WPO 29530

Report to

SANDIA LABORATORIES

on

DEEP DISSOLUTION OF SALT, NORTHERN DELAWARE BASIN NEW MEXICO

by

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CONCLUSIONS

(relative to the W.I.P.P. site)

1. The present W.I.P.P. site is probably the best locality available in the central and northern Delaware basin from the point of view of vulnerability to the effects of regional deep-seated dissolution.
2. Salt in the Delaware basin as a whole has been subjected to extensive dissolution, with 50 percent of the original salt dissolved. The northern part of the basin, however, has been less subjected to deep dissolution than the central part of the basin.
3. The lower Salado salt beds have been the most active zone of dissolution elsewhere in the basin, presumably due to greater permeability related to a break in deposition between the Castile and Salado formations. The advancing effects of lateral deep dissolution at the lower Salado horizon can be expected to reach the disposal site before the removal of the overlying salt beds.
4. Estimates of the rate of deep-seated dissolution cannot be made with any degree of confidence with present data. The progression of deep dissolution has been from the south to the north in the basin and one may expect the same undermining effects of dissolution to develop in the northern basin area as have already developed in the central basin area and these will reach the site locality within the next few million years.
5. Localized features of deep dissolution (breccia pipes, deep-seated sinks) are common in the basin and around the inner reef margin.

These features probably originate as collapse chambers in salt beds immediately overlying the reef and basin aquifers. The process of dissolution and collapse that formed the localized structures is a continuing one, possibly subject to climatic rejuvination.

6. Available information suggests that salt anticlinal and associated deep-seated sink structures are present in the northern part of the disposal area. Locations with similar features have been the sites of expanded or advancing dissolution activity elsewhere in the basin and have been associated with geopressurized brine. A sink in this area may be in communication with the underlying aquifer or with the permeable horizon between the Castile and Salado formations.

RECOMMENDATIONS

1. If a decision should be forthcoming to develop the present W.I.P.P. site for a nuclear waste disposal facility, a number of geologic problems related to deep-seated dissolution remain to be evaluated, as follows:

   a. Several known deep-seated sink features within the basin should be cored near their centers to establish the horizon of active dissolution that produced the sink. One of these should be related to an anticlinal structure and one to a sink with no known associated anticline. The anticipated coring of the depression in Sec. 9 in the northeast part of the site area, in conjunction with the coring of the suspected anticline, may demonstrate the relationships, depending upon the findings.

   b. One large collapsed domal structure in the central or southern Nash Draw area should be cored to establish the horizon of active dissolution. Two-inch (nx) wireline core would be adequate for the purpose.

   c. Several sinks in Nash Draw should be cored to the top of Anhydrite III to establish if generalized dissolution of the Salado has occurred to the west of the site area and to determine the age and rate of subsidence of Nash Draw. NX wireline core would be adequate for this determination.

d. As per an earlier recommendation, Bell Lake sink should be cored to obtain a lake history and sediment record to provide information on the rates of dissolution and collapse in the basin area. If Bell Lake sink should prove to be a deep-seated feature, it should be cored to the horizon of active dissolution.

e. A 1000-1500 foot (305-457 m) core should be obtained from the Cenozoic Salt Basin to the west of the Guadalupe Mountains. The sediment profile should be analyzed and interpreted to determine the age and timing of uplift of the basin and its probable relationship to dissolution.

2. Extensive regional and localized dissolution in the Delaware basin and the random distribution and on-going nature of localized dissolution suggests that this particular basin may have already progressed to a stage of dissolution where geological estimates of site integrity may not be obtained with the required degree of certainty. Studies of the statistical probability of the present and future occurrence of localized dissolution should be undertaken. This information, combined with information obtained from the above recommendations, should be used to review and reevaluate the Delaware basin itself as an acceptable site for the disposal of high-level radioactive waste.

ABSTRACT

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

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

from unloading related to dissolution. Localized collapse, as well as regional dissolution, is an ongoing process.

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

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ILLUSTRATIONS

Deep dissolution of salt, northern Delaware basin, New Mexico

INTRODUCTION

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

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

ACKNOWLEDGMENTS

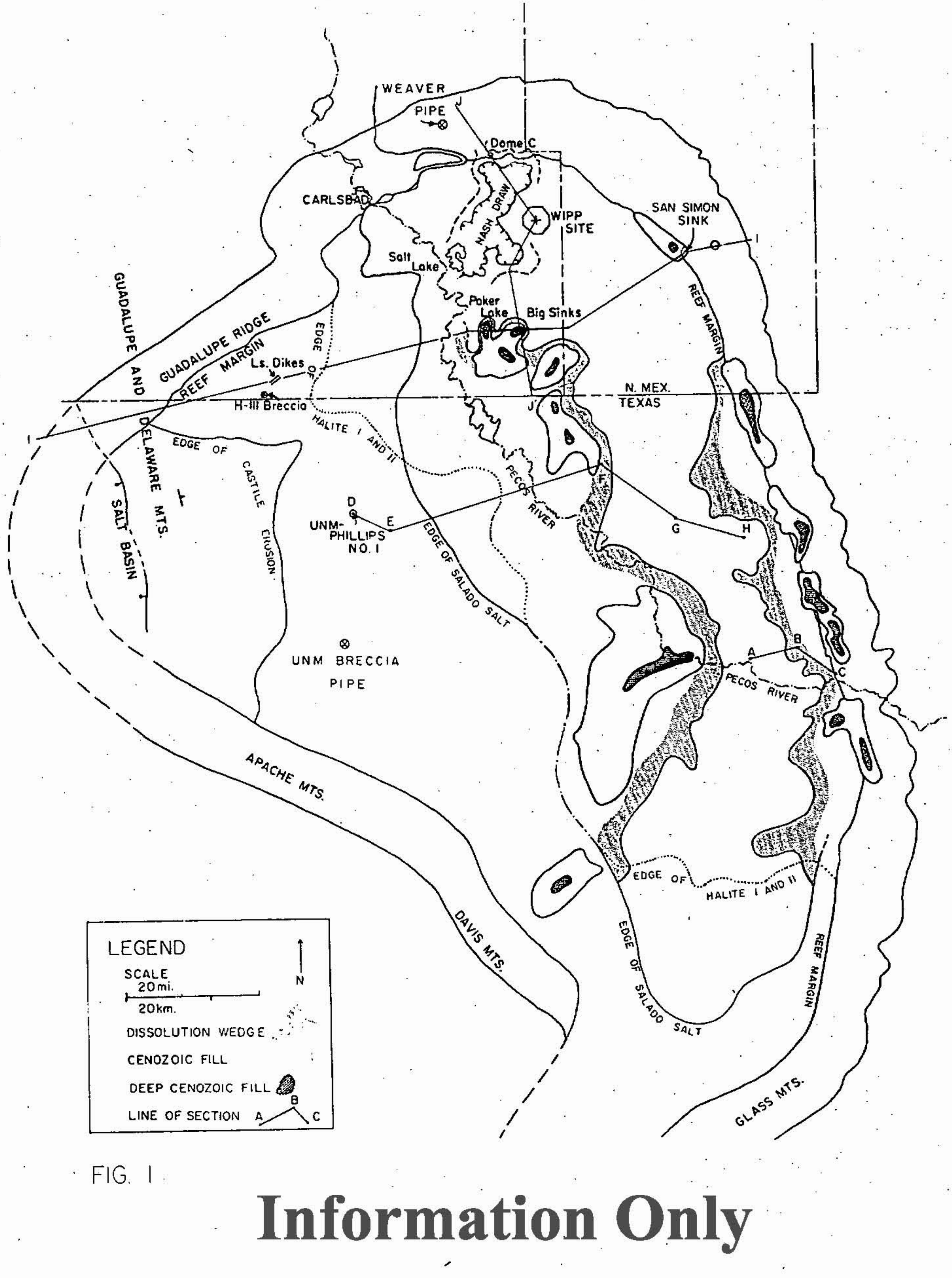
I wish to thank Doris J. Rhodes and Sandra Miller for compilation of log data and help in the preparation of maps. Roberta Widdicombe aided in field work and in preparation of information on domal structures.

DISTRIBUTION OF SALT BEDS

Original Distribution, Thickness, and Volume:

The first problem in determining the extent of salt dissolution in the basin is the recognition of the original extent and thickness of the salt beds at the time of deposition. This problem was simplified with the discovery of dissolution breccias in the western part of the basin that were equivalent to halite beds in the eastern part of the basin (Anderson and others, 1972). Subsequent varve and acoustical log correlations across the basin showed that individual salt beds in Halite III (see Anderson and others, 1972 for definition of stratigraphic units and Figures 2 and 15 for stratigraphic sequence) to the east had a correspondingly thick breccia bed at the appropriate stratigraphic horizon in the western part of the basin (Anderson, Kietzke, and Rhodes, 1978). More work showed that every salt bed in the sequence, ranging from Halite I through the lower part of the Salado Formation (with the exception of the Infracowden halite) had an equivalent breccia bed to the west (Figure 2).

Figure 1. Location map showing dissolution depressions and position of western and eastern dissolution wedge.



WEAVER
PIPE
Dome C
CARLSBAD
NASH DRAW
WIPP
SITE
SAN SIMON
SINK
Salt
Lake
Poker
Lake
Big Sinks
GUADALUPE AND
GUADALUPE RIDGE
REEF MARGIN
Ls. Dikes
EDGE OF
H-III Breccia
N. MEX.
TEXAS
REEF MARGIN
HALITE I AND II
DELAWARE MTS.
EDGE OF
CASTILE
EROSION
PECOS RIVER
SALT BASIN
UNM-
PHILLIPS
NO. 1
EDGE OF SALADO SALT
UNM BRECCIA
PIPE
PECOS RIVER
APACHE MTS.
EDGE OF
HALITE I AND II
DAVIS MTS.
EDGE OF SALADO SALT
REEF MARGIN
GLASS MTS.
LEGEND
SCALE
20 mi.
20 km.
N
DISSOLUTION WEDGE
CENOZOIC FILL
DEEP CENOZOIC FILL
LINE OF SECTION

FIG. 1

Figure 2. East-west section of acoustical logs showing evidence for western dissolution wedge. Note that middle Salado salt overlies dissolved salt beds of lower Salado which have beds of blanket dissolution breccia to the west. See Figure 1 for location of section. (D, UNM-Phillips #1; E, Kirklin Drilling Co., J. H. Fisher #1, PSL 111, Culberson Co.; F, TXL Oil Corp., W. P. Johnson et al. Fee #1, Loving Co.; G, Delfern Oil Co., Ollie #1, Loving Co.; H, Union-University "37" #4, Winkler Co., Texas).

