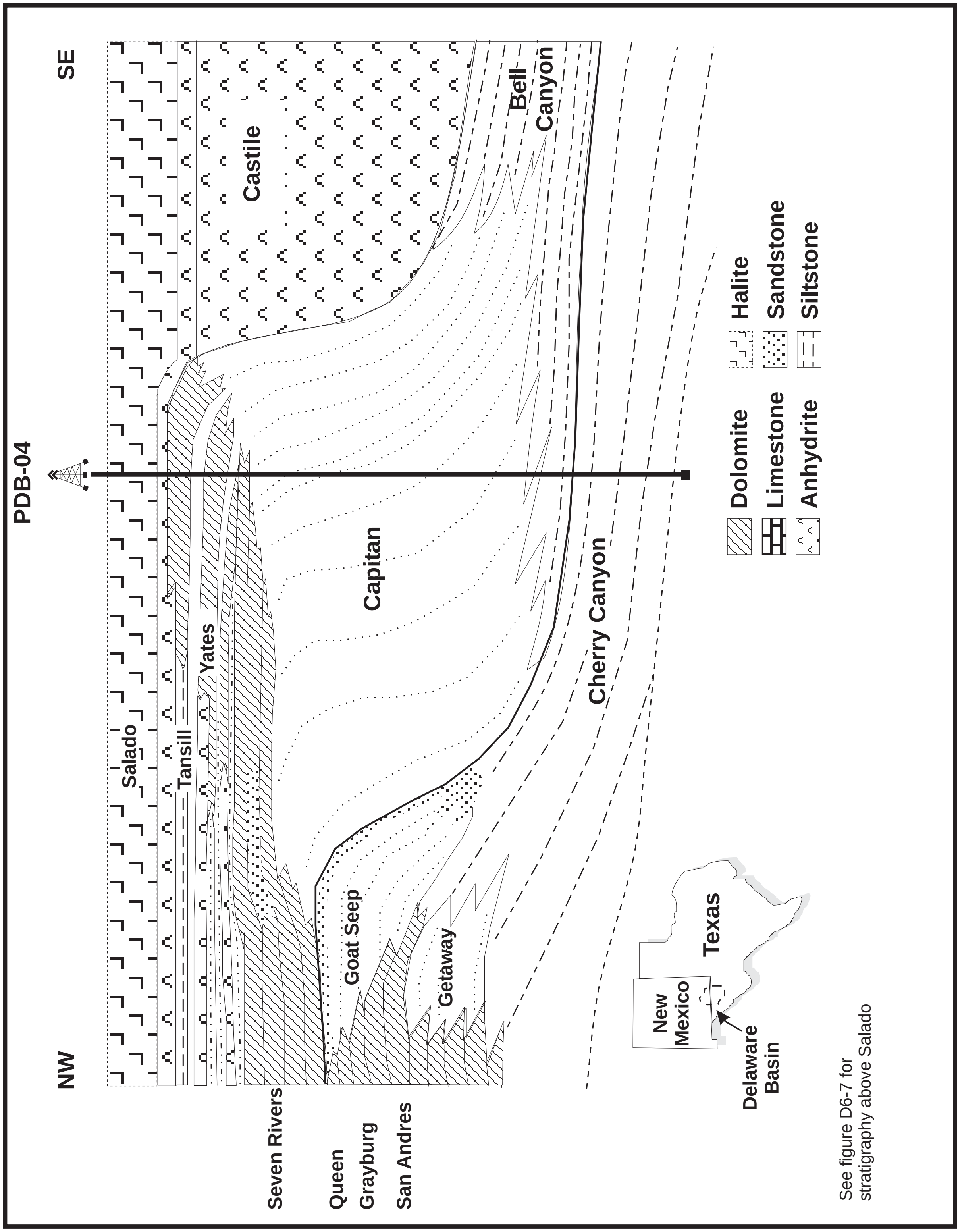


Figure D6-5
Cross Section from Delaware Basin (S.E.) Through Marginal Reef Rocks to Back-Reef Facies

RCRAD605

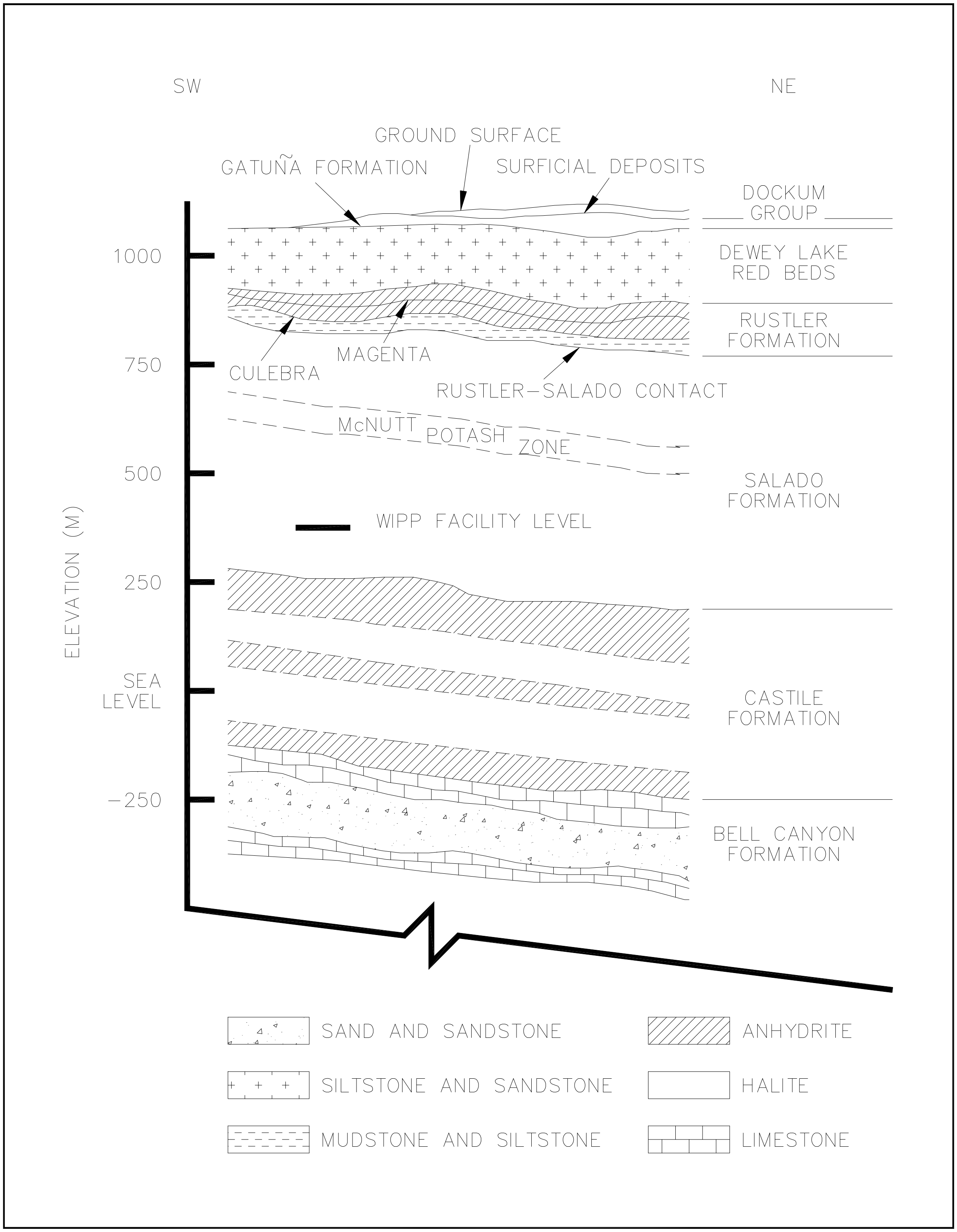


Figure L1-6
Generalized Stratigraphic Cross Section
Above Bell Canyon Formation at WIPP Site