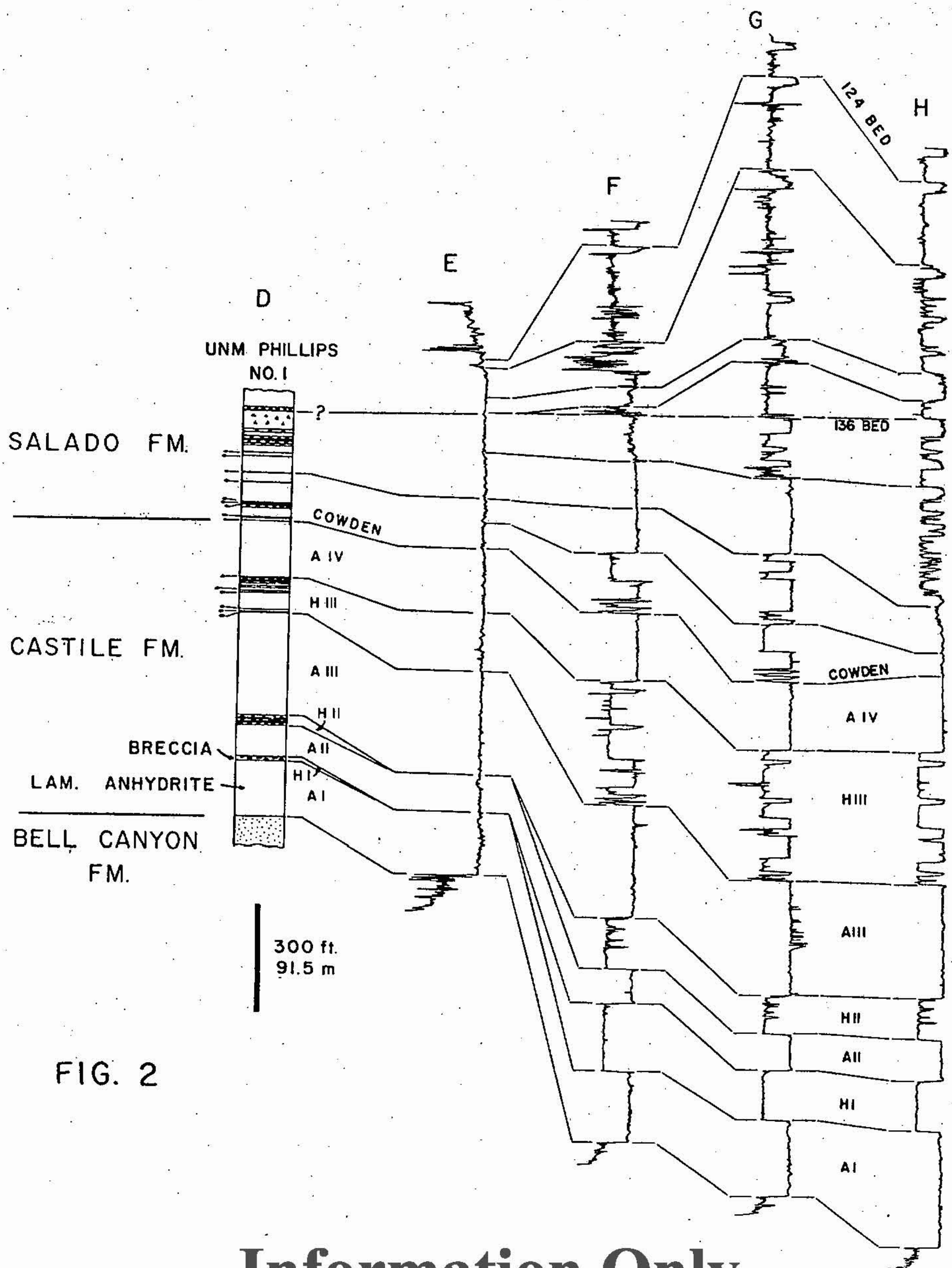

D
UNM PHILLIPS NO. 1
E
F
G
H
124 BED
136 BED
?
SALADO FM.
COWDEN
A IV
H III
CASTILE FM.
A III
H II
BRECCIA
A II
H I
LAM. ANHYDRITE
A I
BELL CANYON FM.
300 ft.
91.5 m
COWDEN
A IV
HIII
AIII
HII
AII
HI
AI

FIG. 2

Most recently, a thin bed of dissolution breccia (Figure 3) was discovered at the stratigraphic position of the lower part of Halite III in an outcrop of Castile Formation on U. S. Highway 62/180 near the Texas State line. This outcrop is only about 6 miles (10 km) from the western edge of the basin and shows that the original distribution of most if not all of the salt beds once extended to the western margin of the basin.

With this information on the pre-dissolution distributions of salt, isopach lines for the major halite units in the basin were reconstructed by assuming that the original salt distribution in the basin followed the same trends in thickness as in the eastern part of the basin where it could be established that no salt dissolution had occurred (see figures 13, 15, 16, and 17 in Anderson and others, 1972). The original volumes of salt for the different stratigraphic units in the basin are listed in Table 1.

Post-dissolution Thickness and Volume:

Present distribution and thickness of the major halite units in the entire basin are depicted in isopach maps published by Anderson and others (1972)[1]. The compilation of volume of salt in the different stratigraphic units (Table 1) shows that approximately 50% of the original salt in the basin has been dissolved. Contrary to what might be expected if surface or near-surface processes were the main agent of dissolution in the basin, the percent of dissolution does not linearly decrease with depth. Rather, the halite units that have undergone the greatest rate of dissolution lie within the body of evaporites. For the lower Salado unit, less than 30% of

1. The distribution of lower Salado in the northern part of the basin differs from that in Figure 17 of Anderson and others (1972) as a result of later interpretations.

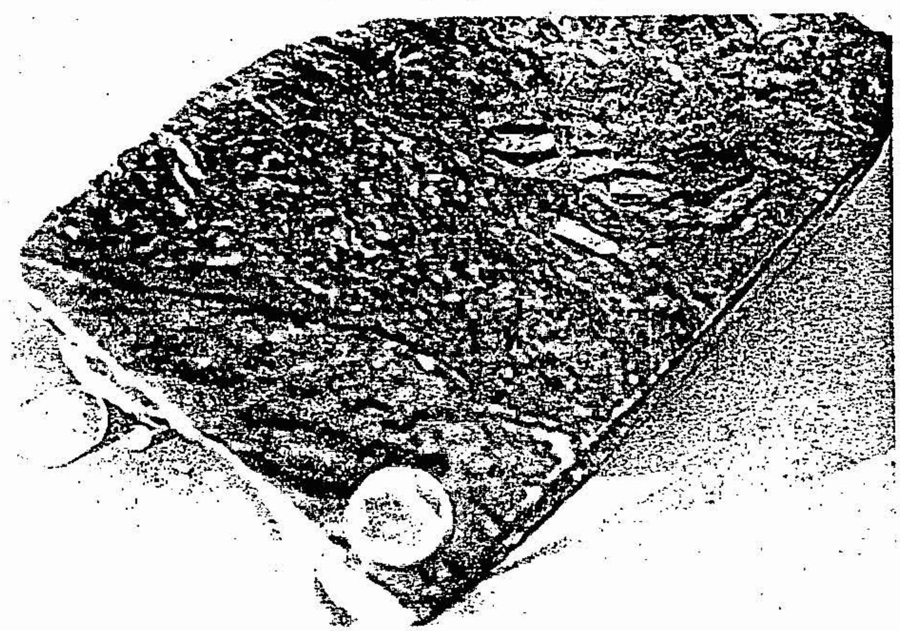


Figure 3. Photograph of dissolution breccia of lower salt bed of Halite III collected from outcrop near Texas-New Mexico State line on U.S. Highway 180/62.

Table 1. Original and post-dissolution volumes of sale in halite units in the Delaware basin.

Halite unit	Original volume $m^3 \times 10^{11}$	Post-dissolution volume $m^3 \times 10^{11}$	Percent dissolved
Middle and Upper Salado			
*1000 ft (305 m) minimum	94.0	49.0	48
*1500 ft (458 m) minimum	126.0	49.0	61
Lower Salado	13.9	3.8	73
Halite III Pre-Salado	#14.4	9.6	#33
Post-Salado	9.6	3.3	65
Halite II	10.3	5.3	49
Halite I	13.5	7.7	43

*Assuming unit was 1000 ft (305 m) thick or 1500 ft (458 m) thick in western part of the basin and 80% of volume is halite.

#Volume of Halite III salt assuming it was once present in northernmost part of basin before Salado deposition. Percent dissolved by pre-Salado dissolution.

the original volume remains in the basin. This departure from a linear trend is the result of processes of deep dissolution in the basin following Cenozoic uplift, tilting, and erosion. The isopach maps of Halite III and the lower Salado salt units show that only a relatively narrow belt (ca 30 mi., 50 km) along the eastern side of the basin has escaped the effects of some regional deep dissolution (see also Figure 1). This same interpretation of the extent of dissolution was made by Hills (1968, p.22).

Regional deep dissolution has had the greatest effect on the western part of the basin. The northern part of the basin, north of Township 25 in New Mexico, has been more protected from some of the effects of deep dissolution than the basin as a whole. More detailed maps of the halite beds and the 124 marker bed were constructed for the part of the basin that lies north of the New Mexico-Texas State line (Figures 4, 5, 6, 7, 8, 9, 10, and 11; see also Map 7, structure on top of Rustler Formation, of Hiss, 1976). These maps, plus information from cores and geophysical logs, as well as observations of earlier workers in the area and personal observations in the field, provide a basis for interpreting the extent, history, and causes of deep dissolution in the basin. The several stages or episodes of dissolution in the basin and the role and extent of deep dissolution are considered sequentially from older to younger in the following sections of this report.

Figure 4. Isopach map of Halite I unit of Castile Formation. Note common occurrence of salt anticlines and associated sinks and other isolated sinks.

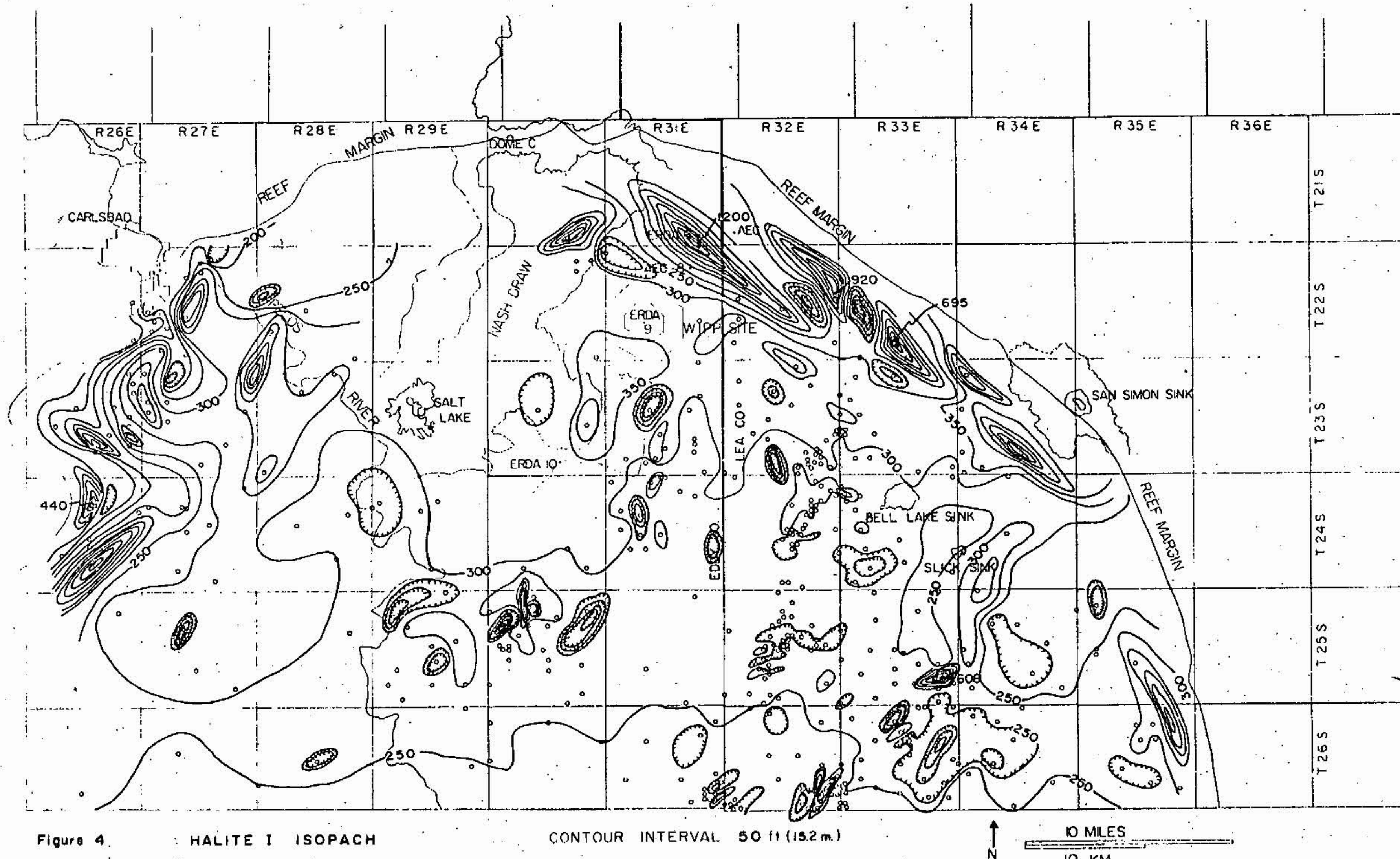


Figure 4. HALITE I ISOPACH

CONTOUR INTERVAL 50 ft (15.2 m.)

Figure 5. Isopach map of Halite II unit of Castile Formation. Compare with map of Halite I to see differential relationships between thickness of the two salt beds.

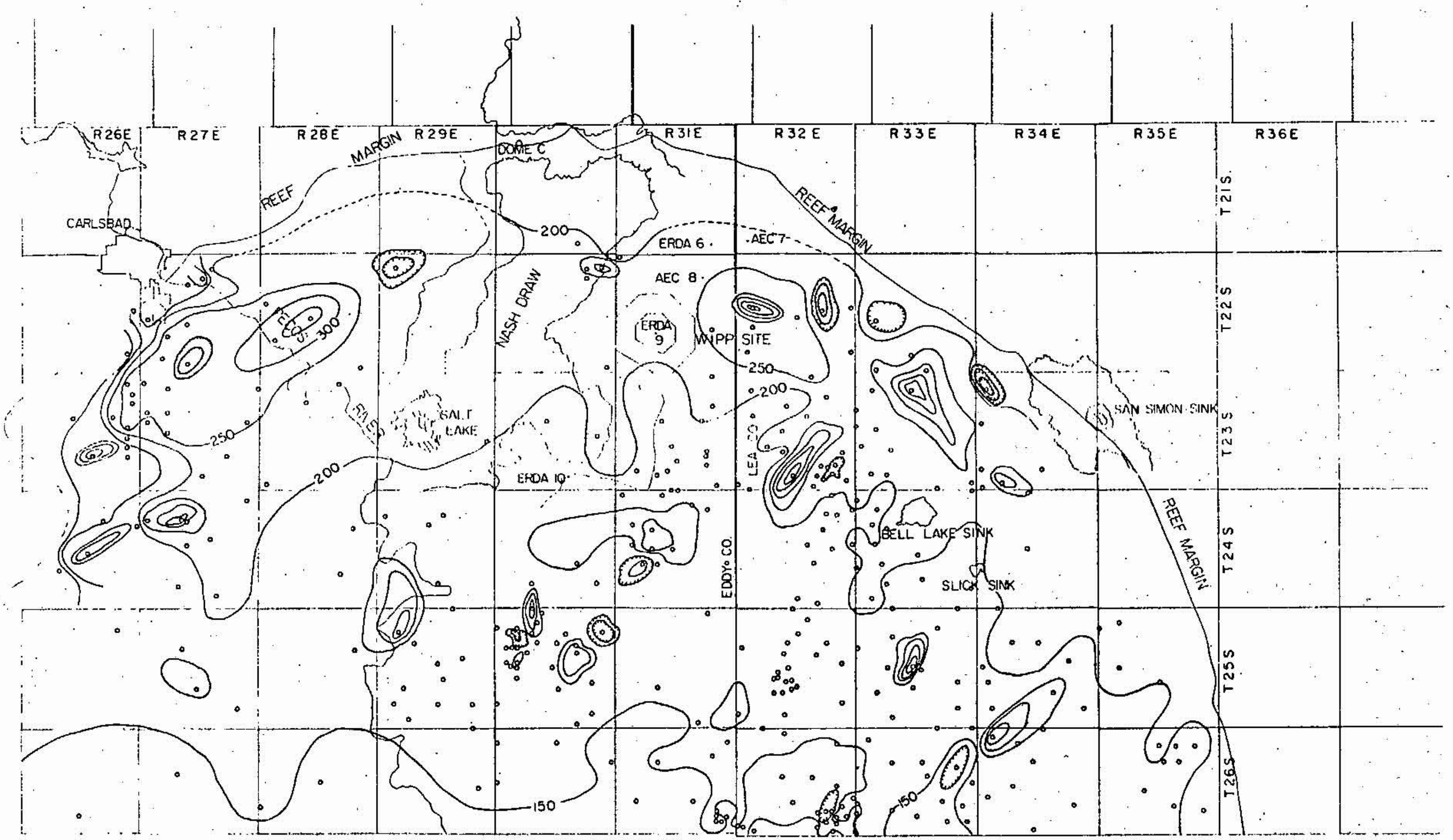


Figure 5 HALITE II ISOPACH CONTOUR INTERVAL 50 ft (15.2 m)

Figure 6. Isopach map of salt in Halite III unit of Castile Formation. Note outliers of salt to the west and north of salt edge and abrupt thinning of salt to the west and above the 100 foot (30.5 m) isopach to the north.

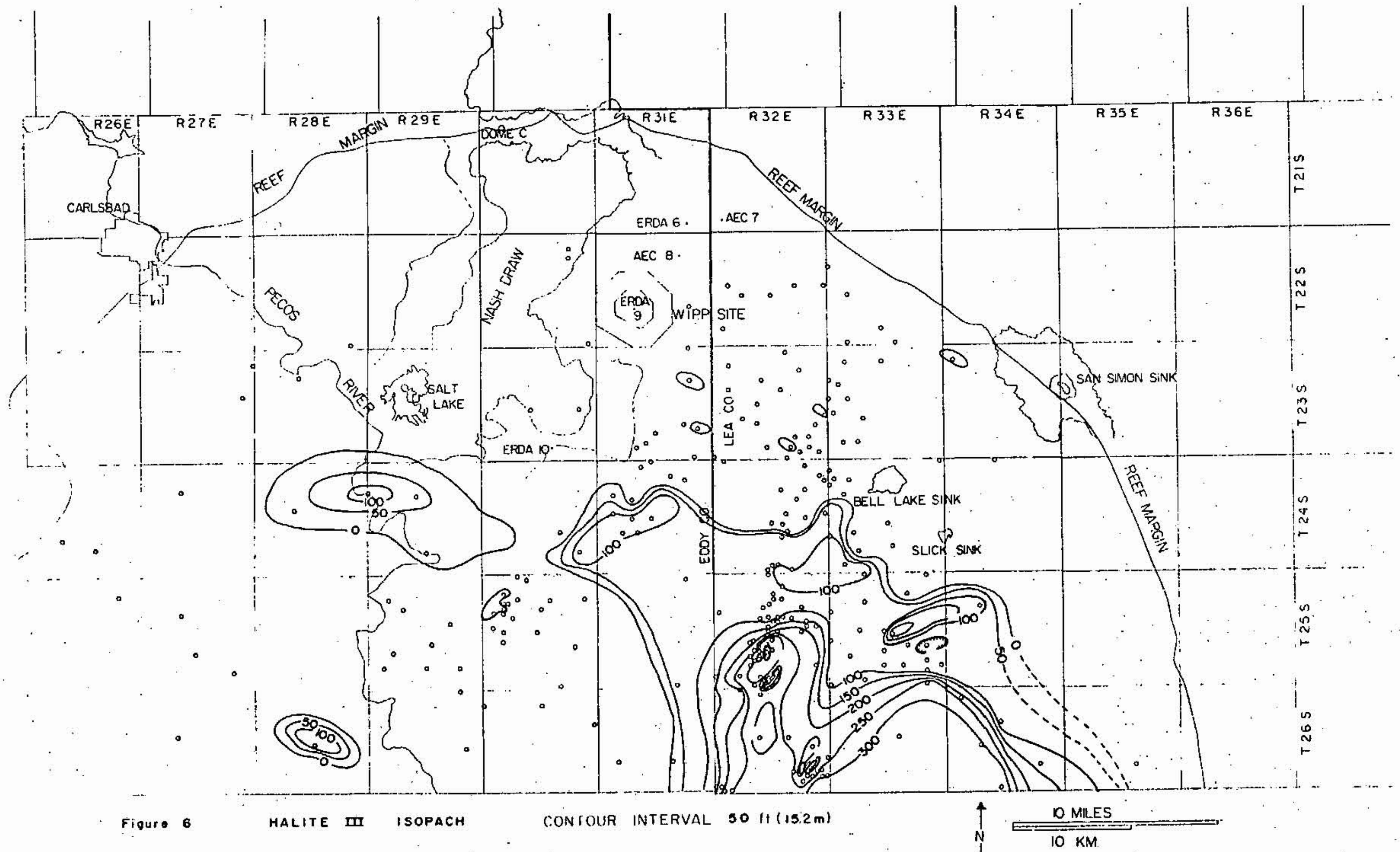


Figure 6 HALITE III ISOPACH CONTOUR INTERVAL 50 ft (15.2m)

Figure 7. Isopach map of Infracowden salt bed of Salado Formation. Note gradually thinning southern margin and thinning of salt over reef.

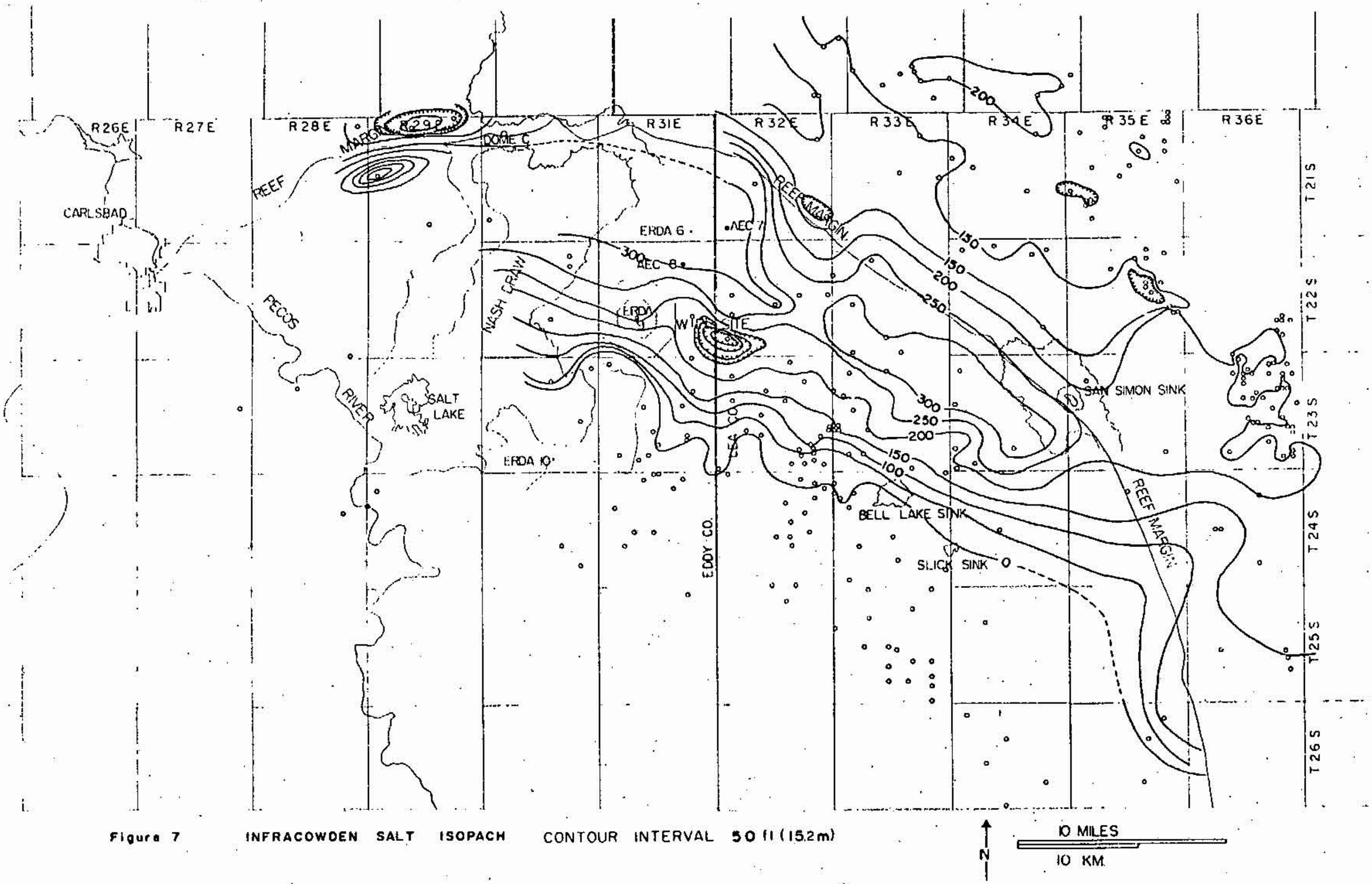


Figure 7 INFRACOWDEN SALT ISOPACH CONTOUR INTERVAL 50 ft (15.2m)

Figure 8. Isopach map of lower Salado (top Cowden to top 136 marker bed), including anhydrite beds. Compare position of salt edge to that of salt in middle Salado (Figure 9) to see extent of dissolution wedge.