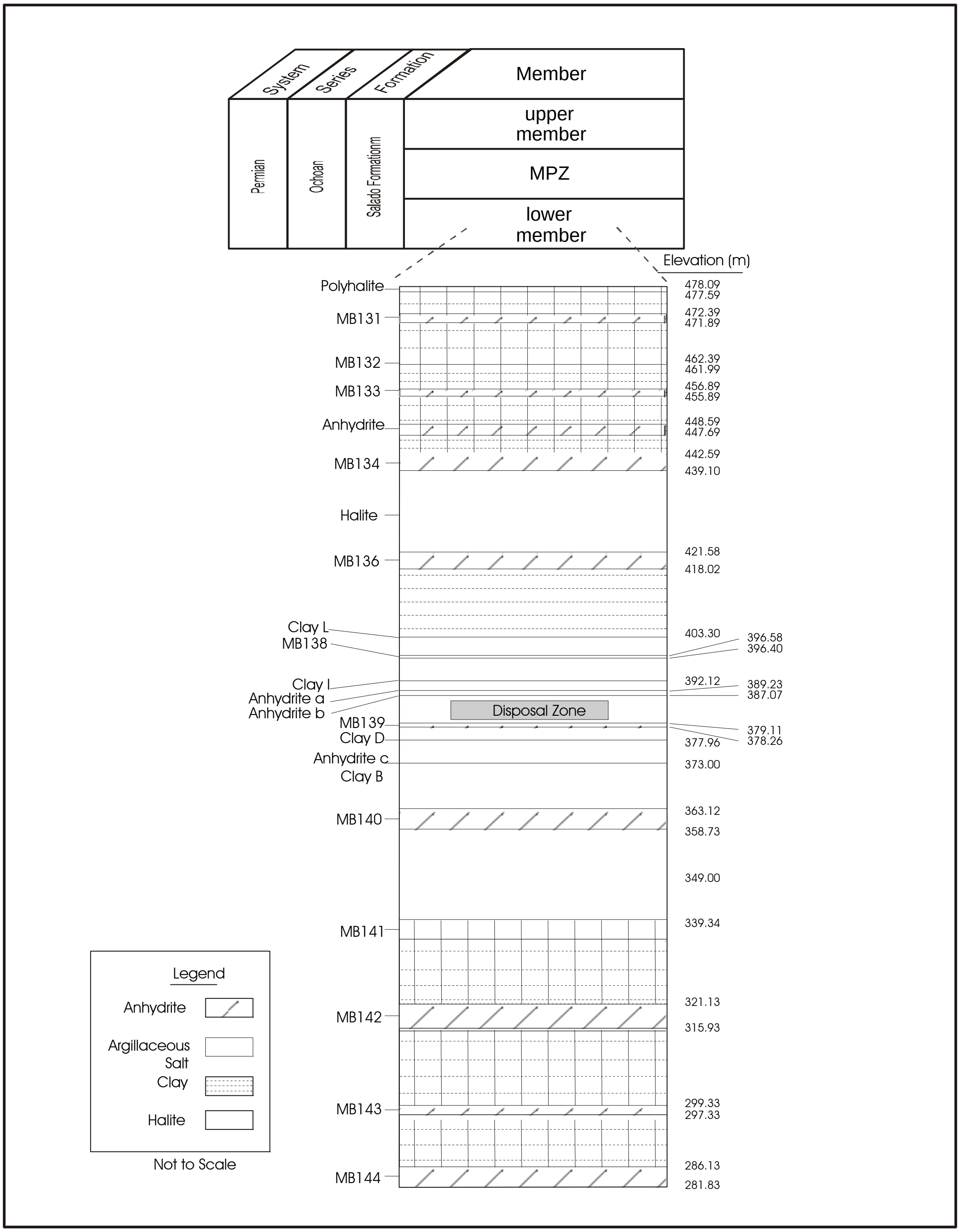


Figure L1-7
Salado Stratigraphy

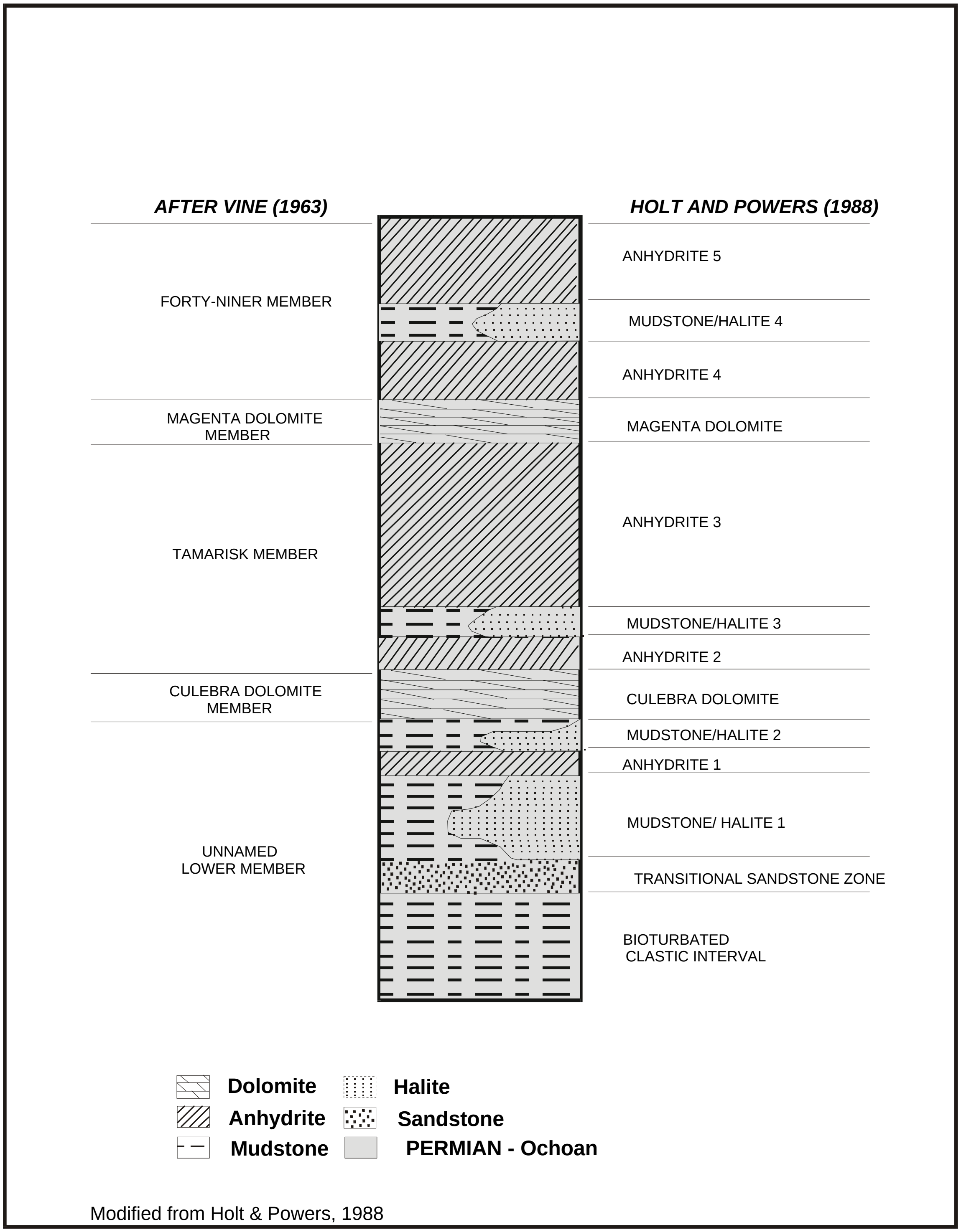


Figure L1-8
Rustler Stratigraphy

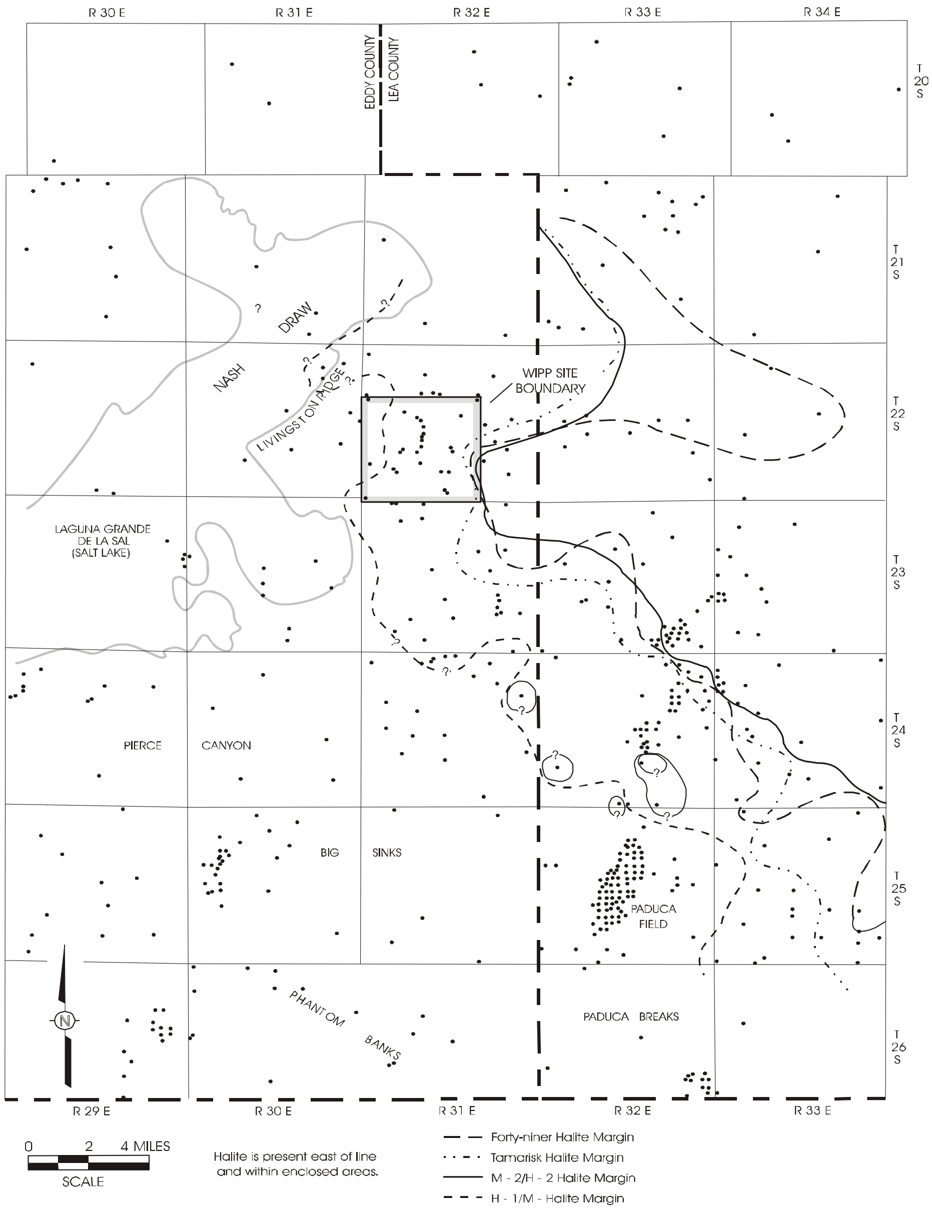


Figure L1-9
Halite Margins in Rustler

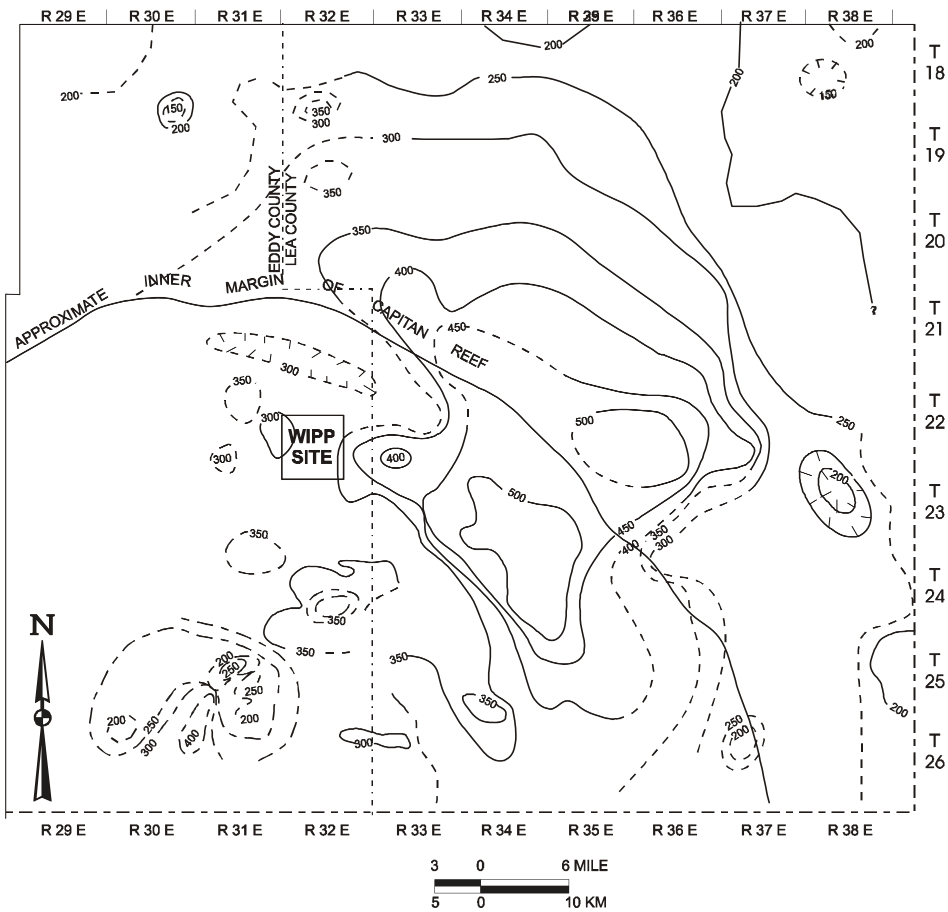


Figure L1-10
Isopach Map of the Entire Rustler

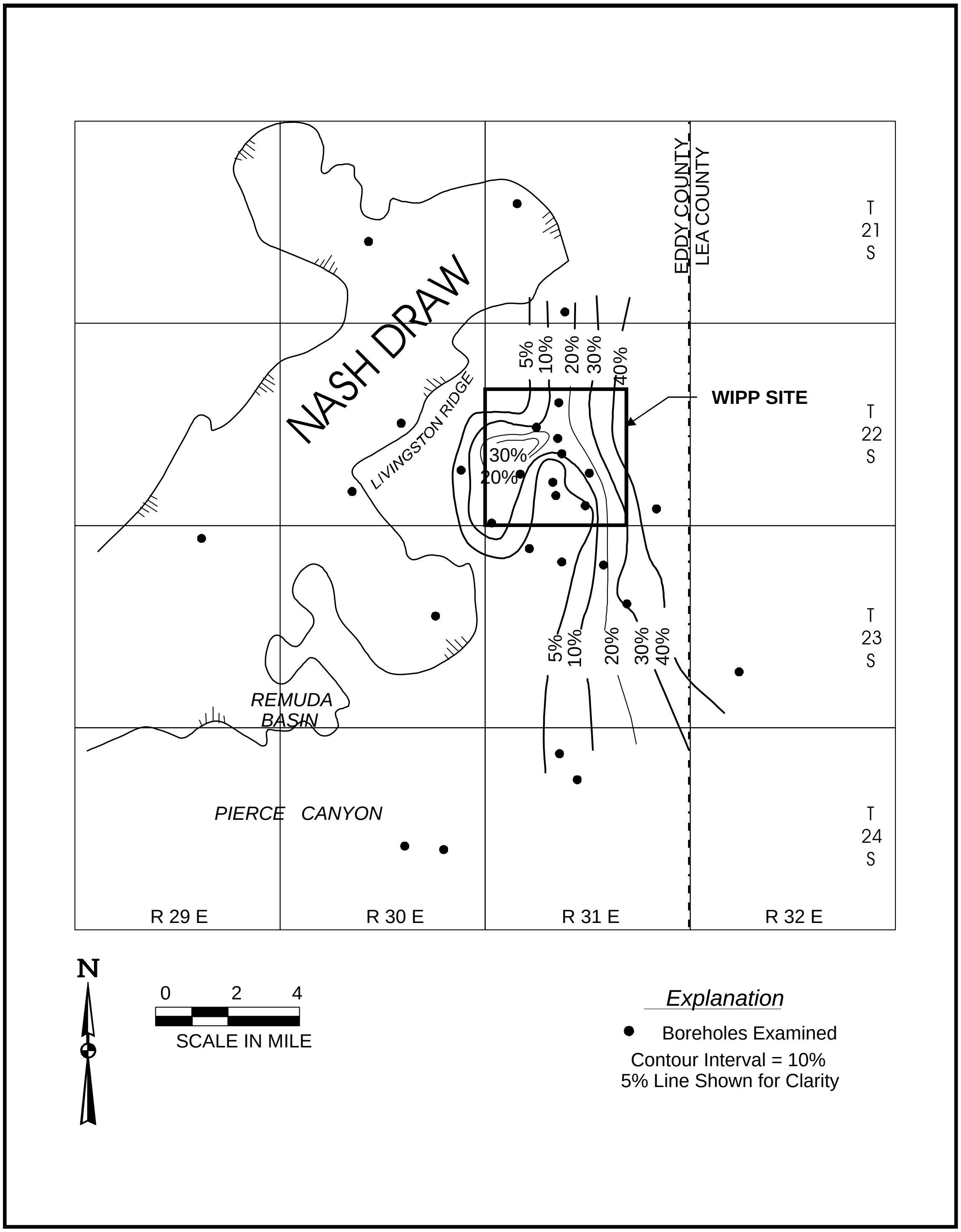


Figure L1-11
Percentage of Natural Fractures in the Culebra Filled with Gypsum

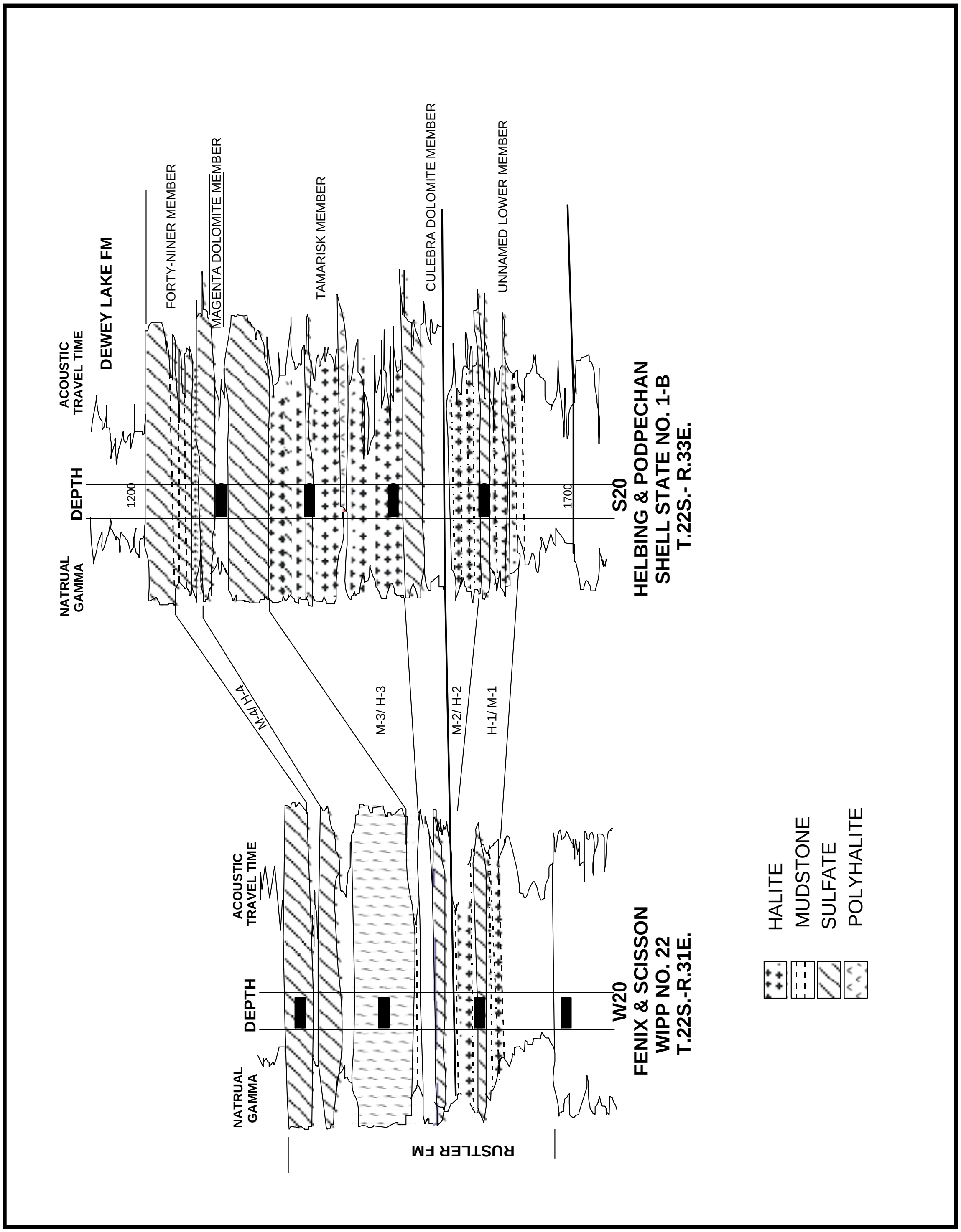
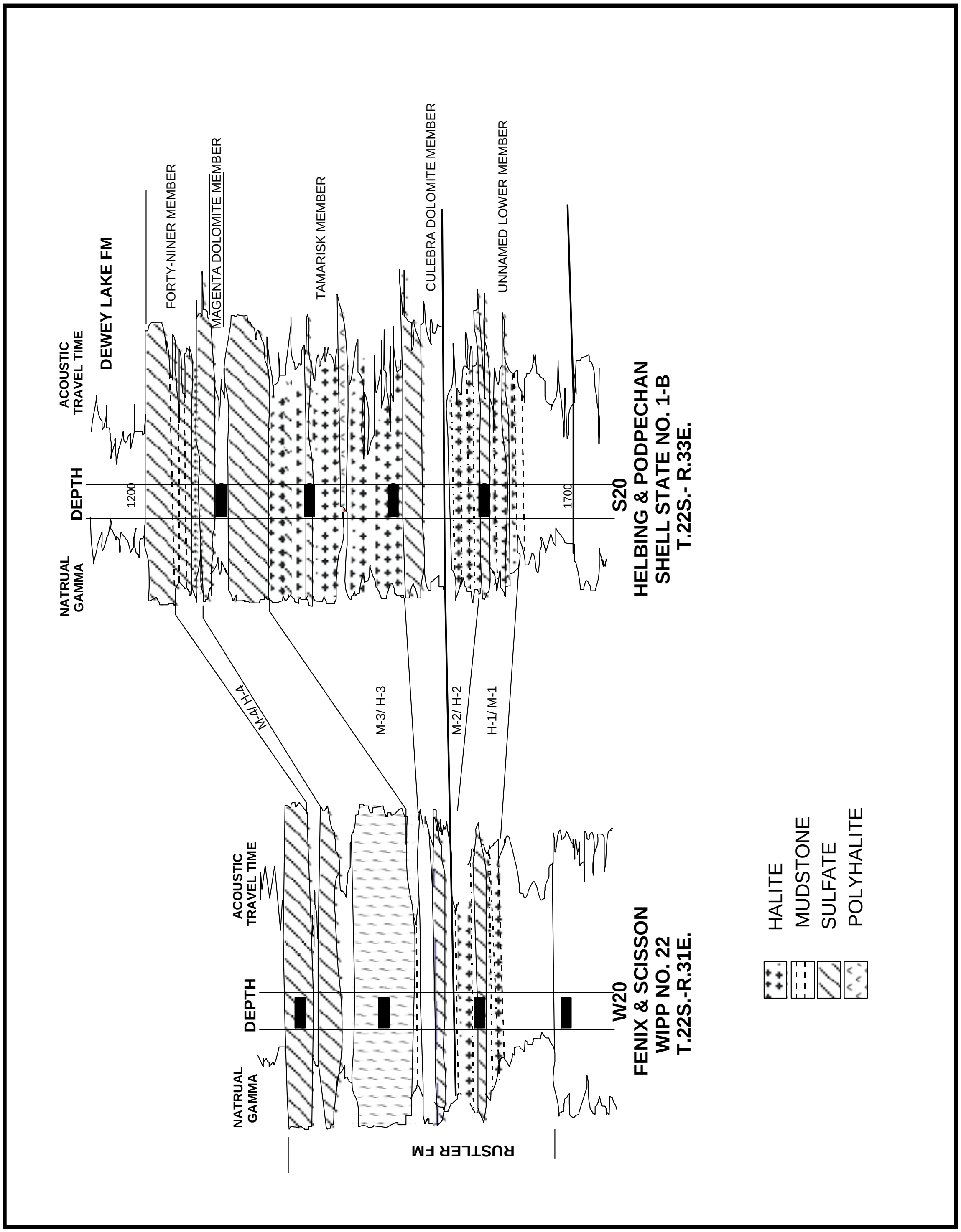