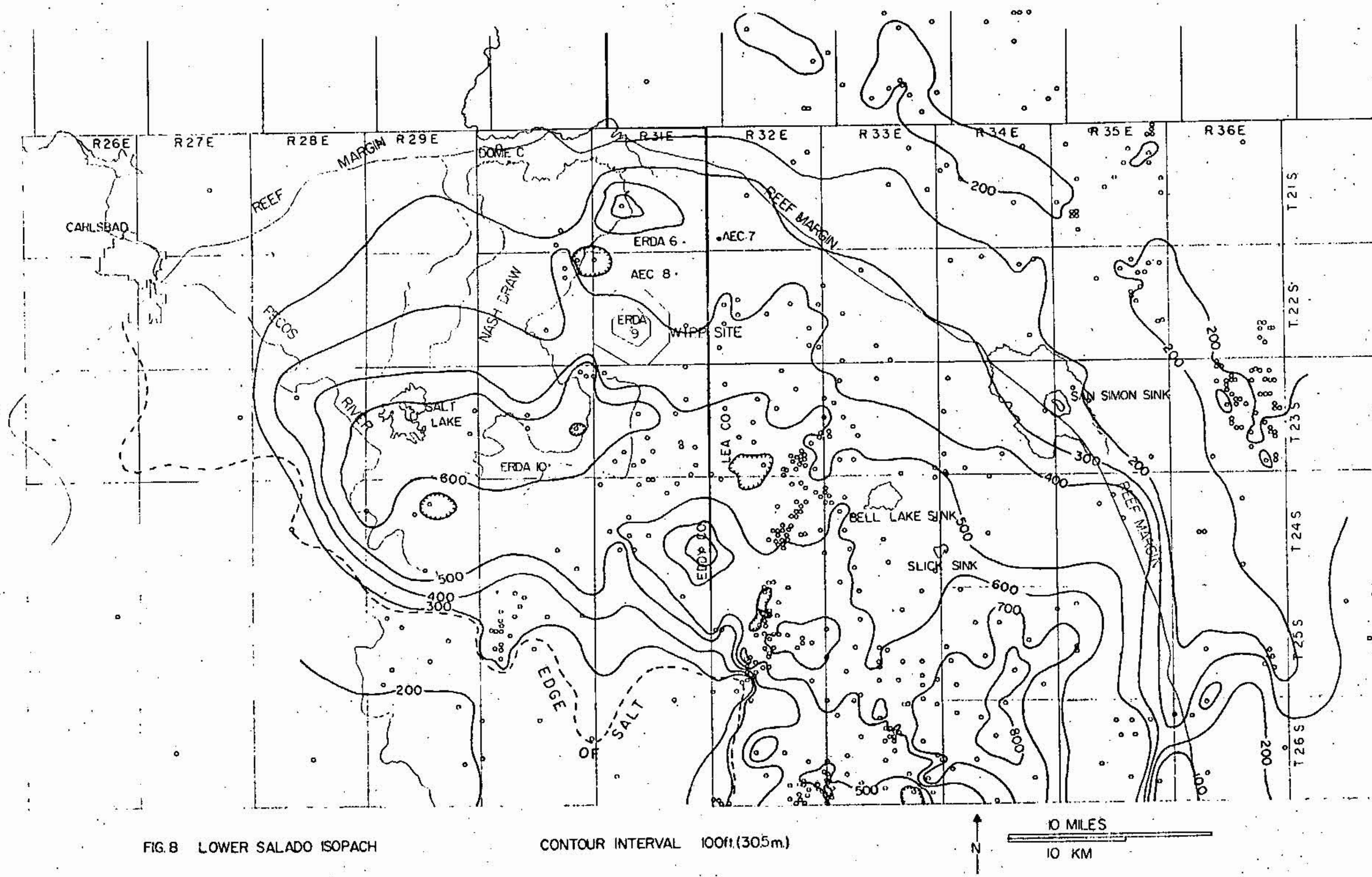


FIG. 8 LOWER SALADO ISOPACH CONTOUR INTERVAL 100ft.(30.5m.)

Figure 9. Isopach map of middle Salado (top 136 to top 124 marker beds), including anhydrite beds. Note position of salt edge.

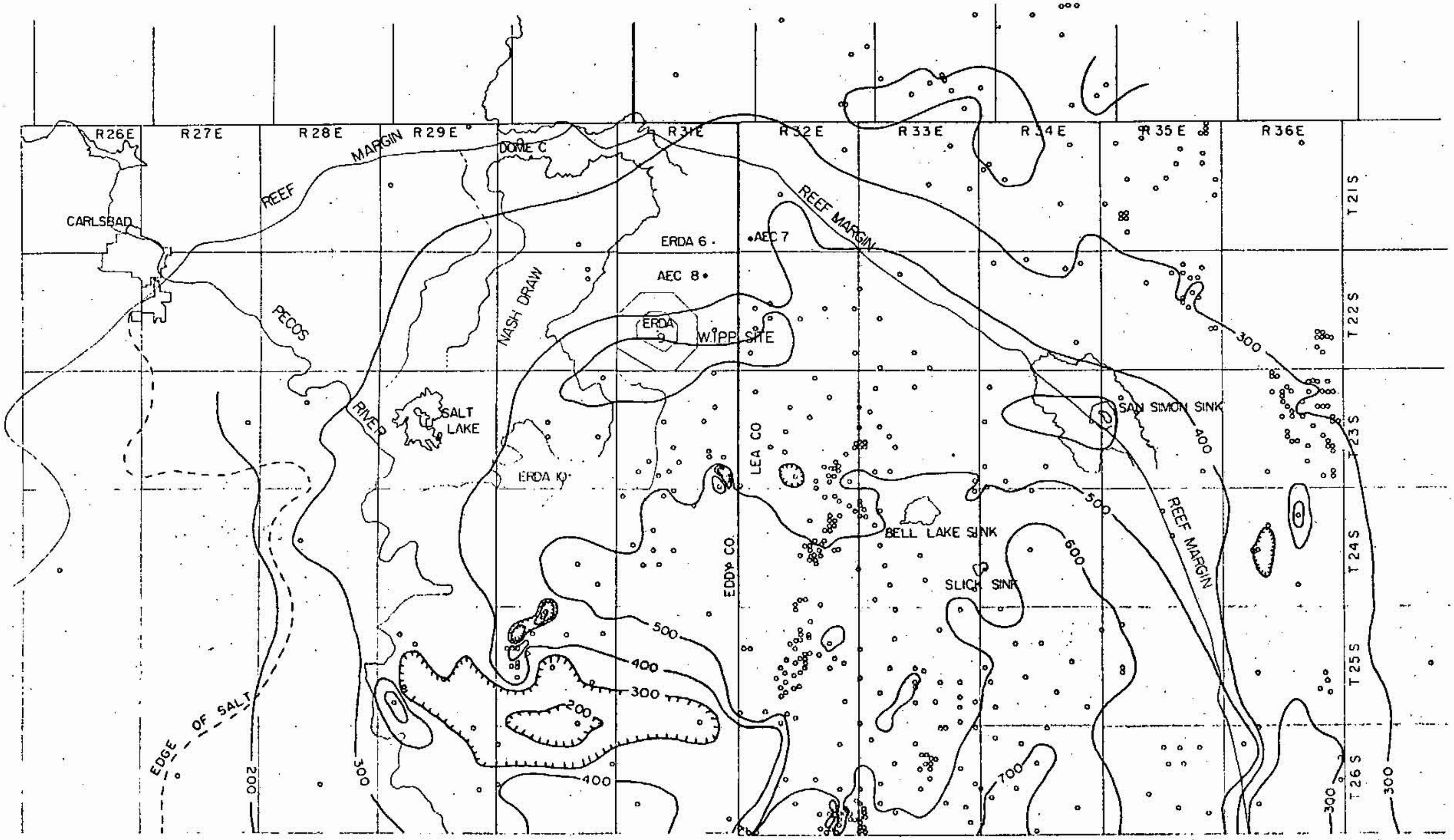


Figure 9 MIDDLE SALADO ISOPACH CONTOUR INTERVAL 100 ft (30.5m)

Figure 10. Isopach map of upper Salado (top 124 marker bed to top of salt), including anhydrite beds.

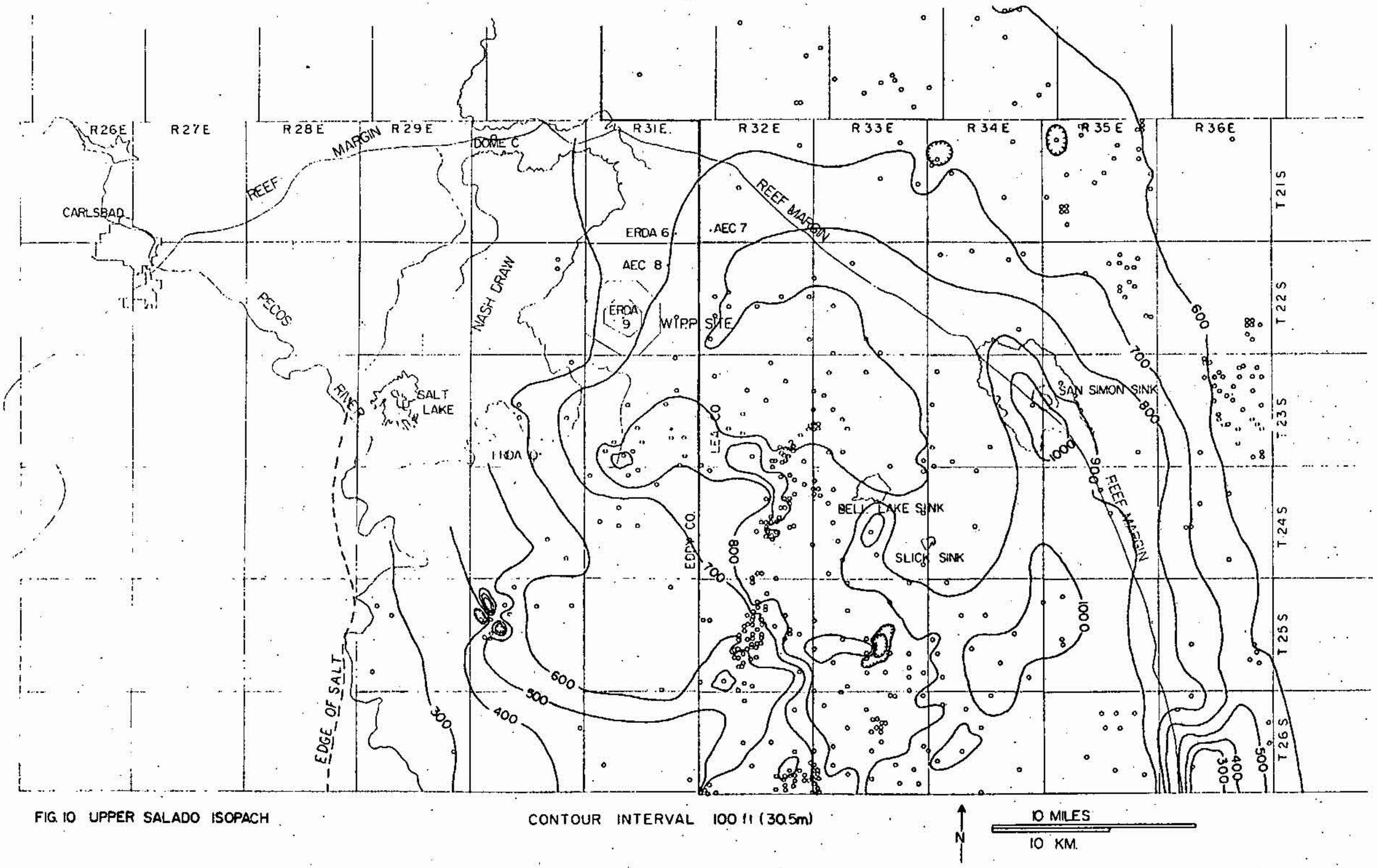


FIG. 10 UPPER SALADO ISOPACH

CONTOUR INTERVAL 100 ft (30.5m)

N

10 MILES

10 KM.

Figure 11. Structure contour map on top of 124 marker bed in the Salado Formation. Note the structural high over salt anticlines in Halite I, low over reef, and additional low west of salt anticlines. (The contours in the vicinity of the W.I.P.P. site were adapted from Griswold, 1977, figure 7).