Figure L1-12
Log Character of the Rustler Showing Mudstone-Halite Lateral Relationships



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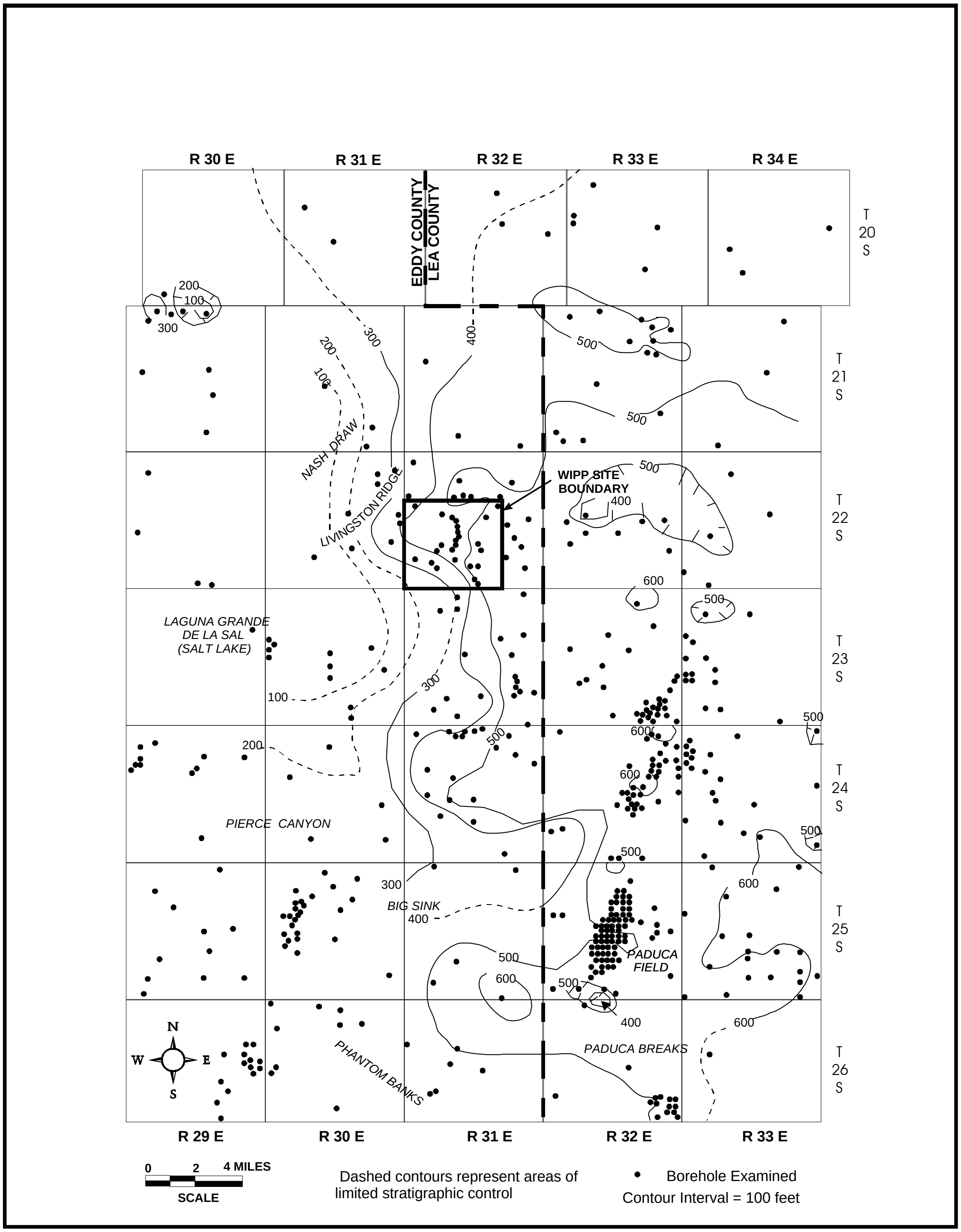