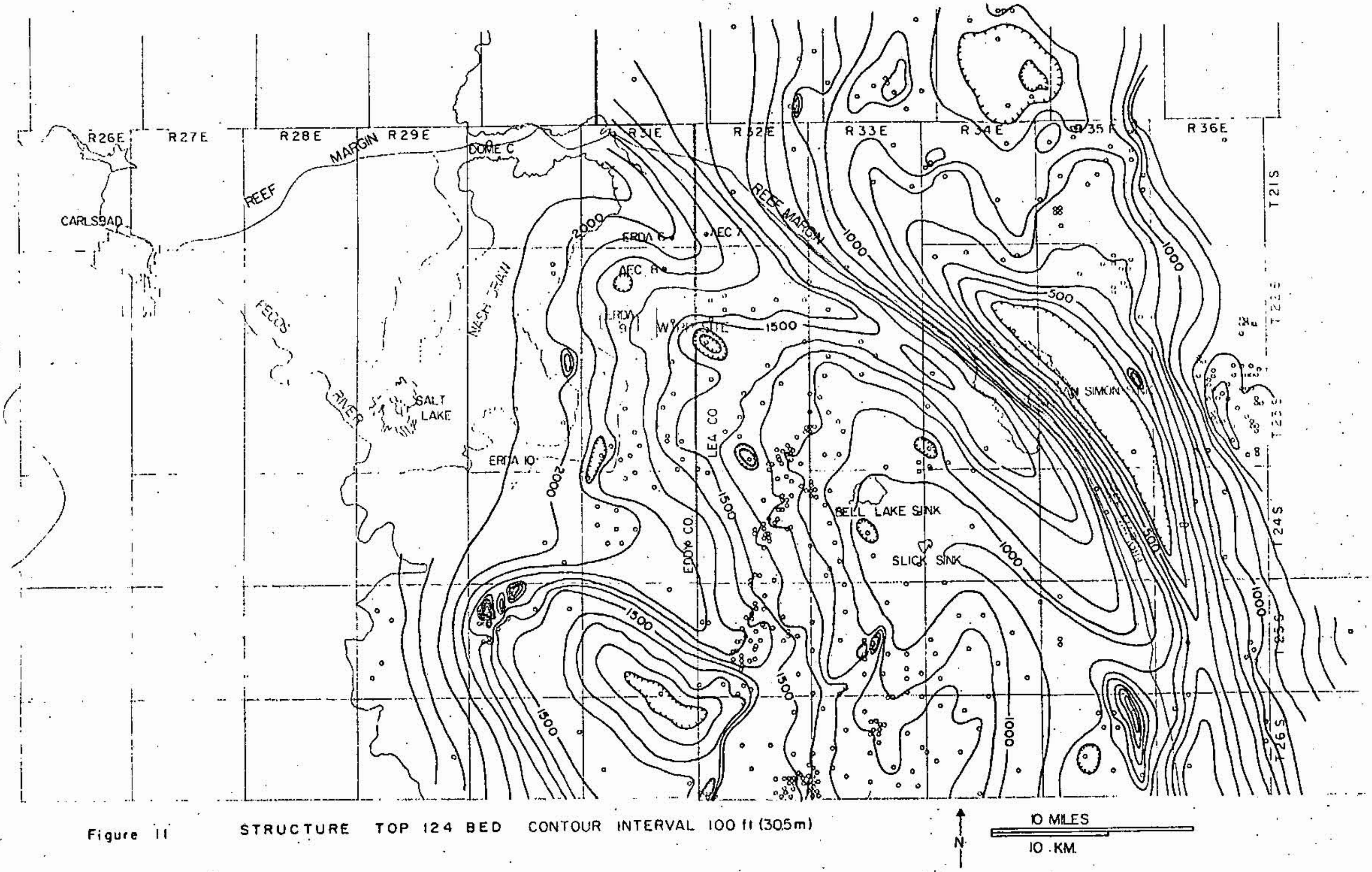


Figure 11 STRUCTURE TOP 124 BED CONTOUR INTERVAL 100 ft (30.5m)

PRE-CENOZOIC DISSOLUTION

Post-Castile - Pre-Salado Dissolution:

The nature of the contact between the Castile and Salado formations has been a troublesome problem for many investigators. Log correlations within the Salado Formation and within the Castile are simple and straight forward but there is a zone of confusion between the two formations that has resulted in different workers selecting different units as the boundary and recognizing different marker beds as the Cowden Anhydrite. The problem has been compounded by deep Cenozoic dissolution at the boundary that has removed some halite beds and merged anhydrite beds to alter original stratigraphic relations.

Evidence for Unconformity and Dissolution

Adams (1944) recognized the presence of an unconformity between the Castile and Salado formations in the northern part of the basin. Jones (1954, p. 108; 1972 in Brokaw and others) rejects this interpretation and believes there is a transitional and intertonguing relationship, with the surface of the Castile descending some 650 feet (200 m) to the north and being replaced by the lower Salado. Correlations of acoustical logs in the basin and the thickness relationships of Halite III support the interpretation of Adams that there was an episode of non-deposition, angular unconformity, and even salt dissolution in the northern part of the basin following the deposition of the Halite III unit of the Castile Formation. The unconformity is of considerable importance to the processes of later deep salt dissolution in the Cenozoic and so the relationships have been examined in some detail.

The edge of Halite III along the western side of the basin and along most of the eastern side is a Cenozoic dissolution margin. This has been determined by correlation of laminae and breccia beds and acoustical logs. The character of the northern margin of Halite III salt, its apparent occurrence in slivers in structures along the eastern basin margin, and suspected thin outliers of Halite III salt in the northern part of the basin suggest that Halite III once extended north of present distribution and that the northern edge is also a dissolution margin (Figure 6). This interpretation is also supported by the locus of thickest deposition of both the underlying and overlying salt beds (Halite I and II and Infracowden Salt) which lie in the area of missing Halite III, implying that Halite III was also thickest in the same area.

If the dissolution of the northern edge of Halite III took place at the same time as the dissolution along the eastern and western margins (Cenozoic) then the northern part of the basin will have been undercut by deep Cenozoic dissolution and the overlying units fractured during the process of salt removal. This does not appear to be the case as the cores from the overlying units do not show the same degree of fracturing as observed in cores above dissolved salt in the western part of the basin. The available evidence indicates that the dissolution of Halite III took place below the unconformity separating the Castile from the Salado and hence was a pre-Salado event.

Other evidence of dissolution and unconformity lies in the mutually exclusive distribution of Halite III salt to the south and overlying Infracowden salt to the north (compare Figures 6 and 7 and see Figure 16). Gorrell and Alderman (1968) observed similar inversions of intraformational "thicks" as a result of salt dissolution in the middle and upper Devonian Prarie evaporites. In that example, removal of a volume of salt was compensated by a thicker section above the dissolved salt. The Infracowden salt appears to have compensated for the surface lowering of the Castile in the northern part of the basin.

The unconformity in the basin is also marked by a profound change in the influx of clastics into the basin with Halite III being essentially free of clastics and Infracowden salt containing a much higher percentage of clay. Around the basin margin, the lower part of the Infracowden contains a siltstone member (La Huerta siltstone of Lang, 1942). Geochemical associations of major and minor components in the system also change markedly following Halite III deposition.

Just how much salt was removed, or the original thickness of Halite III to the north cannot be determined exactly. If depositional trends in Halite III followed those of Halite I and Halite II, the salt would have been in excess of 300 feet (90 m). The core from AEC #8 borehole was examined in detail to determine if evidences of Halite III salt could be found. Thick 1cm to 2cm "Salado type" anhydrite and magnesite laminations were present above and below the suspected Halite III horizon. The suspected Halite III zone occurs about 100 feet (30 m) below the Infracowden salt and consists of about 40 feet (12 m) of disrupted, vuggy, recrystallized, and reorganized laminae. Recrystallization has proceeded to the extent that original brecciated structure would be difficult to observe if it were originally present. Some partially replaced fragments were seen. Intense disruption is confined to a zone about 10 feet (3 m) thick and it is not known if this zone might represent all or part of Halite III salt.

The same horizon as the disrupted zone in the AEC #8 core (100 feet, 30.5 m, below Infracowden salt) contains beds of pure salt, without clastics, about 200 feet (61 M) thick in the core from nearby AEC #7 borehole (about 2 miles, 3 km, separation). This suggests, along with the thin outliers, that all of Halite III salt was not removed during the dissolution interval. Another possibility is that another salt bed underlies the Infracowden next to the reef and that the disrupted, vuggy horizon represents the unconformity. Other slivers of Halite III occur in the deformed zone bordering the reef (Figure 6) but stratigraphic relations in this belt are often confusing owing to salt movement.

Nature and Extent of Unconformity

The unconformity lies beneath the Infracowden salt, apparently at the base of or within the Fletcher Anhydrite of Lang (1942) and occupies the position essentially as described by Adams (1944, figure 3). In T 25 S, R 32 E, Lea County, where Cenozoic dissolution has not obscured the original thickness relationships, as little as 70 to 100 feet (20 to 30 m) of anhydrite separates the upper salt beds of Halite III from the lower salt beds of the Salado Formation. To the north, this same interval is occupied by the Infracowden salt which wedges out to the south superjacent to Halite III deposition (compare Figures 6 and 7). The Cowden Anhydrite south of the Infracowden wedge-out rests on 1.3 feet (0.4 m) of dolomitic mudstone which is underlain by nodular anhydrite with a dolomitic mudstone matrix. Hence the lateral equivalent of the Infracowden salt is a clastic unit and the Infracowden salt edge is depositional.

Figure 12. North-south diagrammatic cross section (J-J'). Note outliers of H-III beneath unconformity and in collapsed depressions. See Figure 1 for location of cross section.

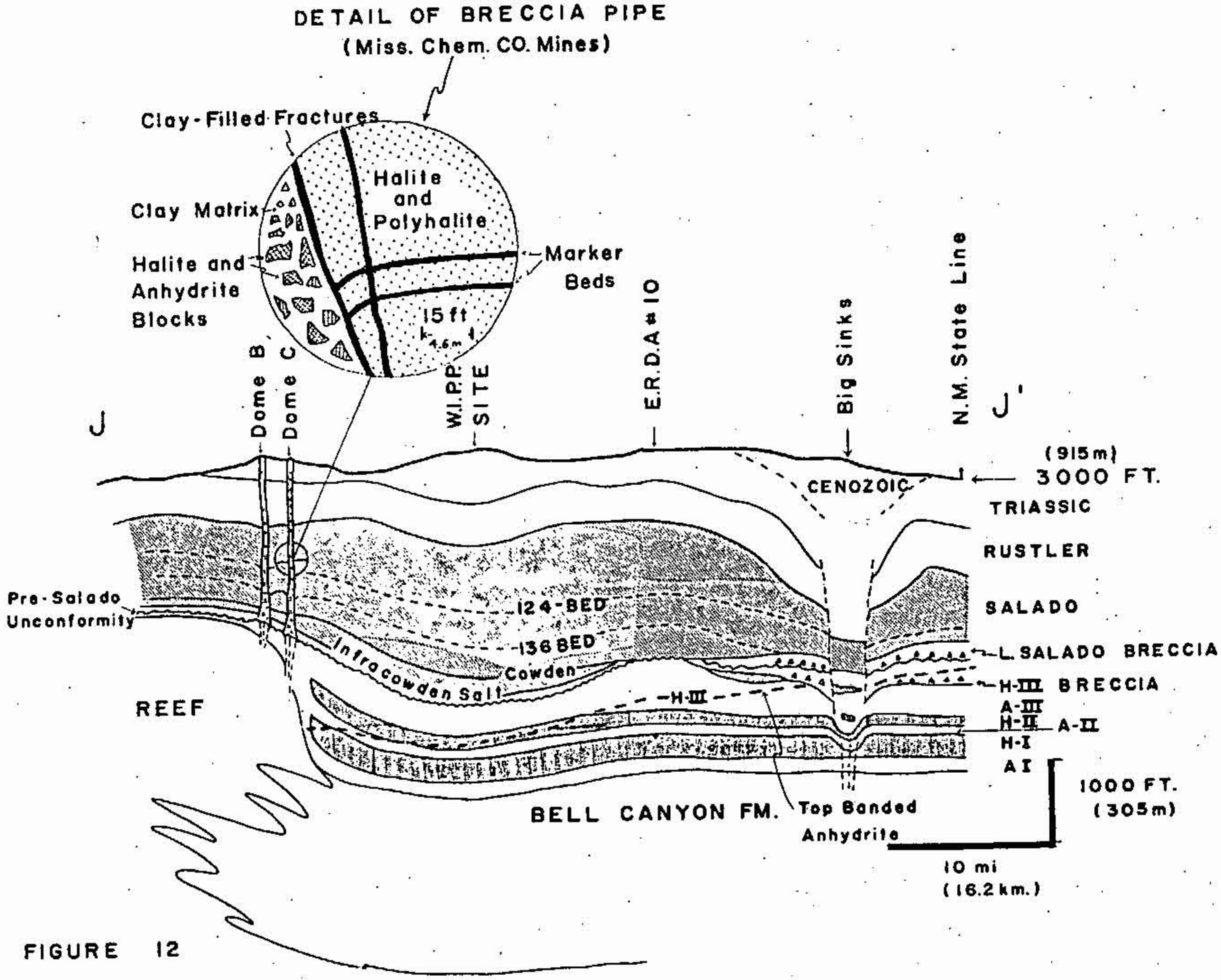

DETAIL OF BRECCIA PIPE
(Miss. Chem. CO. Mines)
Clay-Filled Fractures
Halite and Polyhalite
Clay Matrix
Halite and Anhydrite Blocks
Marker Beds
15 ft
4.6m
Dome B
Dome C
W.I.P.P. SITE
E.R.D.A # 10
Big Sinks
N.M. State Line
J
J'
(915m)
3000 FT.
CENOZOIC
TRIASSIC
RUSTLER
SALADO
Pre-Salado Unconformity
124-BED
136 BED
L. SALADO BRECCIA
Cowden
Infracowden Salt
H-III BRECCIA
H-III
REEF
A-III
H-II
A-II
H-I
A I
1000 FT.
(305m)
BELL CANYON FM.
Top Banded Anhydrite
10 mi
(16.2 km.)