Figure L1-13
Isopach of the Dewey Lake

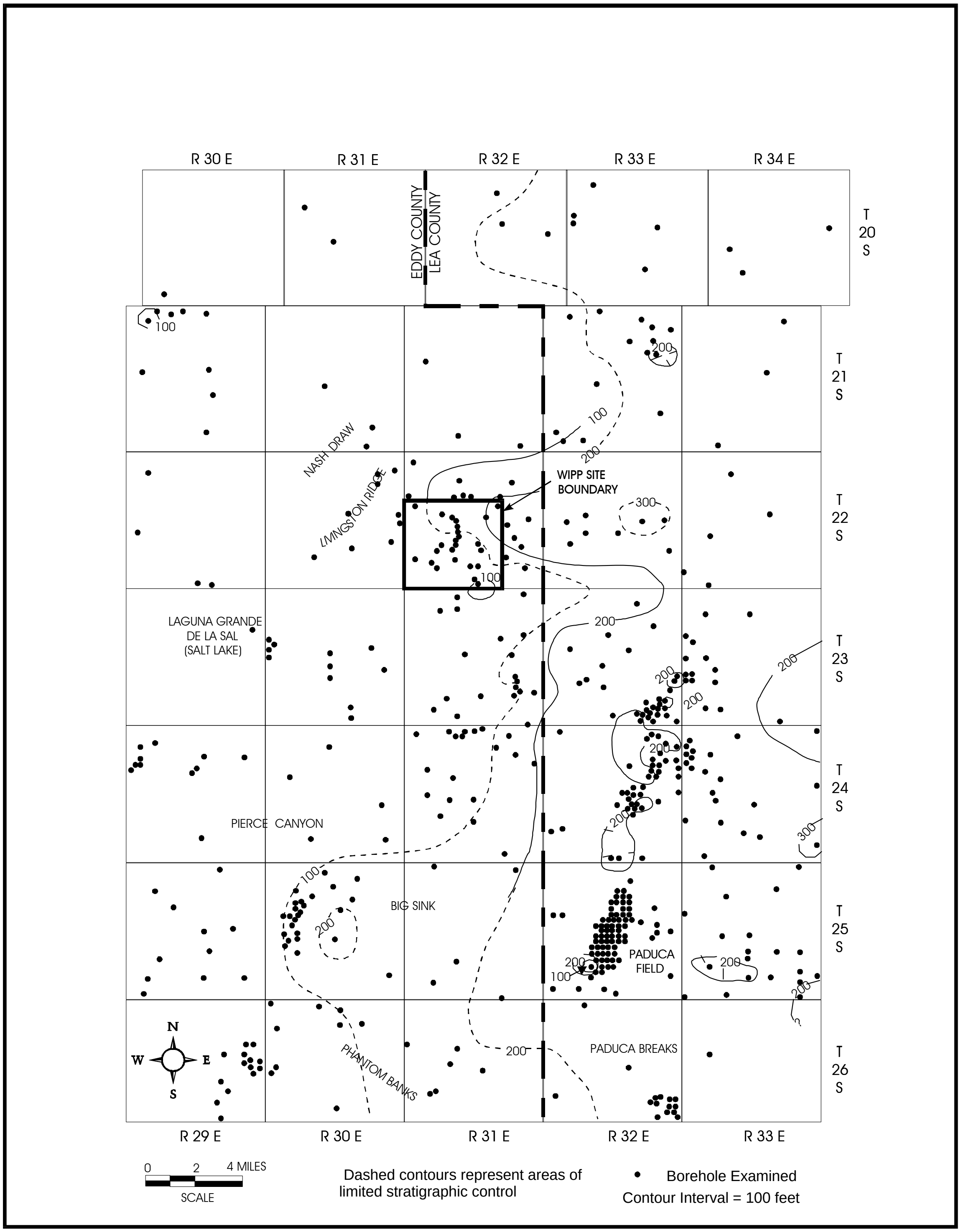


Figure L1-14
Isopach of the Santa Rosa

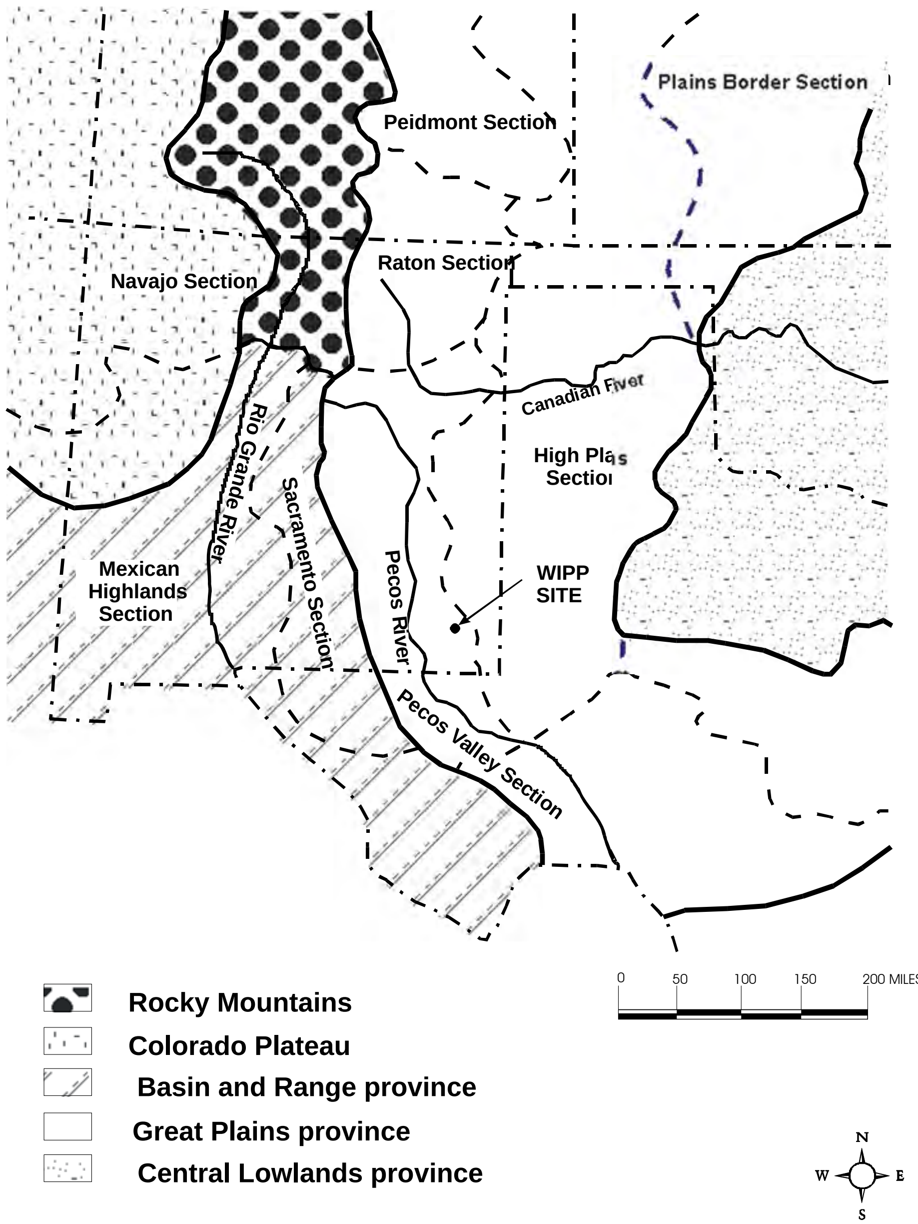


Figure L1-15
Physiographic Provinces and Sections

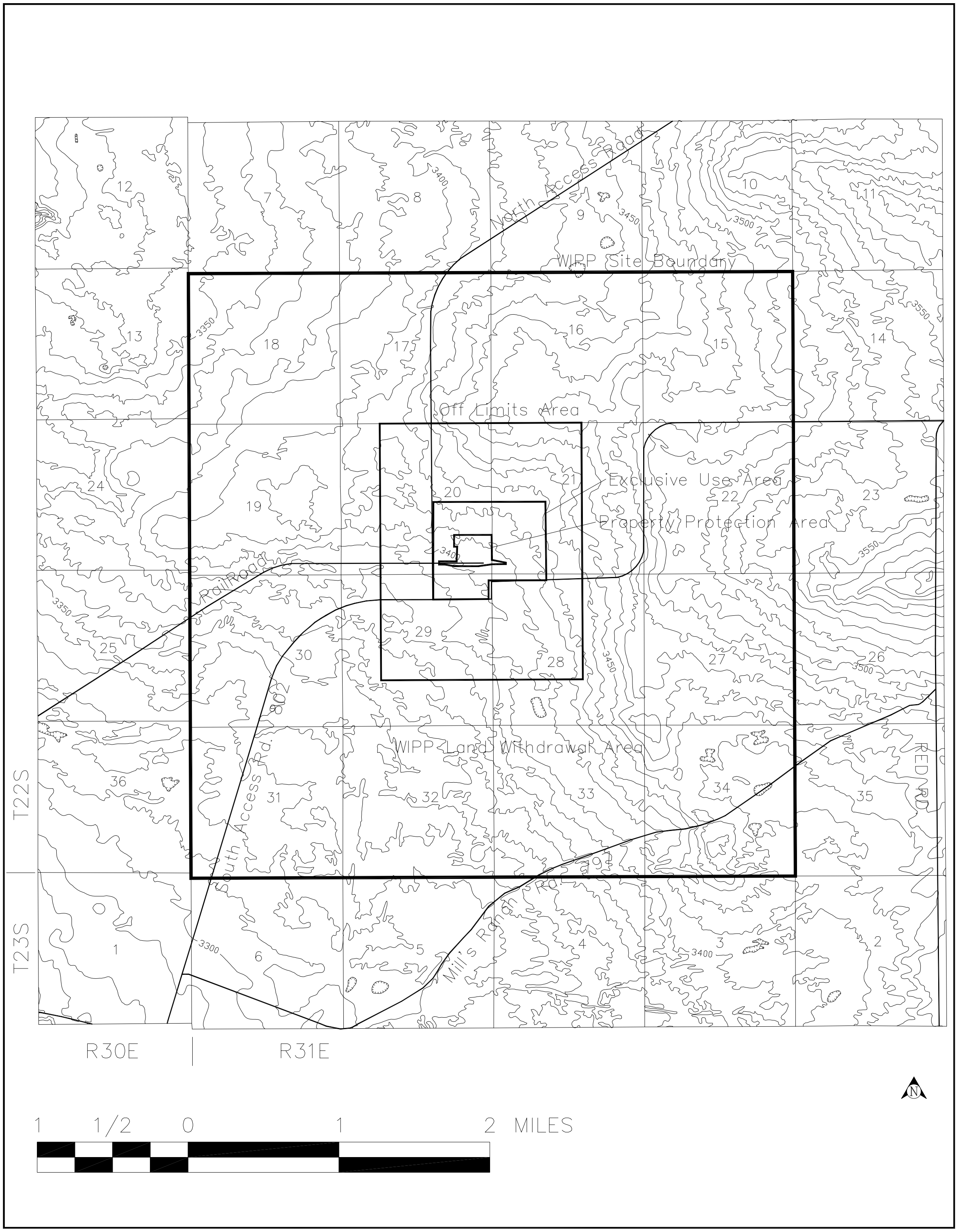


Figure L1-16
Site Topographic Map

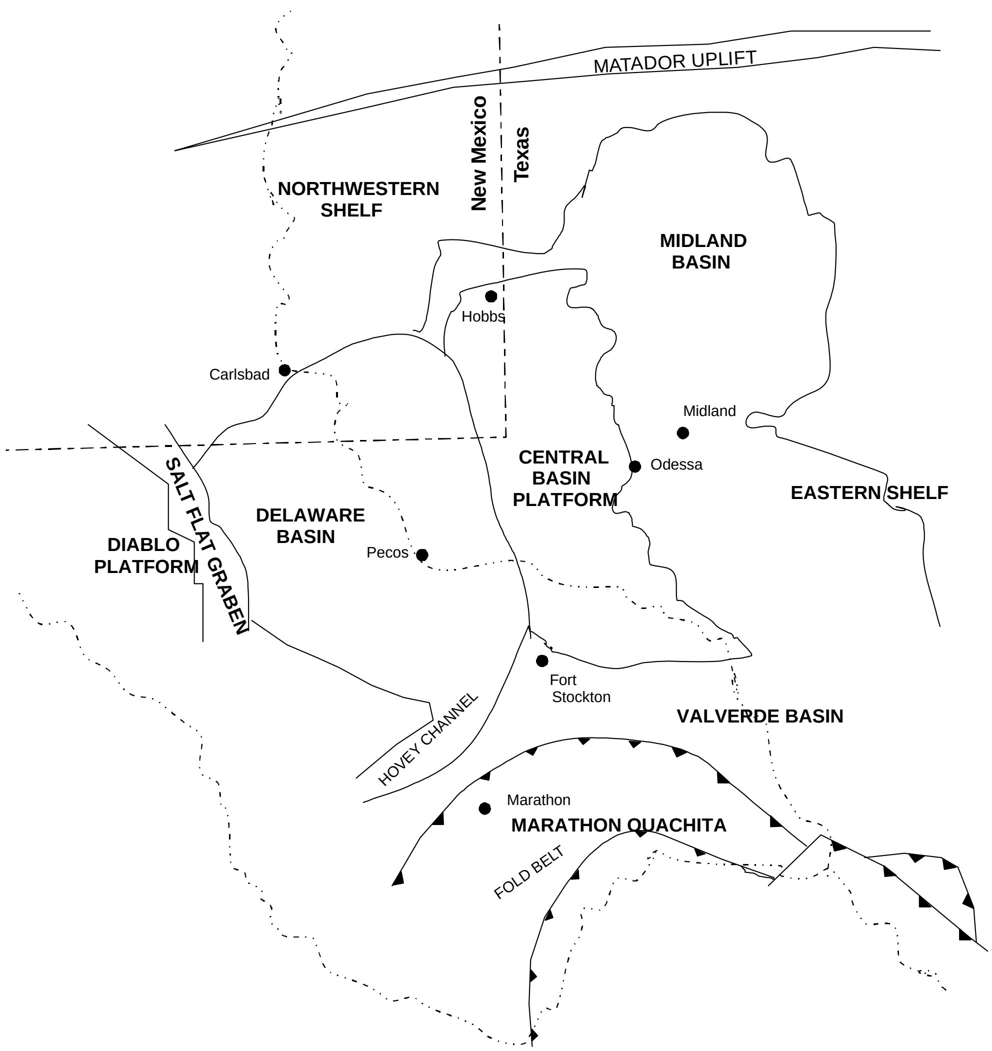


Figure L1-17
Structural Provinces of the Permian Basin Region

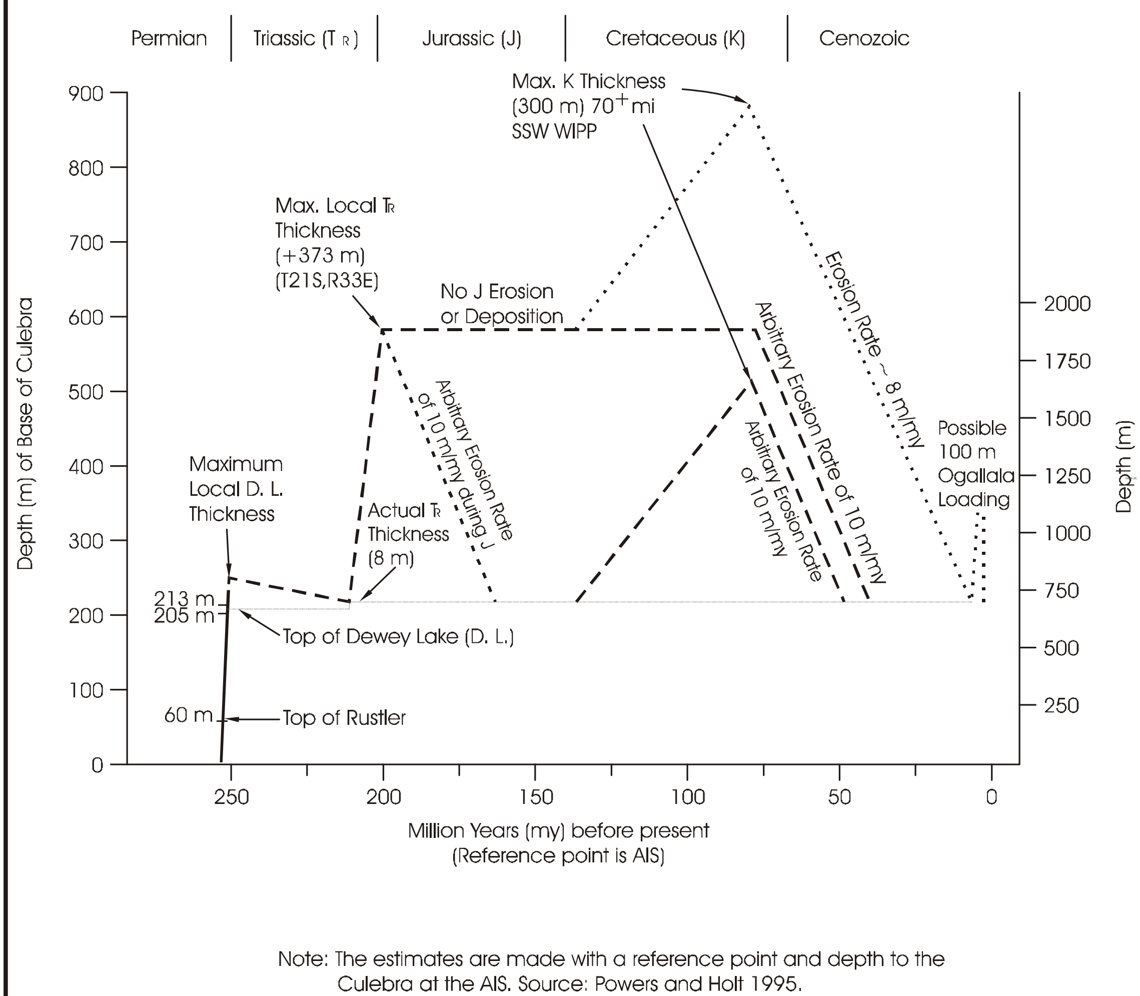


Figure L1-18
Loading and Unloading History Estimated for Base of Culebra

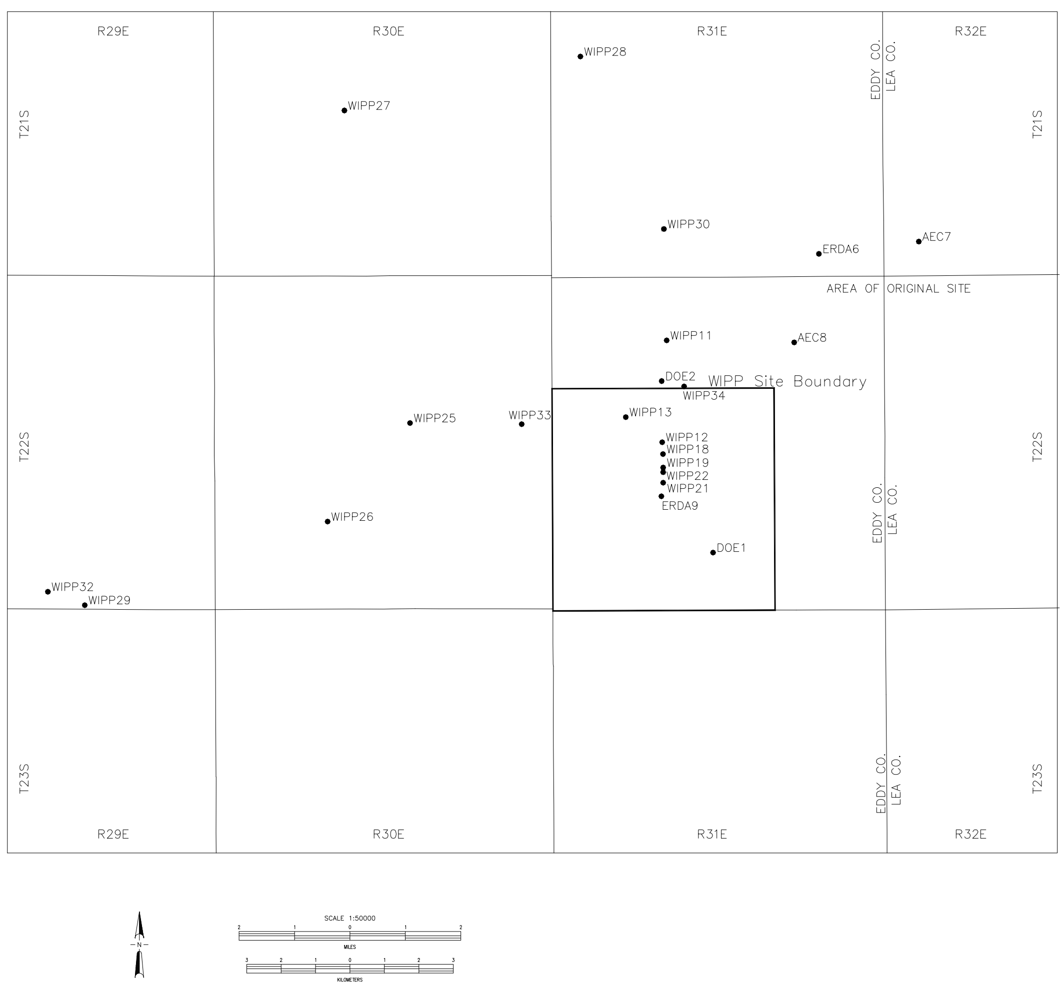


Figure L1-19