FIGURE 12

The few thin salt beds above the Cowden also wedge out to the south, but aside from these exceptions, every other salt bed in the eastern and northern part of the basin has a laterally equivalent breccia bed in the area of Cenozoic dissolution to the west. In the UNM-Phillips #1 core from Culberson County, Texas, (Anderson and others, 1972) the Cowden Anhydrite cannot be recognized as a separate stratigraphic unit and the northern unconformity does not extend to the west central part of the basin. No clastic units were observed in the Culberson County core below the Rustler Formation.

The unconformity appears to be recognizable only in the northern part of the basin, but Adams (1944) says that the time break is even longer in the south. The thickened section of Anhydrite III, where Halite III is suspected of having been dissolved, can be traced southward along the eastern side of the basin to about the New Mexico-Texas state line. The effects of the unconformity, however, appear to be widespread as this was the most active horizon of Cenozoic salt dissolution and increased permeability associated with clastics or salt residues around the margin of the basin is a further suggestion that there was a major disruption in sedimentation before Salado deposition.

History and Environment of Original Deposition in Northern Part of Basin

Sediments in the Castile Formation are characterized by laminations of organic-rich calcite and anhydrite with average couplet thickness of about 2 mm throughout most of the basin. These laminae have been assumed by most observers to represent seasonal and annual deposition (varves). The Salado anhydrite is also laminated, but on a scale of 1 to 2 cm having the anhydrite laminae set off by thin dark films, apparently of organic matter and, in parts of the section, by thin white layers of magnesite. No calcite is present.

The so-called "banded anhydrite" of the Castile persists well up into the Salado Formation in the central part of the basin. The upper surface of the banded anhydrite descends stratigraphically toward the north so that at about T 23 S (location of ERDA #10 borehole) only about the lower third of Anhydrite III is banded. In the northernmost corner of the basin near the reef margin (location of ERDA #6 and AEC #8 boreholes) banded anhydrite does not occur above Anhydrite II and the laminae show evidence of lack of horizontal continuity, scour, development of multiple laminae between better defined sets, reduction in calcite content, and concentration of calcite into thick laminae. At the reef margin (location of AEC #7 borehole) the calcite banding appears to be even lower in the section (Figure 12).

The loss of banding to the north and the reduced calcite content parallels the development of thicker salt beds from south to north in the basin and is probably related to increased salinity of the water towards the northern corner of the basin. The loss of banding has contributed to problems in correlating Halite III and equivalent units. A distinctive limestone marker bed in the lower part of Halite III (at T_0 + 163,000 in figure 6 of Anderson and others, 1972) can be observed in outcrop and traced on gamma ray logs to T 23 S in the basin where it is absent either due to loss of calcite and laminated character or because of truncation at the unconformity (the former explanation appears more probable). The loss of banded anhydrite to the north takes place in a relatively narrow arcuate belt through T 23 S, R 30 E that swings slightly southeastward toward the eastern side of the basin. This belt also corresponds to the thick anhydrite section lying north of Halite III which is thick because it represents the anhydrite above, below, and within Halite III and also because of a trend toward thick anhydrite to the north. This arcuate belt is also the site of what appears to be a thin salt bed in acoustical logs about 100 feet (30 m) above the base of Anhydrite III.

Salado type laminae represent the northern saline facies. This means that the salt beds of Halite III that were once present to the north were interlayered with thick Salado type anhydrite laminae. Removal of the salt by near-surface dissolution during pre-Salado time would have left a residue of different character than the dissolution breccias to the west. Presumably, the near surface Salado-type residue was the material subjected to recrystallization by saline waters in the horizon 100 feet (30.5 m) below the Infracowden salt at the AEC #8 locality.

The locus of thickest deposition of salt is essentially the same for the Infracowden salt as for Halite I and Halite II. The locus for Halite III, however, is now about 30 miles (48 km) to the south. The locus for thickest salt deposition in the lower Salado, above the Infracowden is about 70 miles (113 km) to the south. The timing of the episodes of salt deposition can be determined from correlations with the time-series obtained from the UNM-Phillips #1 core (Anderson and others, 1972, figure 6). These relationships are summarized in Figure 13.

If the present distribution of Halite III represents the original distribution, then some event shifted the locus of thick deposition to the south and then shifted it back to the north before deposition of the

Infracowden Salt. This event could have been a gradual shallowing of the basin to the north so that only thin layers of salt would have precipitated intermittently whereas more continuous deposition would have resulted in thicker salt to the south. In any case, some salt could be expected in the northernmost part of the basin unless one proposes a drastic change in basin geometry. It seem more probable, however, that the locus of thick deposition remained the same and that subsequent dissolution at the unconformity made additional room for the Infracowden salt.

This explanation means that only one episode of tectonism occurred to alter the basin geometry and substantially shift the locus of thick deposition. By the time the unconformity developed above Halite III, the reef-defined basin was essentially filled with evaporites. Uplift and southward warping exposed the salts in the northern corner of the basin to removal by dissolution as a break in deposition occurred around the margins of the basin but not in the central basin area. Deepening of the basin regionally brought the return of sulfate and halite deposition; first to the northern part of the basin and beyond. The Infracowden salt extends beyond the limits of the basin to the north (Figure 7), is thickened significantly in the locus of previous Halite I and Halite II deposition, and is thinned over the top of the reef. This reef-top thinning suggests that the reef still had some control on sedimentation after the warping and the development of the unconformity and throughout Salado deposition (Figures 7, 8, 9, 10). This control may partly account for continued thick deposition of salt in the old Castile-locus of thick deposition. Finally, with the filling of the Castile basin, the geometric controls on salt precipitation and accumulation shifted the locus of Salado deposition to the south-central part of the basin. This final shift in the locus of deposition after the return of

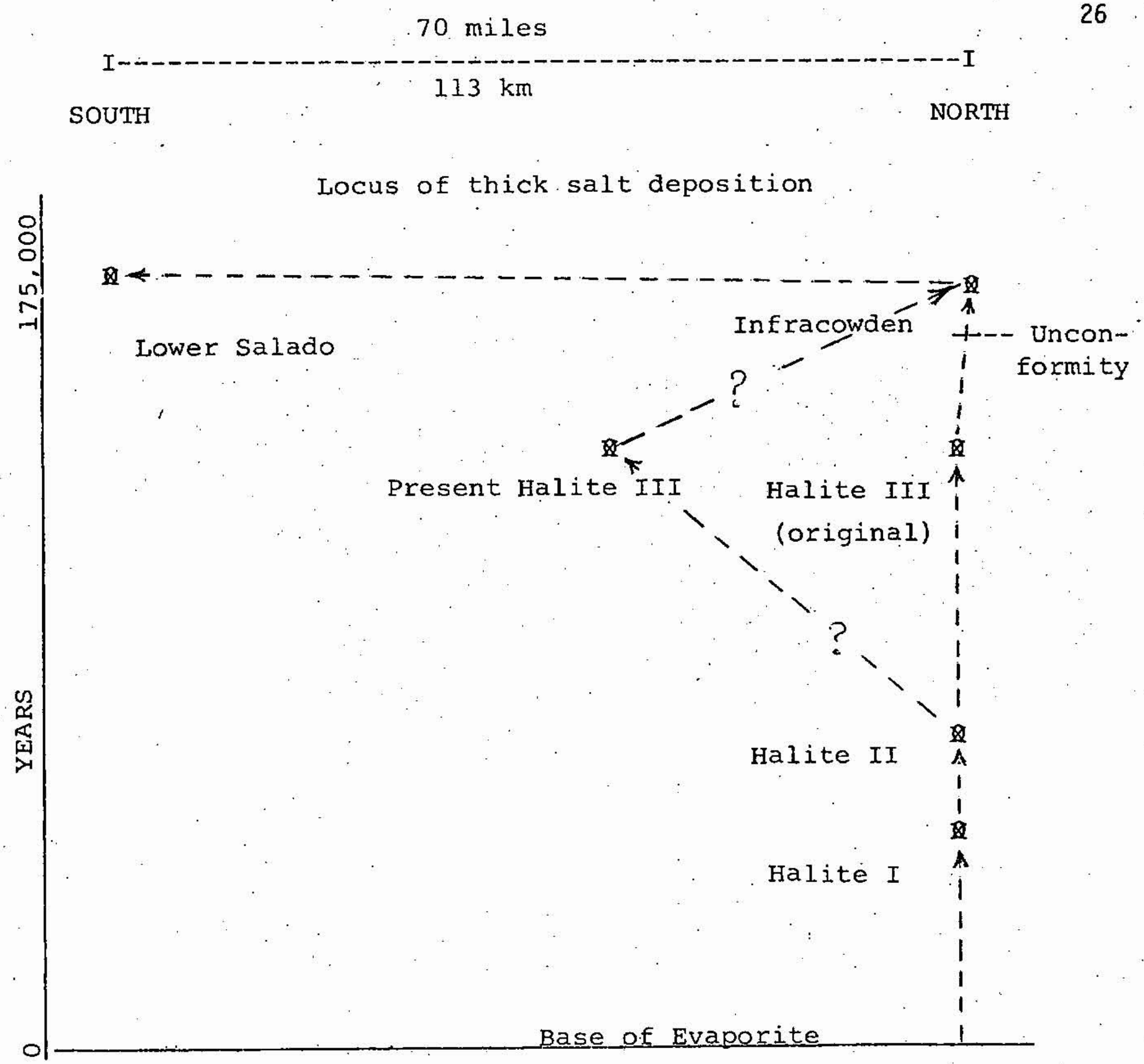


Figure 13. Relationship between time and locus of thick salt deposition in Castile and lower Salado.

waters above the unconformity took place in a few thousand years and was probably the result of depositional filling.

The clastic influx into the basin began with the warping to the north and the development of a surface of non-evaporite deposition around the basin margins. This clastic influx accompanied the final disappearance of the reef as a barrier although the reef was still somewhat of an effective barrier to the Las Huertas silt to the north (see Plate 4 in Jones, 1954). The clastics associated with the unconformity and dissolution residues beneath the unconformity apparently left this particular horizon in the evaporites more permeable and more susceptible to later dissolution in the Cenozoic.

Pre-Rustler Dissolution:

There is evidence for angular contact and loss of upper Salado units underneath the Rustler Formation in the western part of the basin (Baltz, 1959; King, P. B., 1942; and Adams, 1944). This truncation of beds was probably associated with the removal of some salt but the amount of salt cannot be estimated because of the subsequent removal of greater quantities of salt during Cenozoic dissolution and erosional stripping of the western part of the basin. The unconformity, however, is not major and the contact between the Salado and the Rustler within the basin is conformable (Kroenlein, 1939; Pierce and Rich, 1962). None of the deep dissolution features in the basin appear to have been formed at that time.