Location of Main Stratigraphic Drillholes

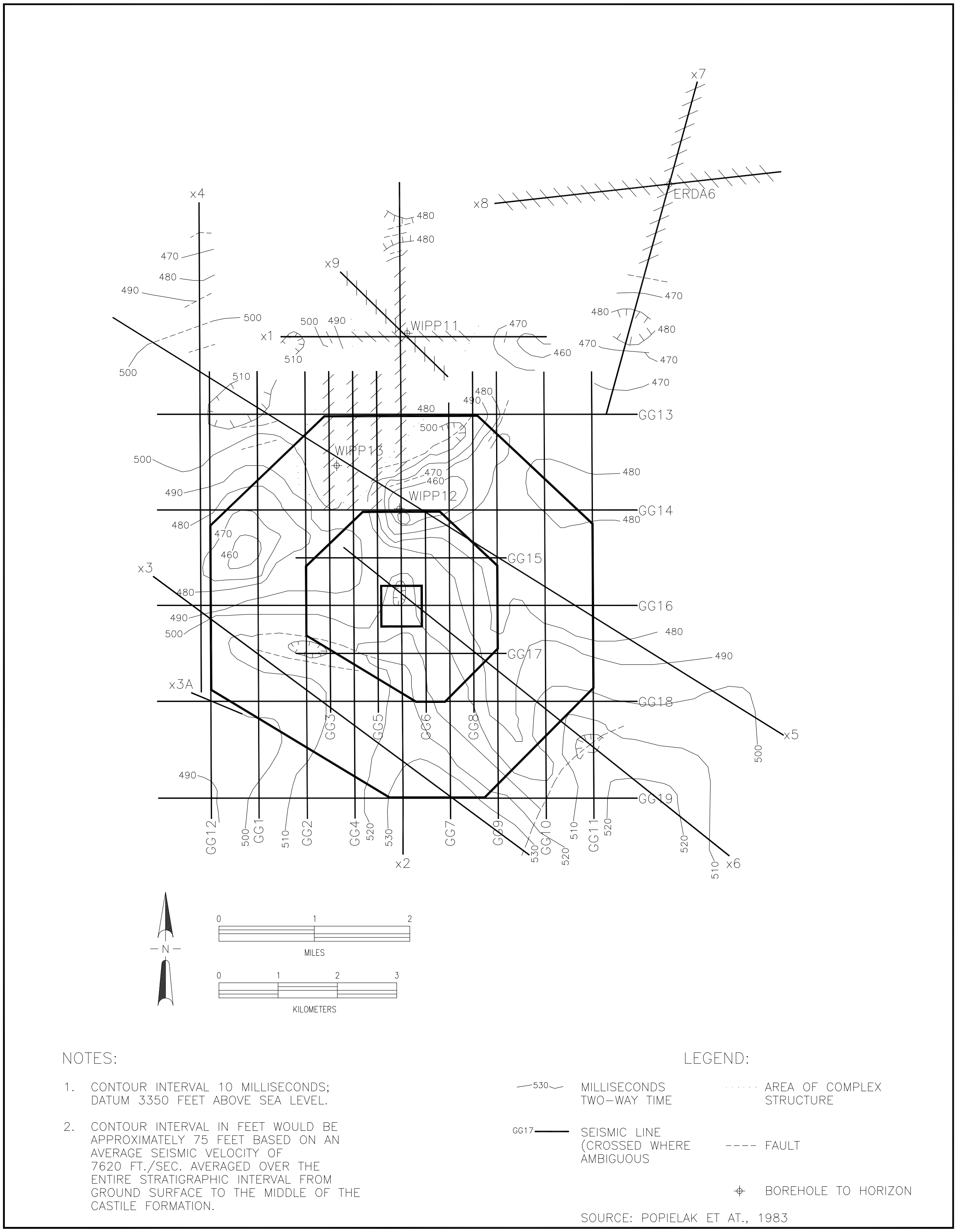


Figure L1-20
Seismic Time Structure Middle Castile Formation

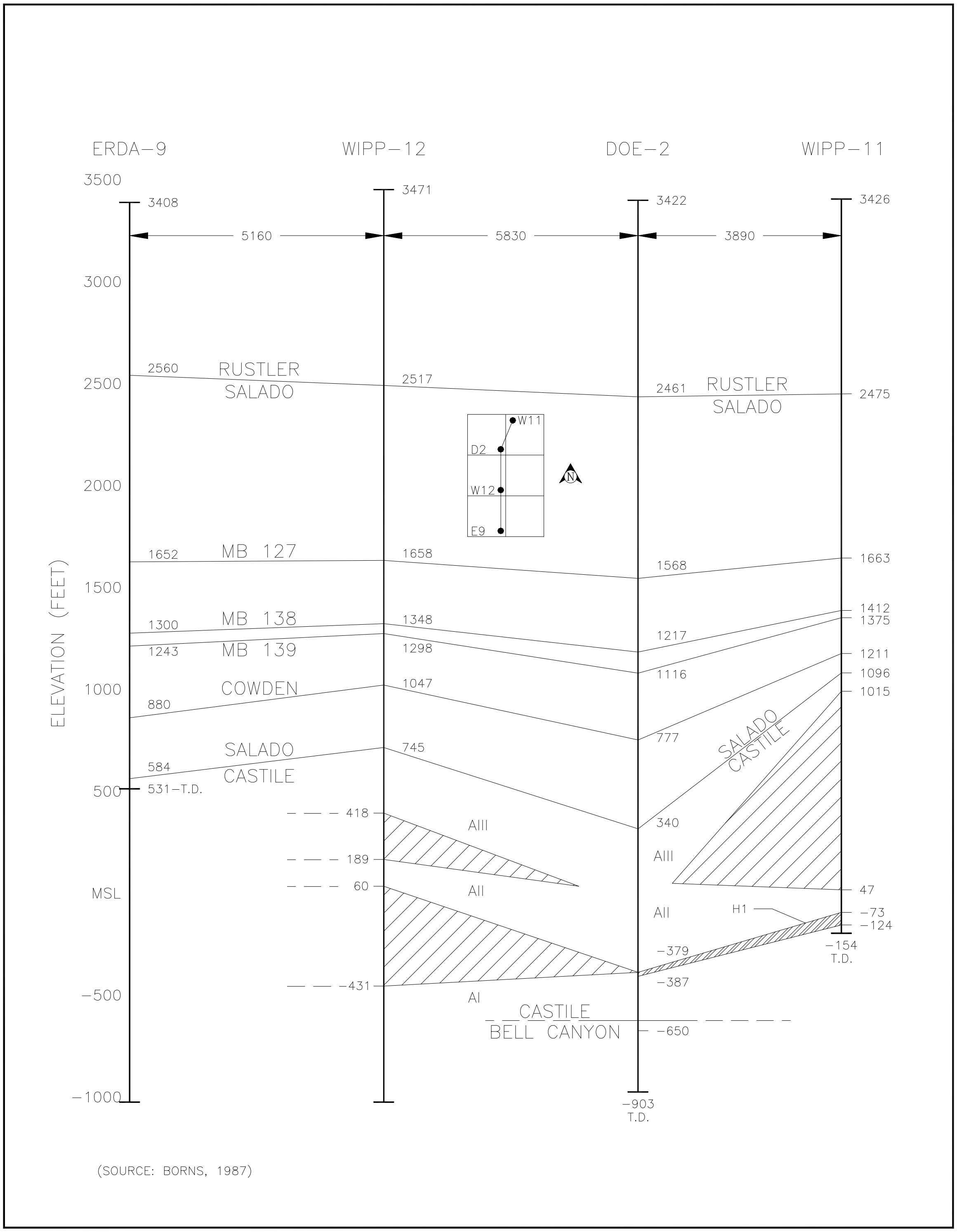


Figure L1-21
Fence Diagram Using DOE-2 and Adjacent Holes

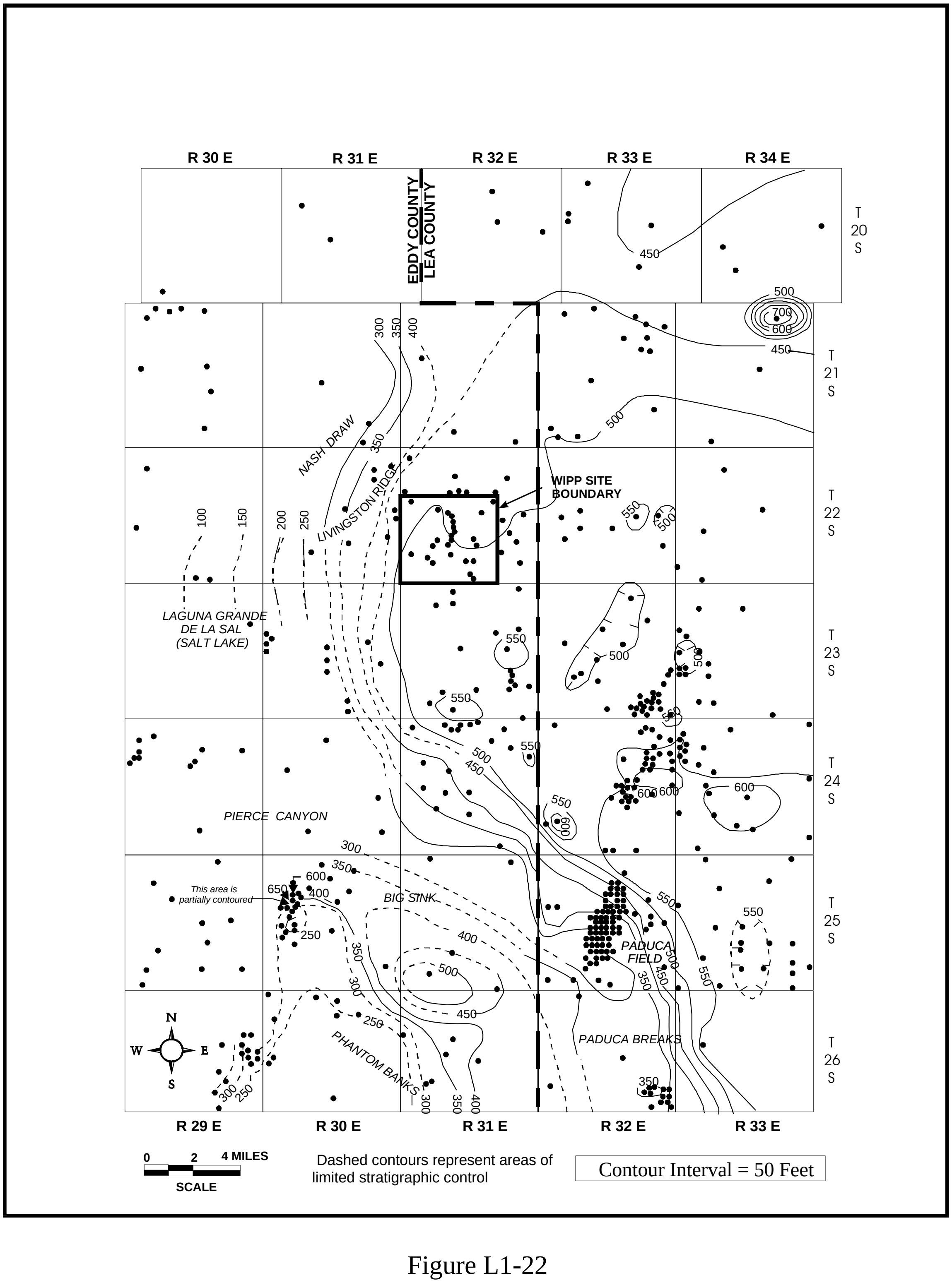


Figure L1-22
Isopach from the Top of the Vaca Triste to the Top of the Salado

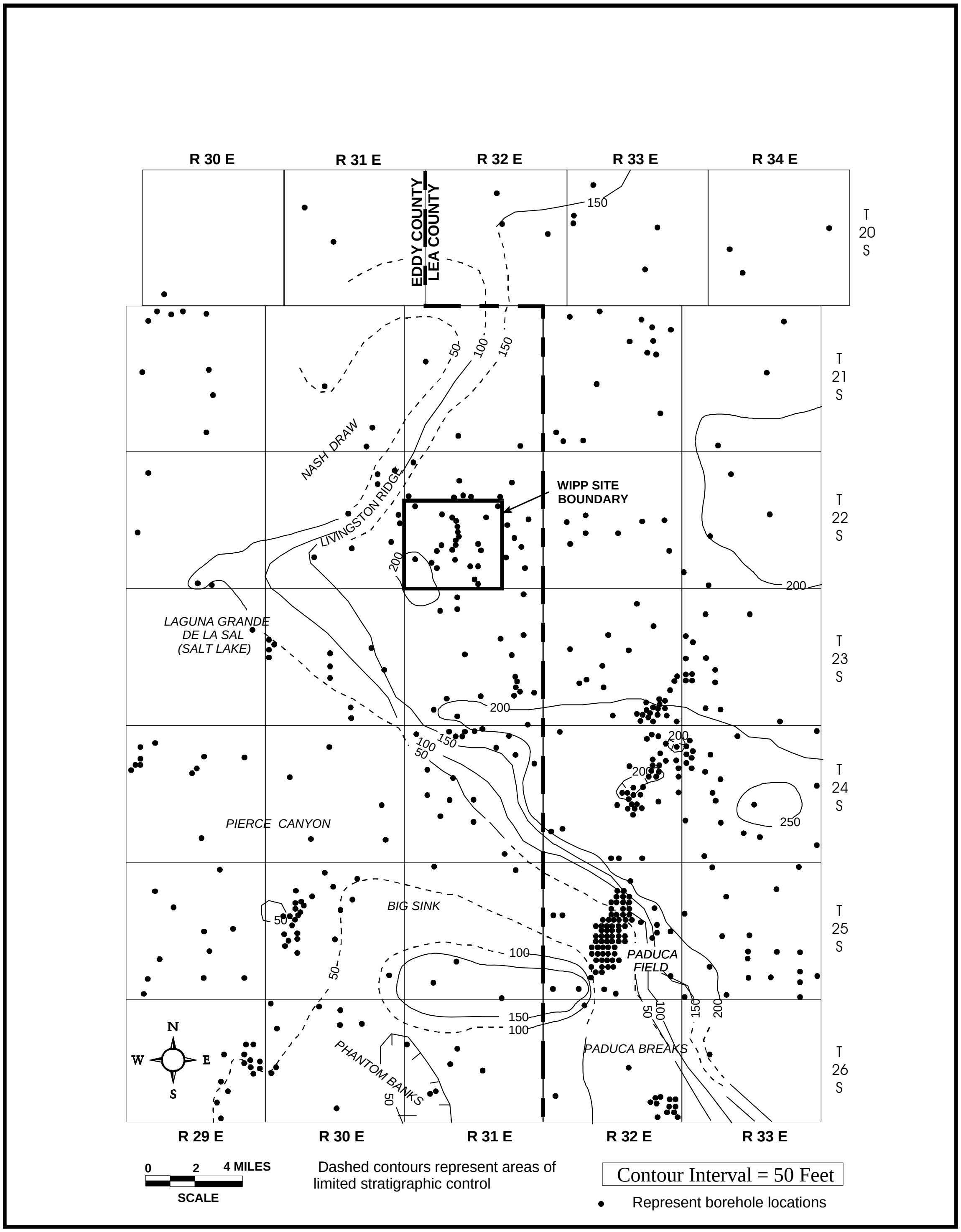


Figure L1-23
Isopach from the Base of MB 103 to the Top of the Salado

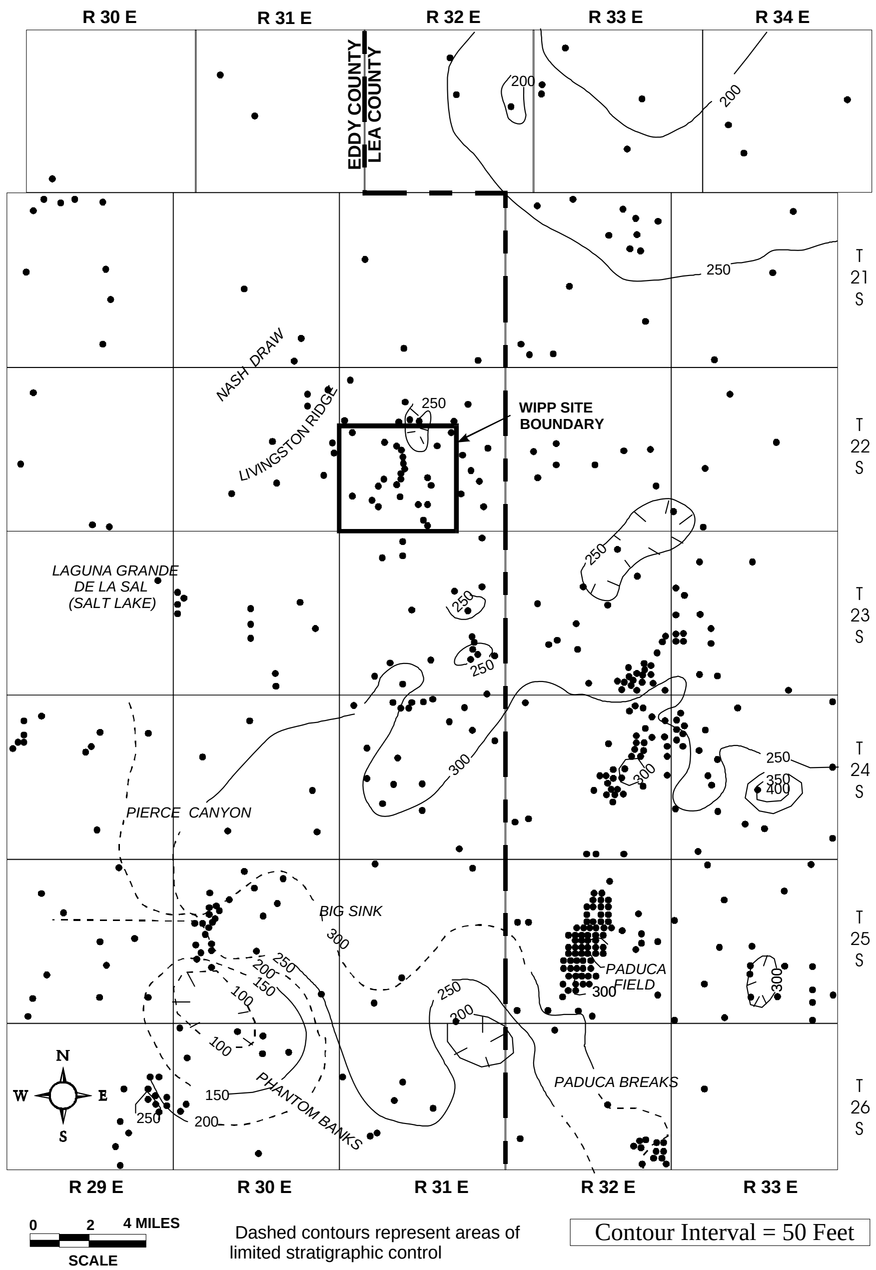


Figure L1-24
Isopach from the Base of MB 123/124 to the Base of the Vaca Triste

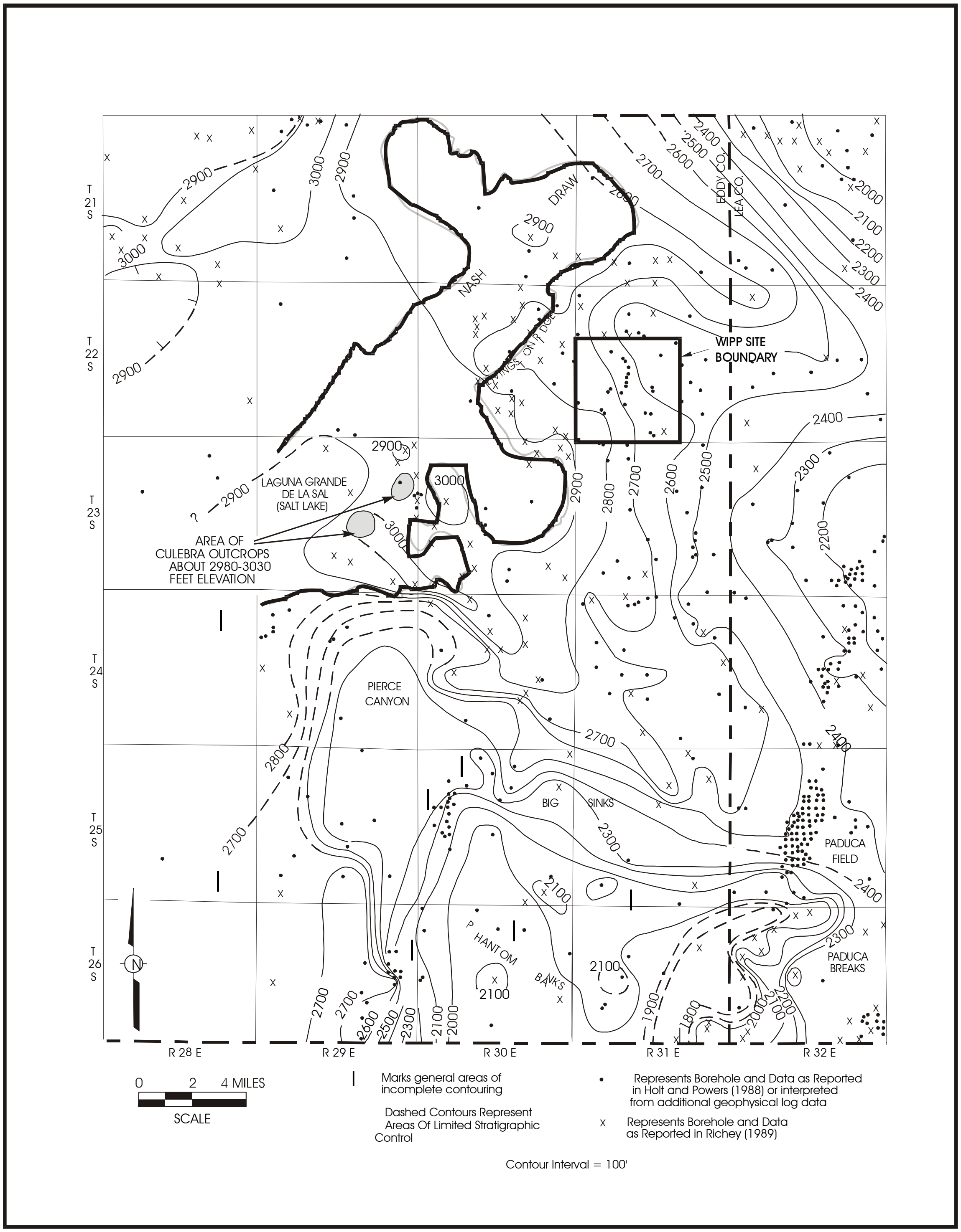


Figure L1-25
Isopach from the Base of MB 123/124 to the Base of the Vaca Triste

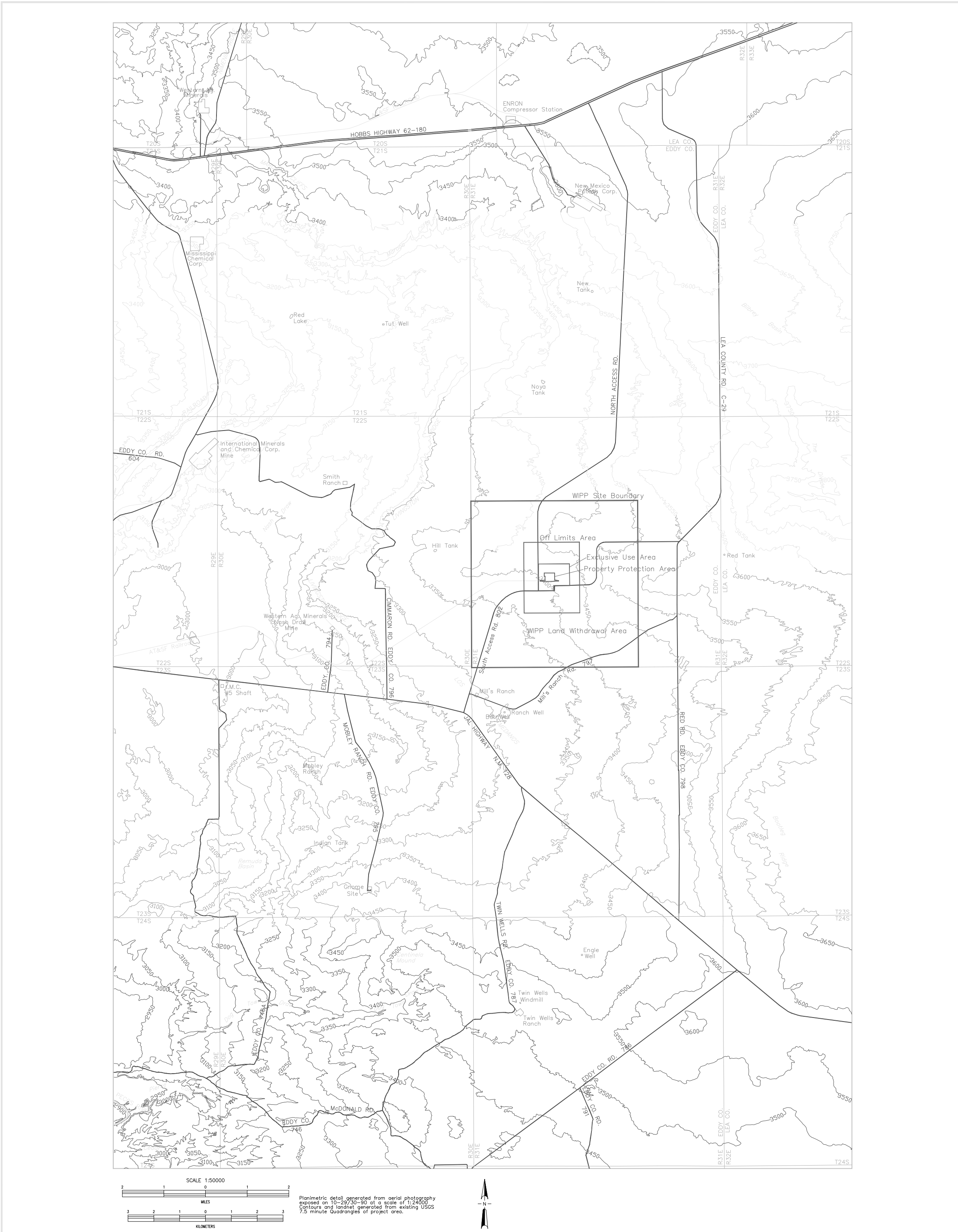
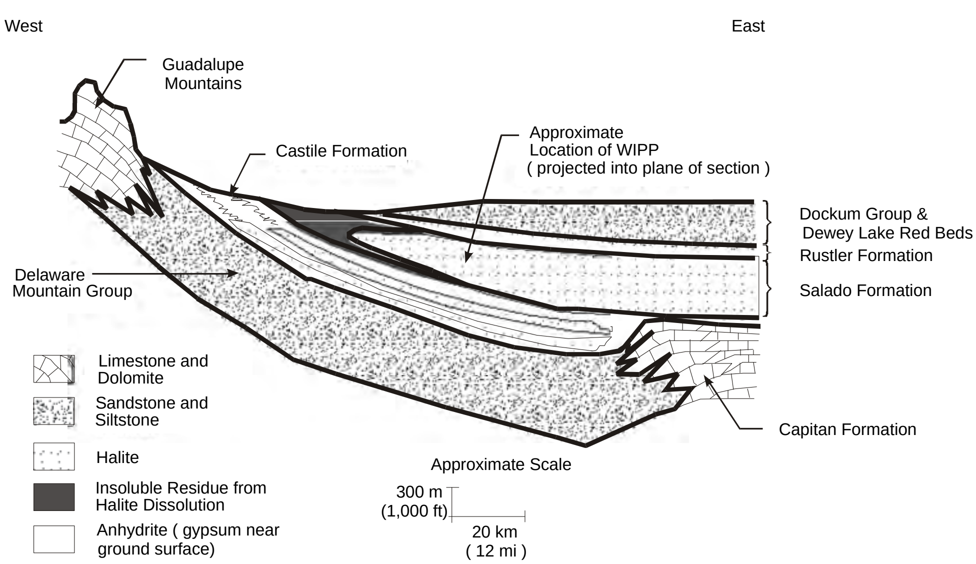
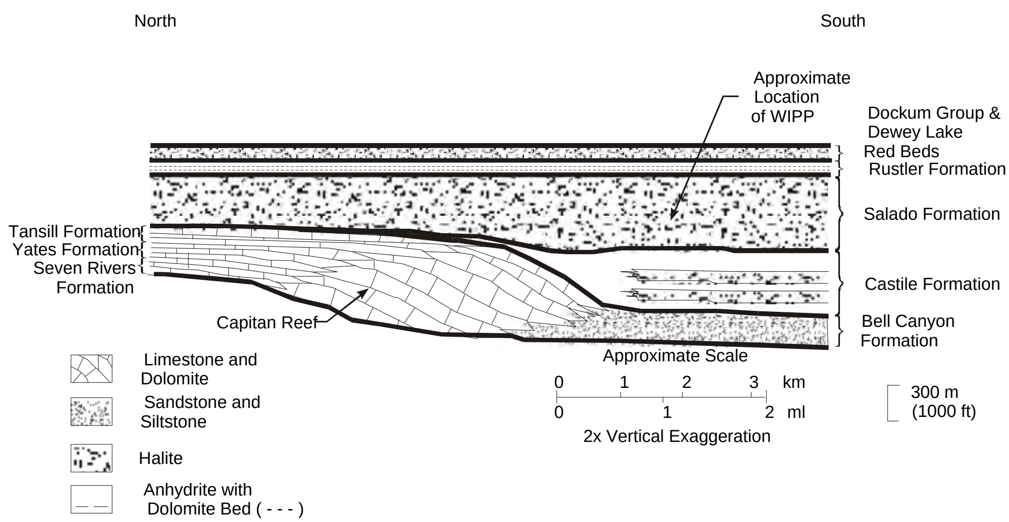


Figure L1-26
Drainage Pattern in the Vicinity of the WIPP Facility



Source: Sandia, 1992, 2, 2-7.

Figure L1-27
Schematic West-East Cross-Section through the North Delaware Basin



Source: Sandia, 1992, 2, 2-8.

Figure L1-28
Schematic North-South Cross-Section through the North Delaware Basin