Pre-Cretaceous Erosion and Dissolution:

Bachman (1974, p. 13) shows an area west of the Delaware basin where Triassic rocks are absent and Cretaceous beds rest directly on the Permian. McKee and others (1959, pl. 9) show that continental Triassic deposits were eroded from the area to the west of the Delaware basin. Some dissolution of the upper part of the evaporites in the western part of the basin may have occurred during this interval. The evidence for removal of Triassic beds from the western part of the basin is the presence of Cretaceous sandstone and conglomerate in collapse depressions along the western margin of the basin.

Malley and Huffington (1953, p. 541) interpret a small area of thicker Triassic rocks in Lea County, north of the Capitan reef and outside the basin, as being associated with Triassic dissolution. Jones (1977, oral presentation) illustrated a band of thin Triassic sediments along the reef area in the northeastern part of the basin. It is likely that some dissolution of the upper part of the evaporite sequence accompanied the erosion interval prior to subsidence and overlapping of Cretaceous deposits. However, it is not believed that pre-Cenozoic dissolution accounts for an appreciable volume of salt removed from the basin because most of the dissolution features are so closely associated with Cenozoic and post-uplift hydrologic and structural controls.

Vine (1976) has proposed that dehydration of gypsum to anhydrite within the evaporites sometime in the Triassic was the source for water for the dissolution of collapsing chambers in deep salt beds that produced the breccia pipes in the northern part of Nash Draw (Domes A, B. and C of Vine, 1960). This interpretation was made after the discovery of the deep-seated nature of the breccia pipe under Dome C made earlier interpretations of the shallower origin of the domes (Vine, 1960) unacceptable. This last interpretation of Vine is also unacceptable because there is no apparent reason to delay dehydration of gypsum until Triassic or later time and because other nearby and similar collapse structures contain tilted blocks of Pleistocene Gatuna Formation. There is no reason to assume that such similar structures were formed at widely separated times.

The domal structures, breccia pipes, and other features of deep-seated dissolution are believed to have formed during the most recent and most extensive period of salt removal following Cenozoic uplift, erosion, and exposure of the evaporites. These features are considered in the subsequent sections of this report.

CENOZOIC DISSOLUTION

Structural and Stratigraphic Controls:

Large-scale dissolution of salt from the Delaware basin occurred during the Cenozoic Era following uplift and tilting and exposure of the reef and evaporites. Much of this happened during the past few millions of years. Understanding the present patterns of dissolution and the factors involved is, therefore, largely a problem in existing geometry and the nature of hydrologic flow. The Delaware basin, as a whole, responded to late Cenozoic uplift and tilting as a single unit. The uplift occurred mostly along the western side of the Delaware and Guadalupe mountains to the west of the basin and tilted the basin to the east-northeast so that present regional dip of the evaporite beds and aquifers is about 100 ft per mile (19 m per km). The bounding faults on the west intersected the reef (Capitan aquifer) at the southern end of the Guadalupe Mountains in Texas (Figure 1). The maximum uplift was somewhat greater to the south than in the northern part of the basin so that the Capitan aquifer became exposed and breached to the south first and the uplifted mountain mass became a major catchment for surface waters. The reef was also uplifted and exposed to the south in the Glass Mountains of Texas which became another catchment area for surface waters entering the reef aquifer system (Figure 1). Following uplift, the salt beds were systematically dissolved from the surface as erosion and dissolution progressed west to east and south to north across the basin.

The geometry of the permeable (aquifers) and impermeable layers (evaporites) in the basin directed the subsurface flow of ground waters to produce the present patterns of regional and localized deep dissolution. The Permian reef that rings the basin (Capitan aquifer) is the major water-carrying unit in the system. This aquifer has had a major influence on the movement of salt-dissolving waters, especially around the margin of the basin where the reef and the salt beds are in close proximity. (In Permian time it was the reef that was the principal factor that formed the basin and that determined the geometry of evaporite deposition. In Cenozoic time, it was also the reef that played a significant role in the removal of the evaporites.) Exhumation of the reef along the uplifted western and southern margins of the basin allowed entrance of meteoric waters. The permeable aquifer carried the waters to the low northeastern part of the basin where they escaped through leakage into the San Andres Limestone aquifer (Hiss, 1975).

The other major aquifer, related to deep dissolution, in the system underlies the evaporite sequence (Bell Canyon Formation, Delaware Mountain Group). In contrast to the reef, this aquifer is relatively impermeable but is under high artesian pressure and does conduct water eastward across the basin to eventually emerge through leakage into the San Andres Limestone aquifer. The upper part of this aquifer (Delaware sand) is more permeable than lower units. The catchment area includes parts of the reef and the exposed aquifer and evaporites along the western margin of the basin.

The Cenozoic uplift and tilting of the basin was accompanied by minor differential warping and flexuring and the development of well-defined fracture systems in the basin and reef-margin areas. Faults exist at depth, below the evaporites, along the inner eastern reef margin and parallel to the reef margin within the basin. These faults are not thought to have penetrated the evaporites (Haigler, 1962) but flexuring along the reef margin accompanying uplift is thought to have fractured the reef and the overlying evaporites (Adams, 1944, p. 1623; Hiss, 1975, p. 118).

Within the basin, joint sets with both a northeasterly and a northwesterly strike are recognizable. The northeasterly set appears to be better developed and has fractured the lower anhydrite of the Castile Formation along the western basin margin where it is exposed (King, 1948; Olive, 1957). This same direction of fracturing has also controlled the emplacement of "dikes" of replacement limestone in the middle part of the evaporite sequence. A fault graben with a displacement of about 80 feet has the same bearing as the joint set and intersects both the lower anhydrite (Anhydrite I) and the underlying Bell Canyon Formation (Smith, 1978; Appendix C).

This brief survey of the structural and stratigraphic controls on the movement of deep ground waters in the basin forms a setting for considering the distribution and origin of regional and localized features of deep dissolution. The Capitan limestone, Delaware sand, pre-Salado unconformity, and the reef-margin and basin fracture systems have placed moving undersaturated waters in contact with salt to produce a variety of dissolution features.

Features of Deep Regional Dissolution of Salt:

It has been known to geologists who have worked in the Permian basin that large volumes of salt have been removed from local areas in the Delaware basin by dissolution (see Malley and Huffington, p. 541). Many of these features have been previously described in a general way and attributed to solution effects but the deep-seated nature of the process or a mechanism to produce them has not been recognized. The discovery of beds of dissolution breccia and detailed knowledge of the stratigraphic position of the breccias from varve correlation has made it possible to use acoustical logs to identify particular horizons of dissolution in the basin. This, in turn, has shown that deep dissolution of salt is a common process and many of the dissolution features in the basin are of this origin.

Western Dissolution Wedge and Depressions

Anderson and others (1972, figure 8) and Anderson, Kietzke, and Rhodes (1978) showed that the salt beds of the upper and middle Salado had been undercut by dissolution along the western margin of the basin. This wedge-like effect of dissolution is illustrated in Figure 2. These studies show that the most active horizons of dissolution along the wedge have been the salt beds of the Lower Salado and the upper salt beds of Halite III. These salt beds lie above and below the position of the pre-Salado unconformity. The effect of the wedge on volume of salt dissolution is reflected in Table 1 which shows that the lower Salado has been the most active horizon of deep dissolution related to the wedge.

The position of the wedge is depicted approximately in Figure 1. The wedge apparently terminates in the southern part of the basin where the Pecos-Reeves County line joins Jeff Davis County. It follows a general north-south trend in most of the basin to T 25 S in New Mexico and then swings westward toward a prominent re-entrant in the margin of the basin southwest of Carlsbad. In T 24 S, R 28 E the wedges of both H-III and lower Salado salt merge with the western margin of overlying salt where the wedge terminates (Figure 16). In southern New Mexico the leading edge of the wedge has undercut the overlying salt beds of the Salado for a distance of 30 miles (49 km) and extended for 45 miles (73 km) beyond the western position of the lower salt beds (Halite I and Halite II) of the Castile. The greatest distance that the wedge has traveled from the western margin of the basin is about 80 miles (130 km).

The position of the eastern margin of the wedge is closely associated with large features of dissolution and collapse (dissolution depressions). These are the large areas of dissolution filled with Cenozoic sediments in the central part of the basin approximately along the axis of the Pecos River and which were described by Malley and Huffington (1953). This is the axis of dissolution described by Hiss (1975) as the Balmoreaha-Loving trough. The dissolution of the salt beds in the center of these large depressions reached to deeper levels in the evaporites and involved the thinning of both Halite II and Halite I salt.

Only the northernmost of the western dissolution depressions extend into New Mexico, and these are depicted particularly well on a map of the top of the Rustler Formation (Hiss, 1976, Map 7) and on the top of the 124 bed (Figure 11). Two of the areas of deepest depression occur in T 25 S, R 30 E. One is associated with the Poker Lake salt anticline (Anderson and Powers, 1978) and another is apparently an isolated feature in the Big Sinks area. Both of these deep depressions contain downdropped blocks of Halite III salt. The Big Sinks depression was depicted in a cross section by Vertrees (1964) and is also illustrated diagrammatically in Figures 12 and 14. It is dissolution of salt from Halite III that forms the leading edge of the depression (Figure 16). A third depression lies mostly in T 26 S, R 31 E and in this depression it is the Lower Salado salt that has been dissolved to form the leading edge of the wedge (Figure 16).

Figure 14. East-west diagrammatic cross section (I-I') across northern Delaware basin. Note that western dissolution wedge penetrates to Poker Lake and Big Sinks depressions. Note also that San Simon sink lies above eastern reef margin.

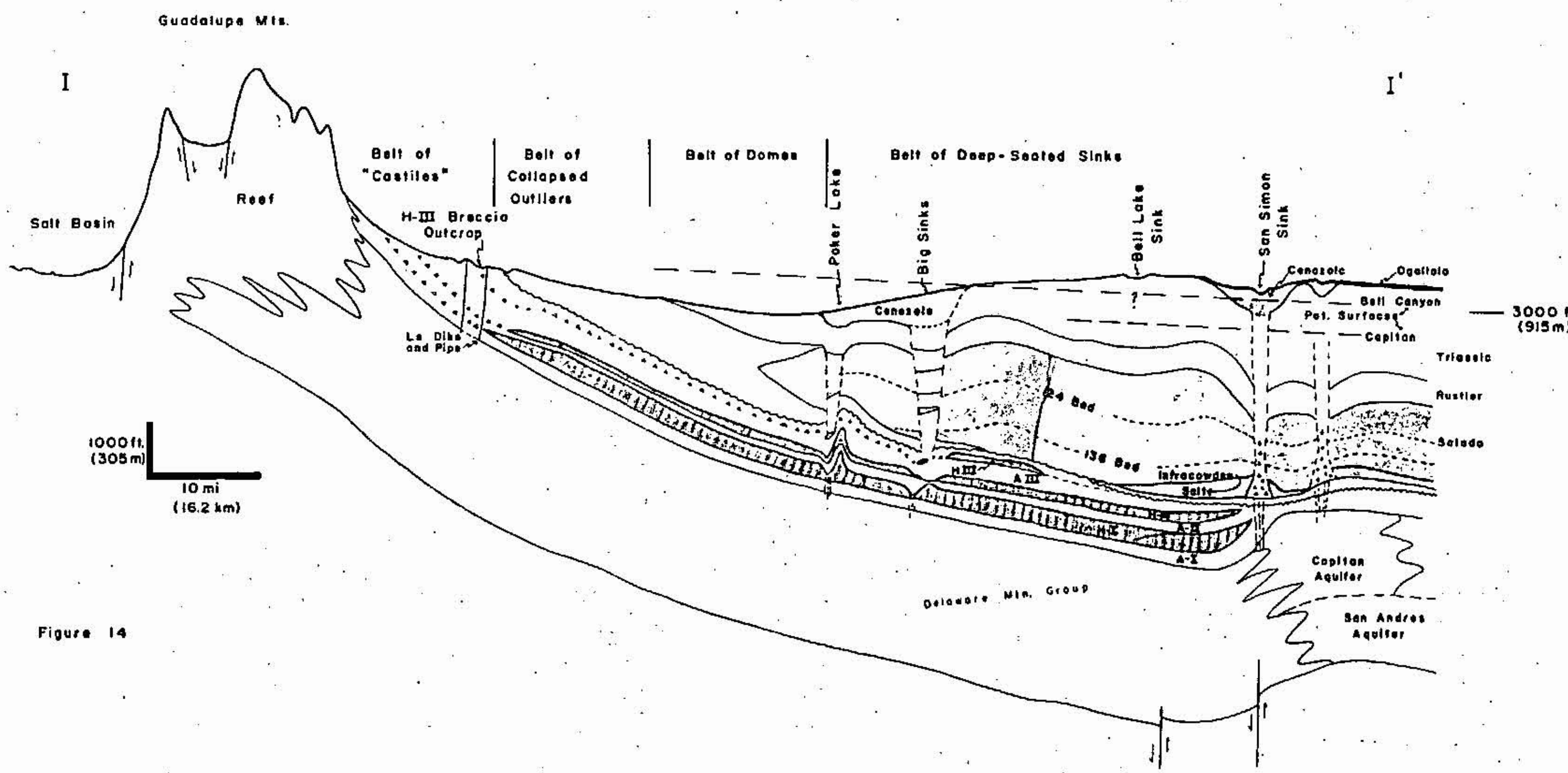

Guadalupe Mts.
I
I'
Salt Basin
Reef
Belt of "Castiles"
Belt of Collapsed Outliers
Belt of Domes
Belt of Deep-Seated Sinks
H-III Breccia Outcrop
La Dike and Pipe
Poker Lake
Big Sinks
Bell Lake Sink
San Simon Sink
Cenozoic
Ogallala
Bell Canyon
Pot. Surfaces
Capitan
3000 ft. (915m)
Triassic
Rustler
Salado
24 Bed
136 Bed
Infracowden Salts
Capitan Aquifer
San Andres Aquifer
Delaware Mtn. Group
1000 ft. (305 m)
10 mi (16.2 km)