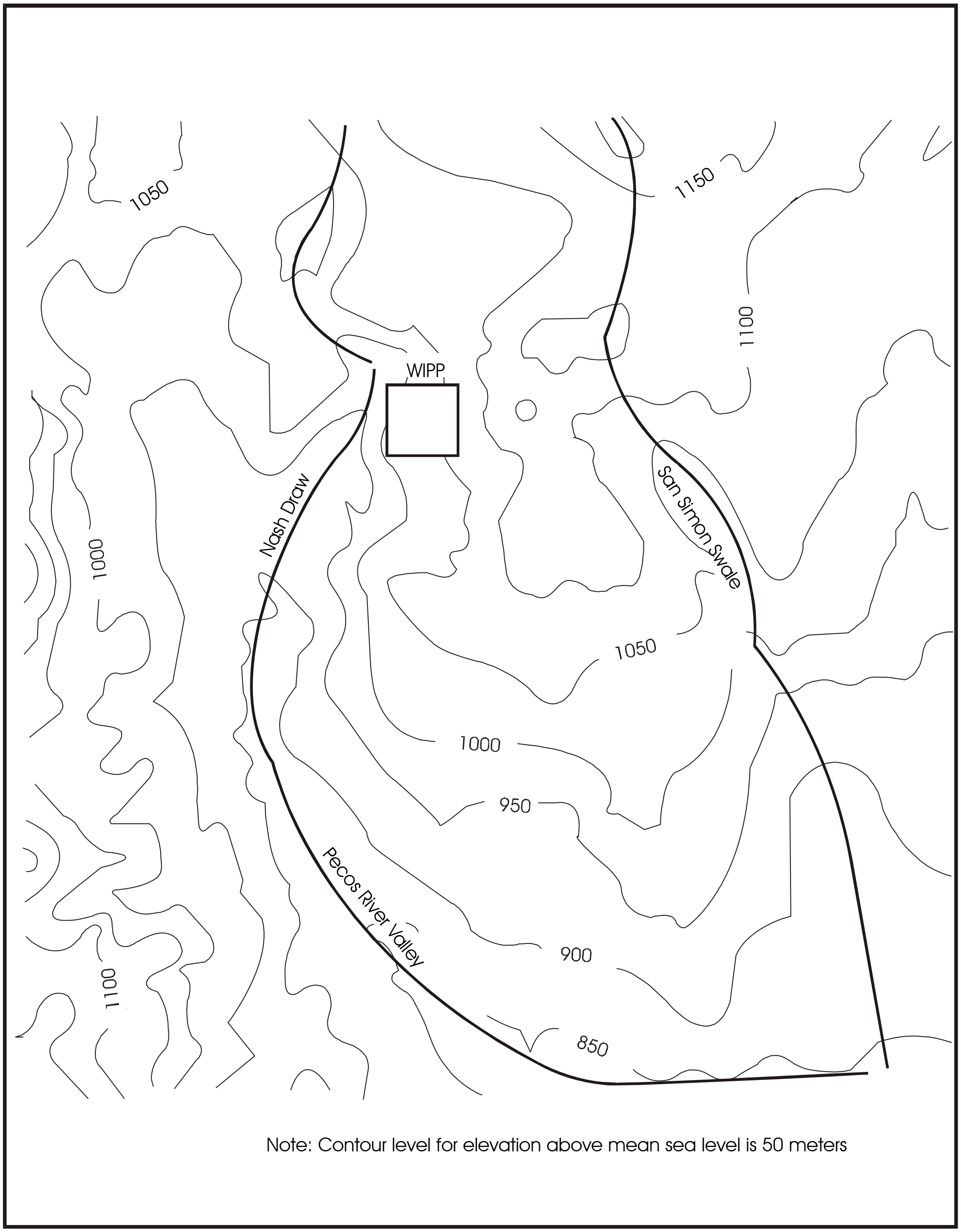


Figure L1-29
Outline of the Groundwater Basin Model Domain on a Topographic Map

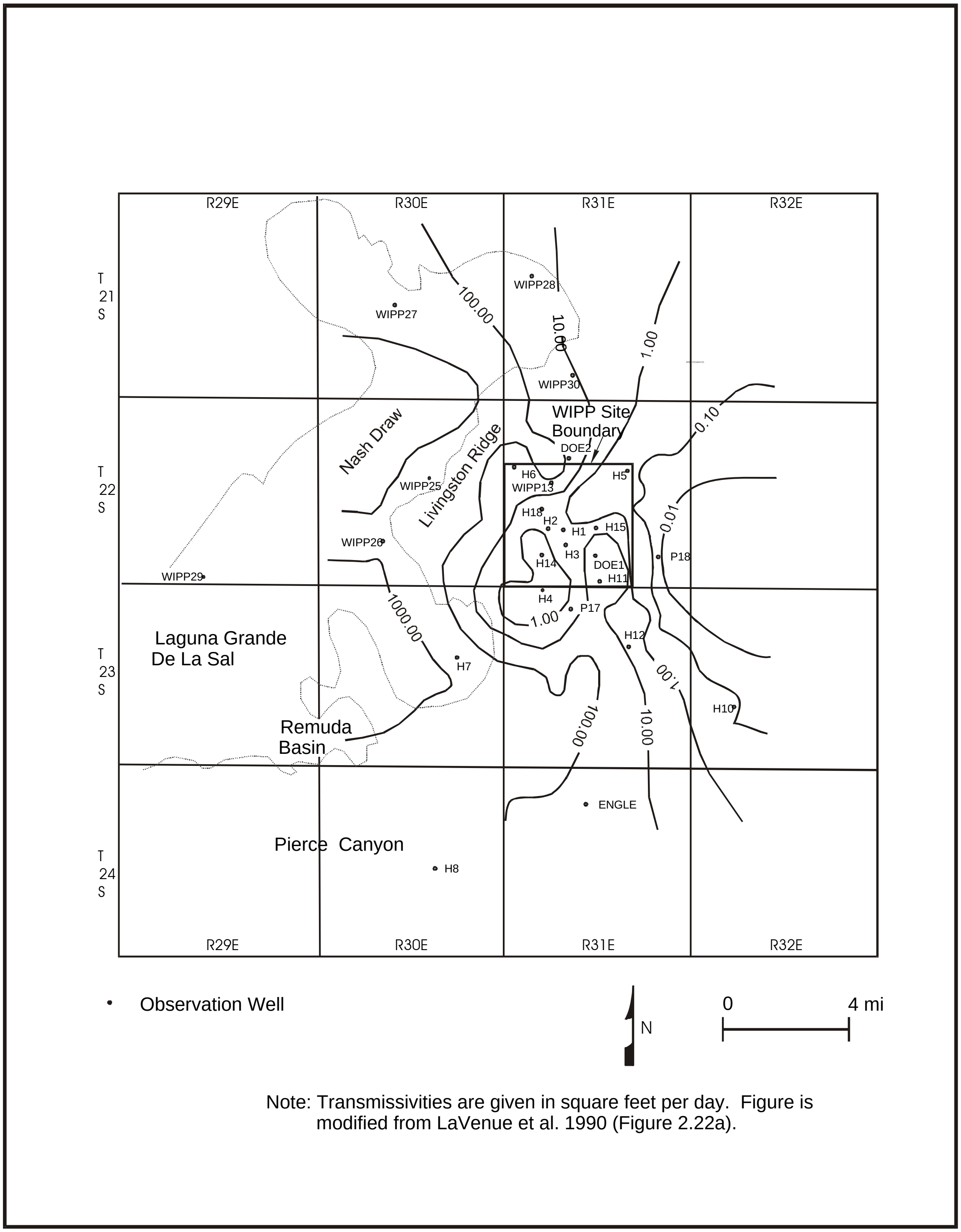


Figure L1-30
Transmissivities of the Culebra

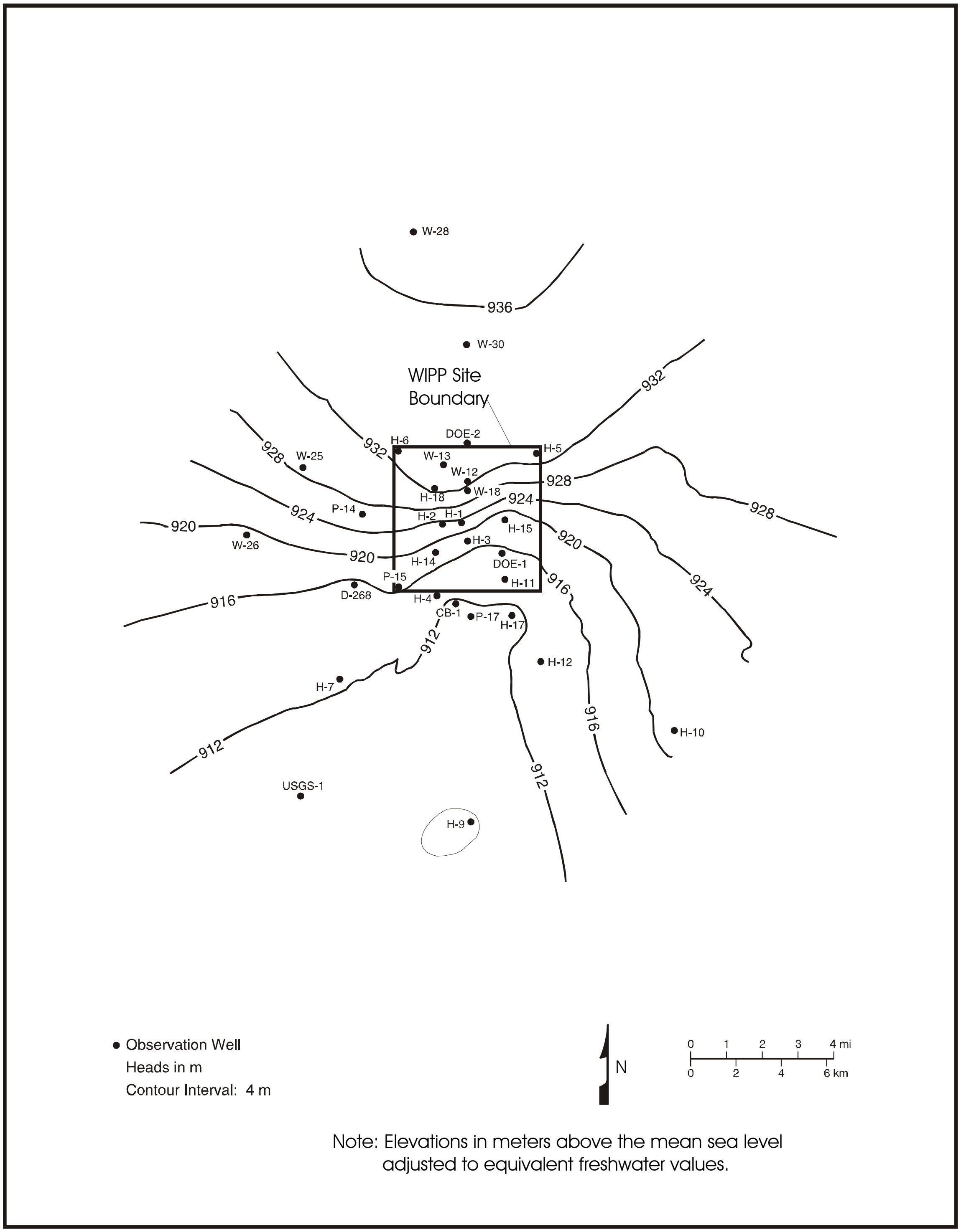


Figure L1-31
Hydraulic Heads in the Culebra

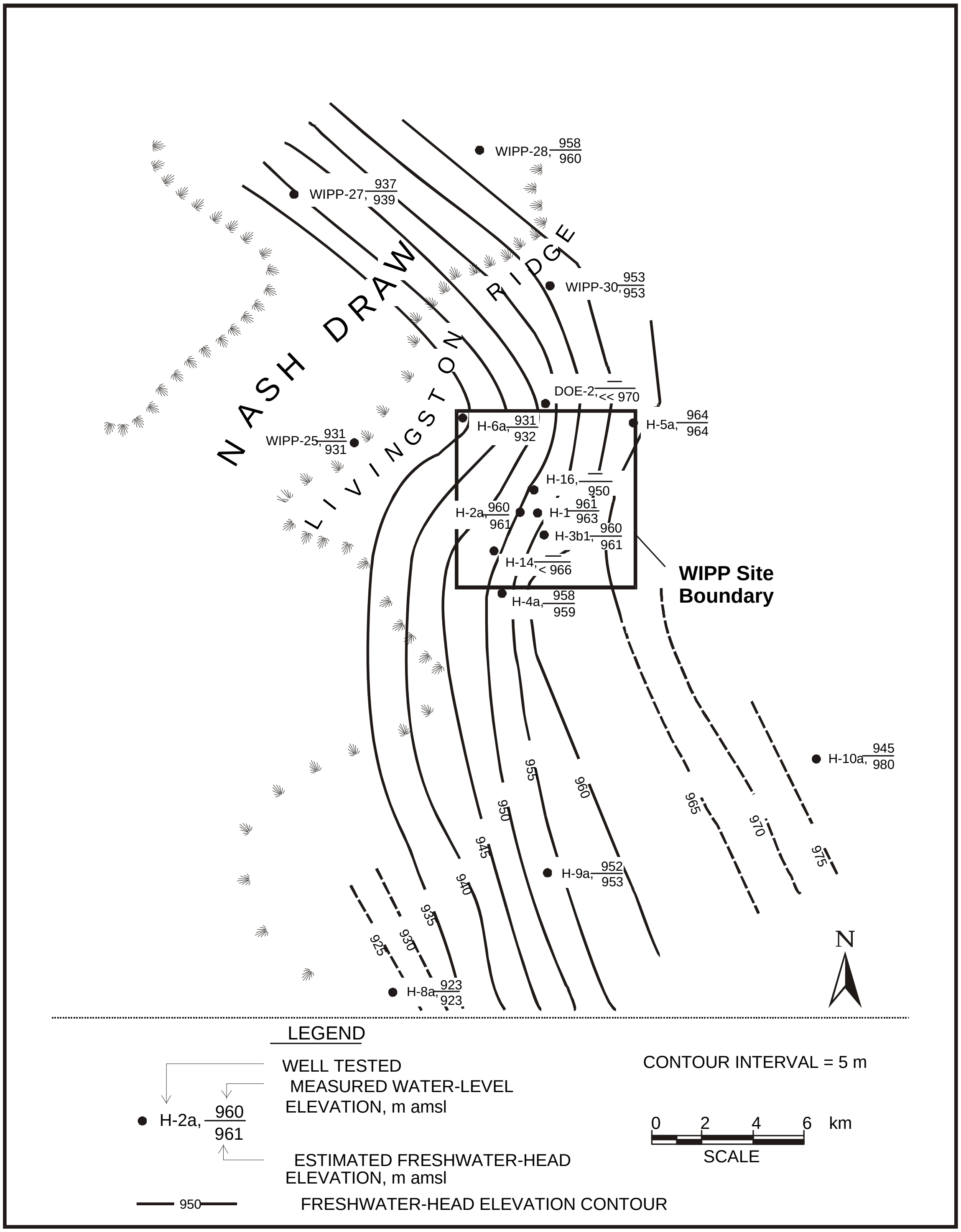


Figure L1-32
Hydraulic Heads in the Magenta

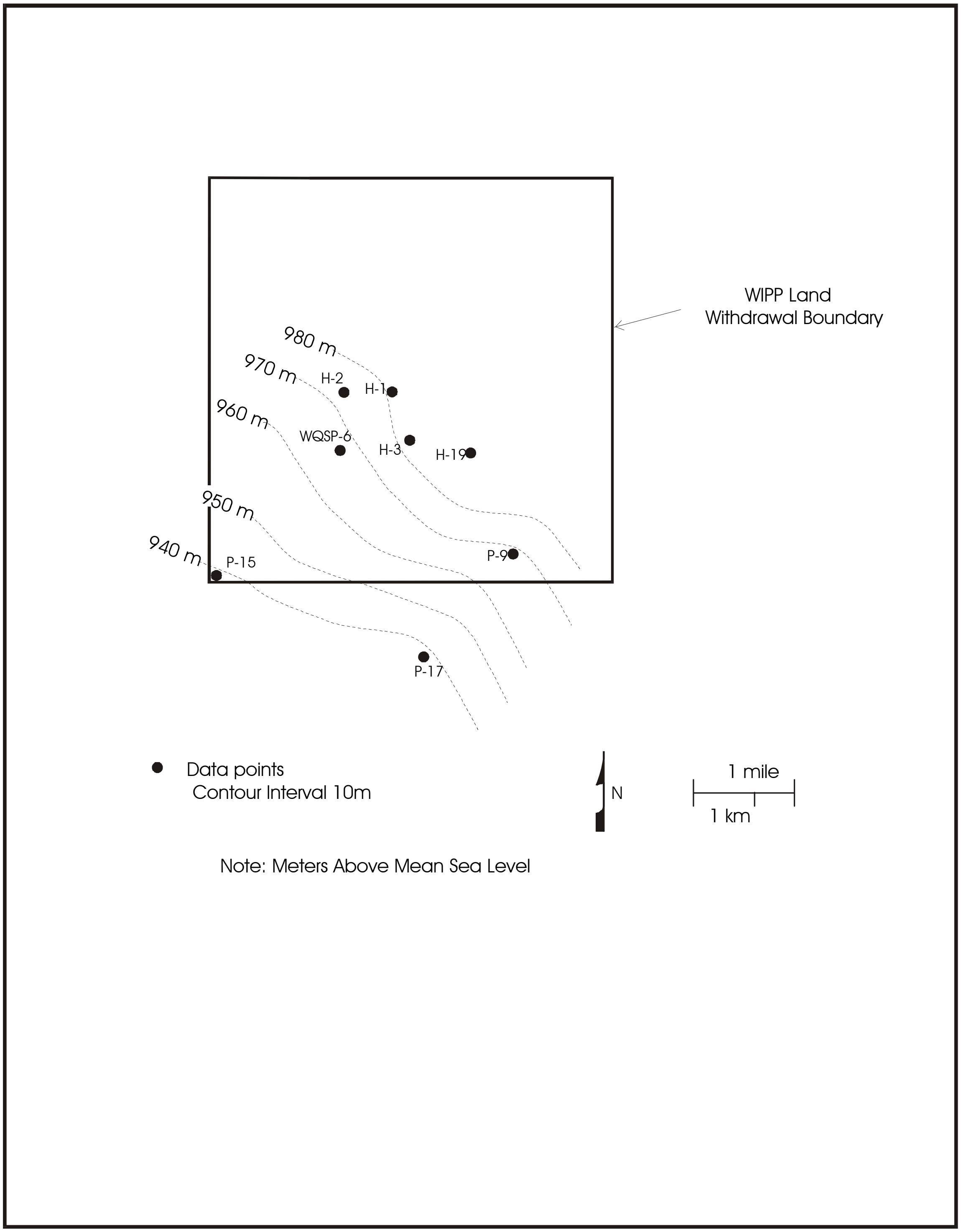


Figure L1-33
Interpreted Waste Table Surface

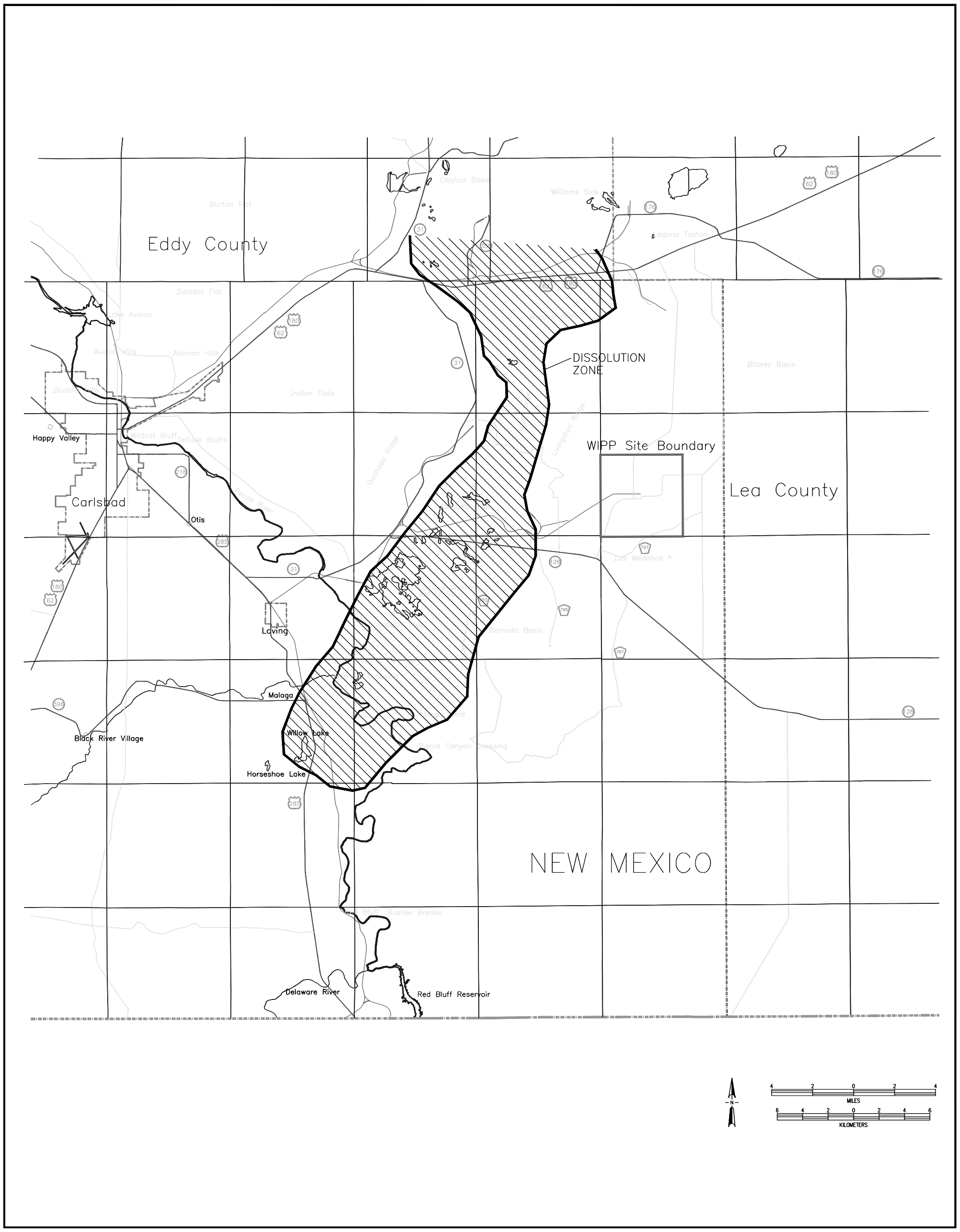


Figure L1-34
Brine Aquifer in the Nash Draw

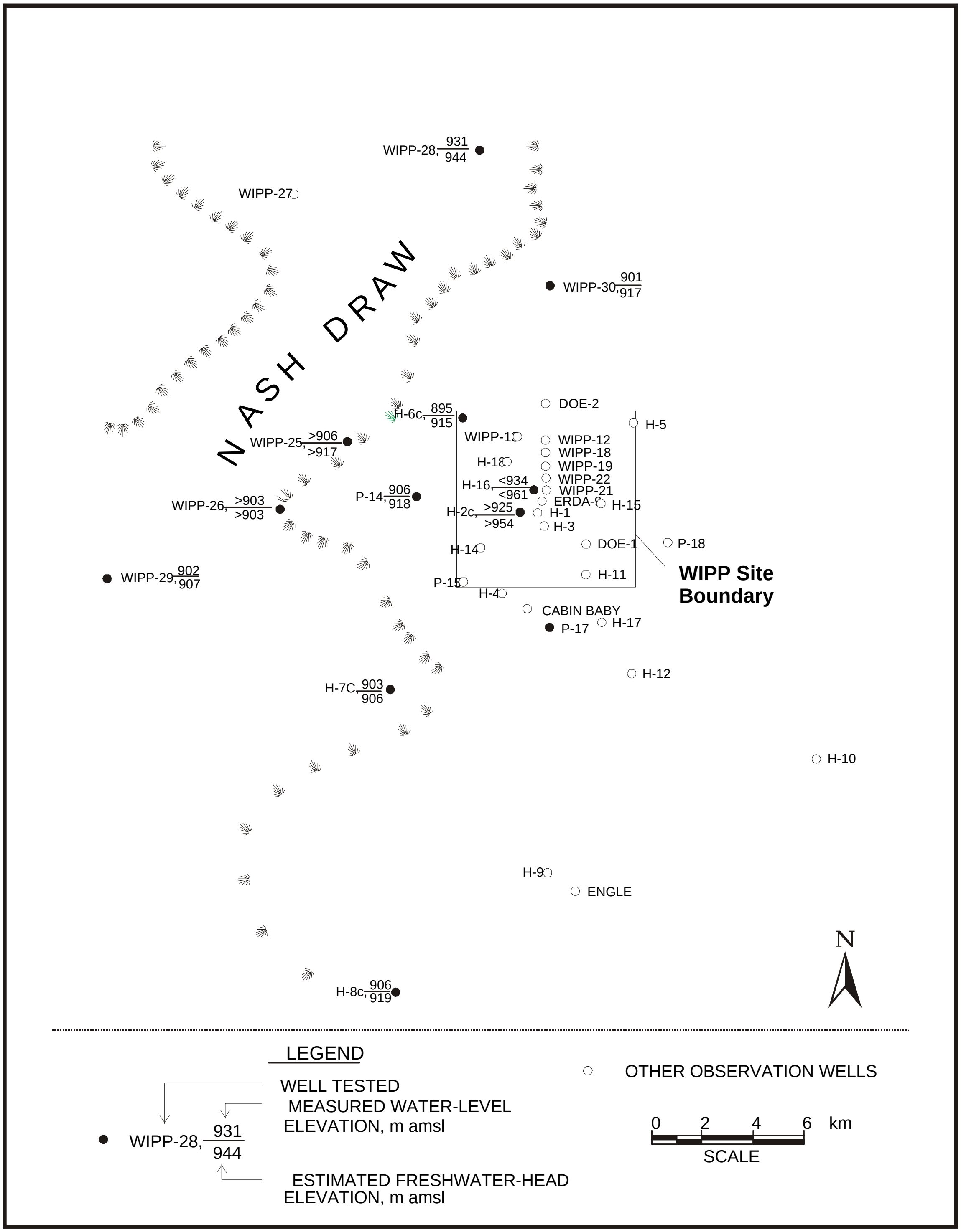


Figure L1-35
Measured Water Levels and Estimated Freshwater Heads
of the Unnamed Lower Member and Rustler-Salado Contact Zone

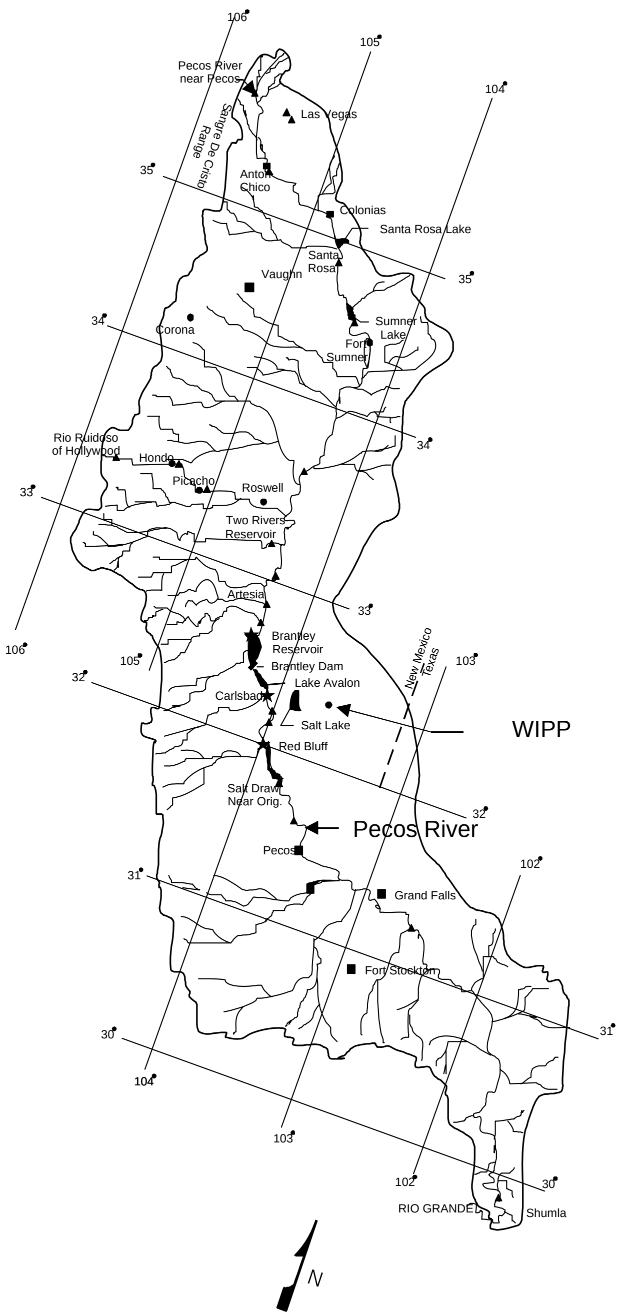


Figure L1-36
Location of Reservoirs and Gauging Stations in the Pecos River Basin

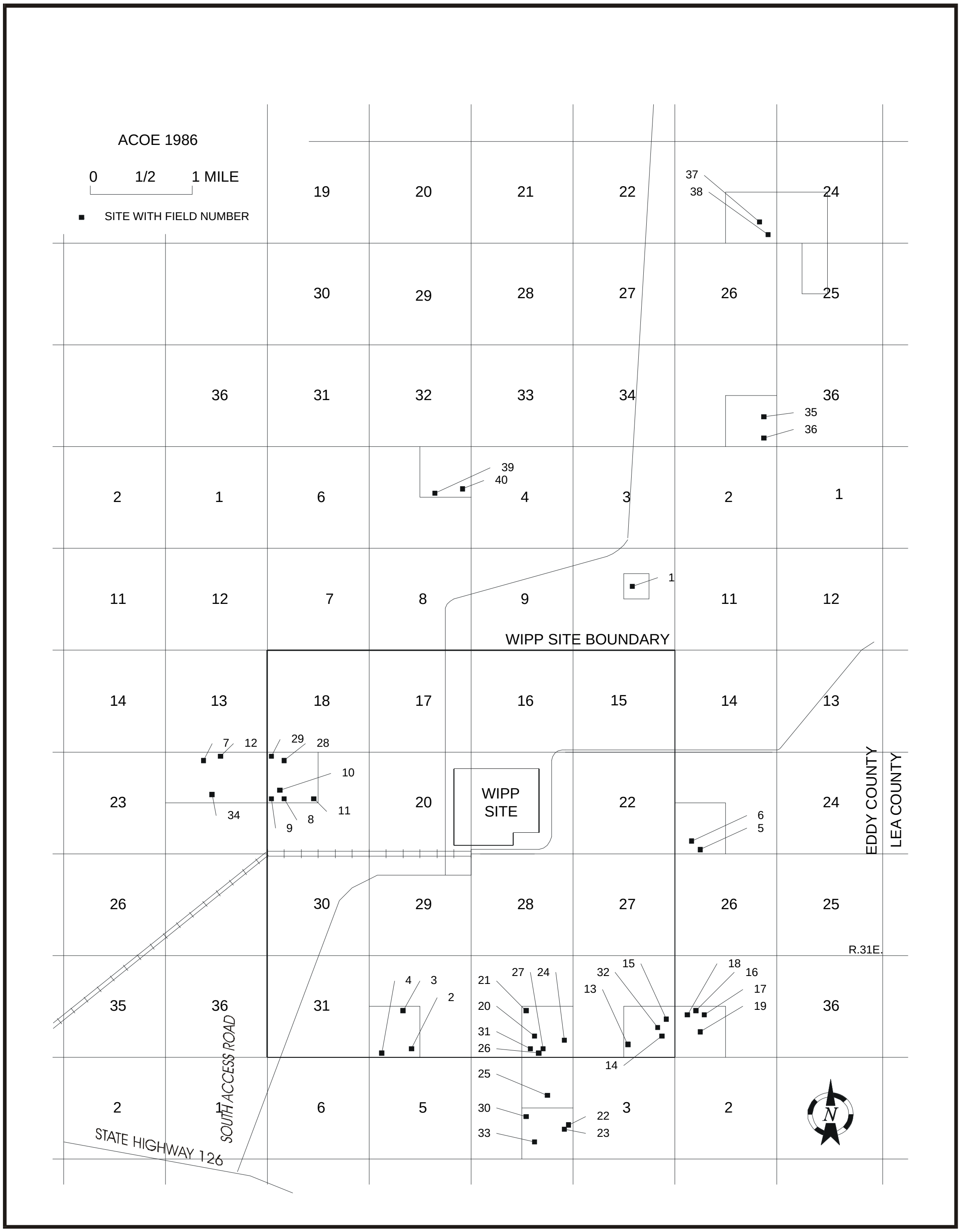


Figure L1-37
Mariah Study Archaeological Sites

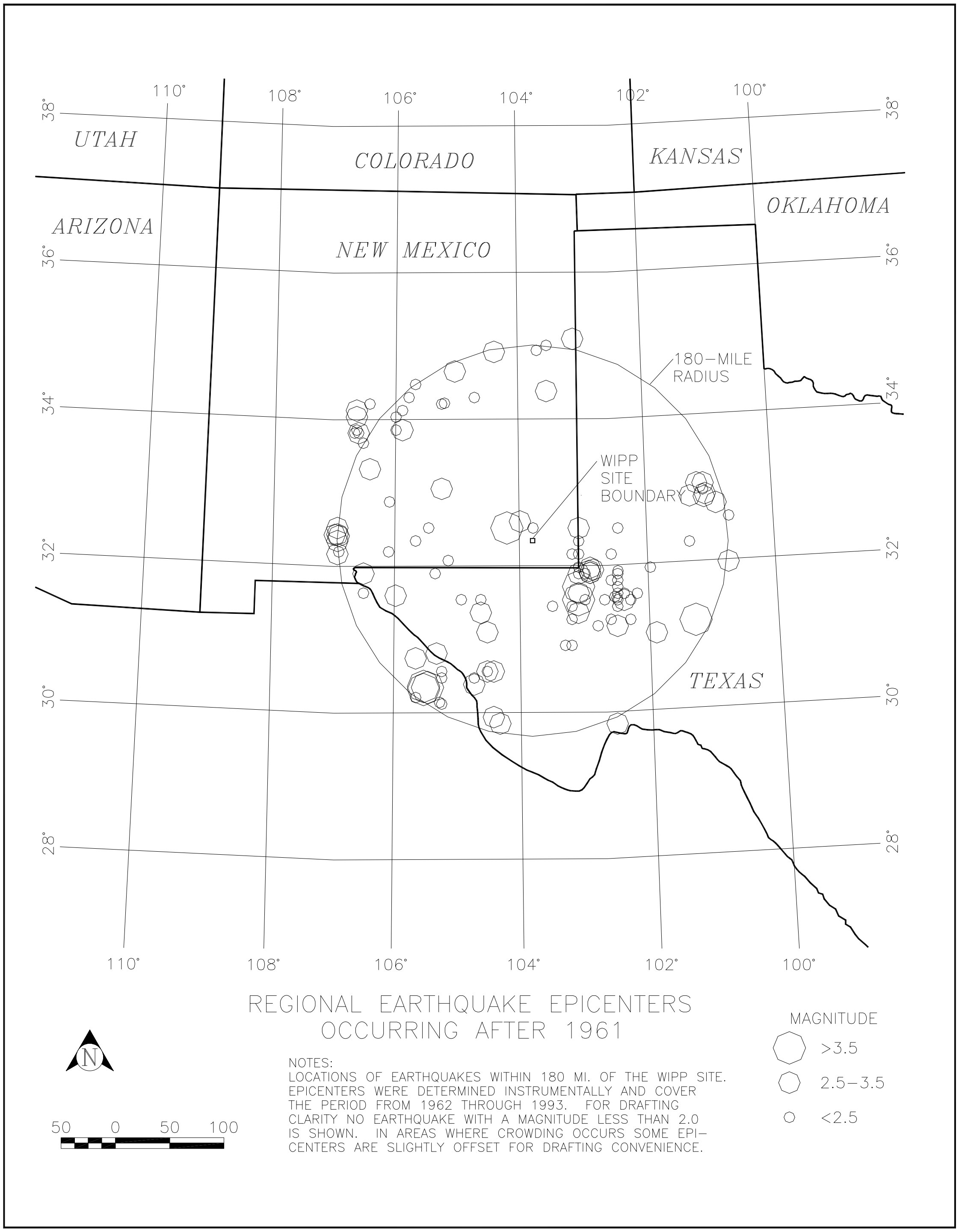


Figure L1-38
Regional Earthquake Epicenters Occurring After 1961