Figure 14

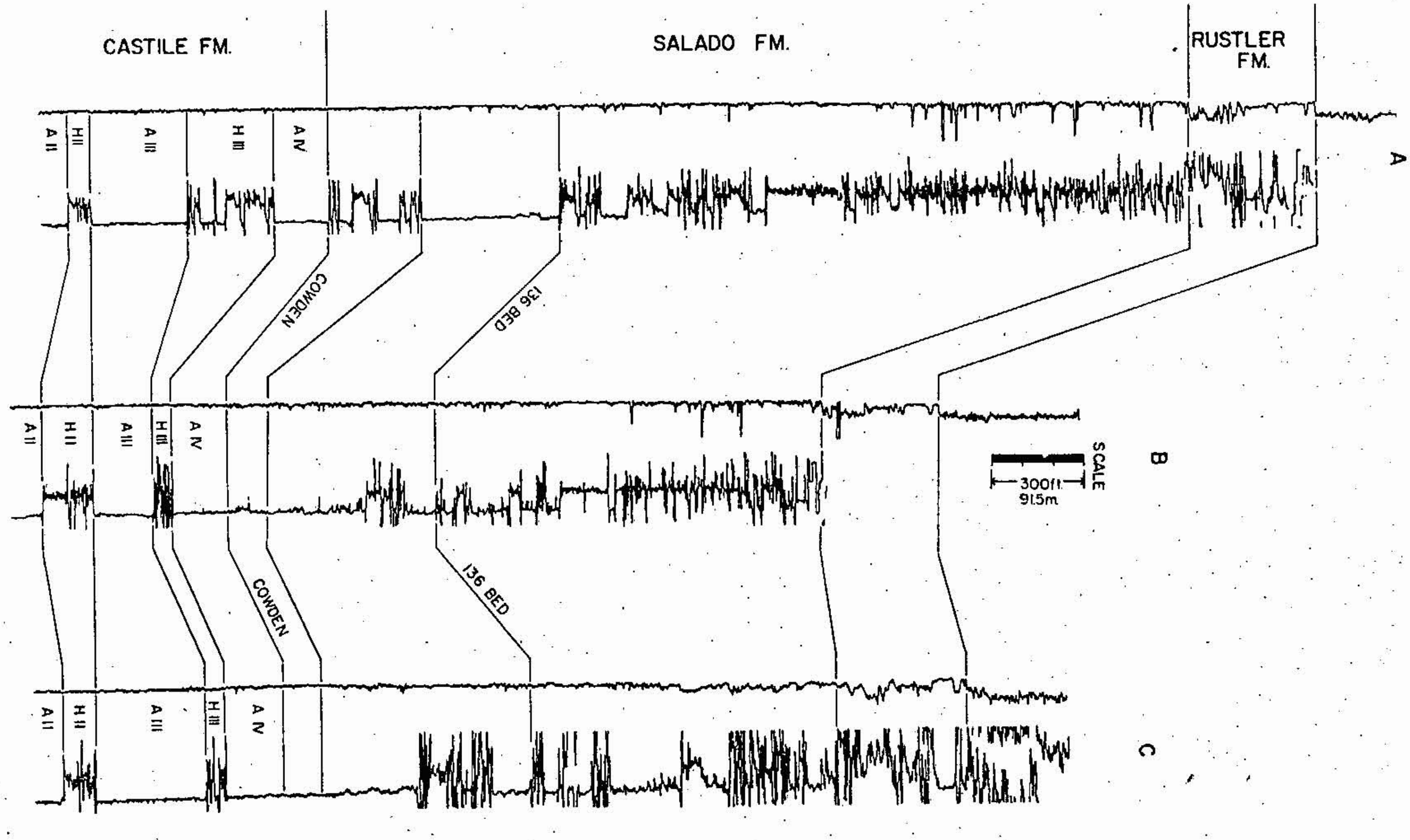
Eastern Dissolution Wedge and Depressions

The horizon of salt dissolution responsible for the reef-margin depression can be identified in profiles of acoustical logs extending from areas of undissolved salt on the west to the area of active dissolution adjacent to the reef. One such profile in Ward County, Texas (Figure 15) shows dissolution of upper Halite III salt beds and lower Salado salt under areas where Rustler Formation has collapsed into the dissolution depressions. Hence, the same horizons along the eastern reef margin as along the western dissolution wedge are the active zones of dissolution. The edge of salt dissolution along the eastern margin of the basin is also a wedge (Figure 1).

A series of large, deep dissolution depressions filled with Cenozoic sediments lie above the inner margin of the reef along the eastern side of the basin. These were originally described by Malley and Huffington (1953) and are characterized more completely by the structure map on top of the Rustler Formation compiled by Hiss (1976, Map 7). The northernmost of the eastern depressions described by Malley and Huffington (1953) extends into New Mexico in T 26 S, R 36 E. Another similar depression, which is also located above the inner reef margin, occurs about 15-20 miles (25-35 km) to the north and has surface expression as San Simon swale and sink. The depression in T 26 S contains more than 1000 feet (305 m) of Cenozoic fill. The San Simon swale depression contains about 500 feet (152 m) or more (Bachman, 1974, fig. 12).

Still another feature that is of about the same scale as San Simon swale and occupies the same position above the inner reef margin occurs along the northern margin of the basin northeast of Carlsbad (Brokaw and

Figure 15. East-west acoustical log correlations showing evidence for eastern dissolution wedge. Note that depression of Rustler formation (Rustler low) corresponds to the removal of salt from the lower Salado and upper part of Halite III. (A, Harvey L. Hurley, Wilson #1, Sec. 127, Blk. 34, H&TC Survey; B, Gold Metals Cons., Houston Heirs #1, Sec. 18, SF 7082, G. G. Houston Survey; C, T. F. Hodge, Edwards Lumber Co. #1, Sec. 99, Blk. 34, H&TC Survey; Ward County, Texas). See Fig. 1 for location of section.


CASTILE FM.
SALADO FM.
RUSTLER FM.
A II
H II
A III
H III
A IV
COWDEN
136 BED
A
B
C
SCALE
300ft.
91.5m

others, 1972, figure 4), (Figure 1). This depression contains about 700 feet (213 m) of Cenozoic fill.

San Simon Sink and Swale:- The San Simon depression is of particular interest because it contains an active sink at its southeastern end and because the depression lies along and parallel to the northeastern margin of the basin. It follows the same reef-margin trend as the deeper and larger collapse depressions to the south and may represent the early stages of dissolution in the northern part of the basin.

San Simon sink is an elongate collapse structure about 0.5 mile (0.8 km) wide and 1 mile (1.6 km) long with the axis parallel to the basin margin. The sink is defined by a 90-ft (27 m) surface depression and by a series of ring fractures. The most recent ring fracture occurs only in the northwestern part of the sink. It developed when the sink collapsed after a period of heavy rain in 1927 and was 15 feet (4.6 m) deep and flat bottomed after formation. San Simon sink occupies the southeastern end of San Simon swale which is a gradually sloping topographic depression about 4 miles (6.5 km) wide and about 8 miles (13 km) long. The swale has about 100 ft (30 m) of topographic expression (excluding the sink) and also trends parallel to the basin margin.

The W.I.P.P. 15 core, collected in March, 1978, probably represents the thickest and most nearly complete sequence available in the swale. The core was collected from the center of San Simon sink (see Figure 18). The map of the red bed surface compiled by Nicholson and Clebsch (1961, pl. 1) shows a thickness of 170 feet (52 m) of fill above the "red beds" in the swale near San Simon sink. This thickness corresponds to the top of a red clay unit in the lake sediments and is not the top of the Triassic red beds. Bachman's (1974, p. 12) map of the bedrock surface recognized the true depth to the Triassic in the swale to the northwest but not in the sink area. The greatest depth or thickness of fill represented by Bachman in the area northwest of the sink (location of proposed W.I.P.P. 17) is actually no greater than the thickness of fill in the San Simon sink area. Further evidence for swale sediments throughout the sink area can be found in the thickness and purity of the red clay unit of lake sediment which suggests deposition in a much larger basin than San Simon sink. Younger sink sediments also persist beyond the immediate area of the sink. In addition, a weak artesian flow was derived from the lower sands during coring operations suggesting their persistence over a wide area and a slope toward the sink.

San Simon sink was cored to a depth of 810.2 feet (247 m). Eolian sand and silt and clay rest on the reddish brown and green claystone and siltstone of the Dockum Group (probably Chinle Formation) at a depth of 545 feet (166 m). This depth corresponds approximately to the predicted depth to red beds of Bachman (1974, p. 12). A spore and pollen flora containing forms closely resembling those of the Triassic Dockum Group, and described by Dunay and Traverse (1971), was encountered in a dark gray siltstone at a depth of 705 feet (215 m). The reddish brown and green siltstone and claystone above the fossil flora contain no recognizeable fossils but the similar lithology and a similar state of preservation of carbonized plant fragments suggests that Triassic sediment persists to the contact with the dune sand at 545 feet (166 m).

The sand sequence is overlain by about 60 feet (18 m) of brick red, green, and brown clay containing zones of sand and silt. The lower part of this clay unit yielded a flora containing abundant Artemisia and modern confier pollen indicating that the clay-rich sediment represent a pluvial climatic episode. The clay layer is overlain by dune sand which becomes increasingly calcareous and fine-grained upward and is in turn overlain by alternating layers of calcareous sand and silt. The upper part of the sink sequence consists of tan playa clay containing concentrations of plant detritus and a modern pollen flora. This unit is overlain by a thin gypsum sand and gray clayey silt.

Gray sand dune accumulations and calcareous lake sediment mark the highest elevation of the most recent Holocene lake at about 3370 feet (1027 m), which is about 20 feet (6 m) above the present floor of the swale. This is the same level as the sill opening to the southeast and the lake probably overflowed. Diatomaceous and calcareous lake sediment occur just below the high shoreline. It may be possible to obtain a radiocarbon date from these sediments. A preliminary estimate by Bradbury (Appendix B) suggests that the last high lake stand probably occurred between 8000 and 9000 years B.P.

Dips in the lower, Triassic part of the core are variable, ranging from 10^{o} to 30^{o}. Minor normal faulting and vertical fracturing of the harder claystone and siltstone units was observed but no displacement greater than about 10 cm was seen. The rock was not brecciated.

Comparison of the elevation of Triassic units in W.I.P.P. 15 with correlative units in adjacent boreholes indicate that about 500 to 700 feet (152 to 183 m) of depression has occurred within a 2 mile (3.2 km) area adjacent to San Simon ridge. A hard sandstone, containing numerous Indian grinding holes at a level just above the high shoreline of the lake, crops out at the western edge of San Simon ridge. This sandstone is underlain by reddish brown and green shale and is probably Triassic in age. The sandstone and shale unit is apparently faulted off and downthrown into the swale and the outcrop contains a well developed set of joints parallel to the axis of the swale and ridge.

Two apparent episodes of faulting or depression and collapse are represented in the sink and swale sediments. The first is the formation of the swale itself which allowed space for the accumulation of the thick lower dune-sand sequence. A lesser event may have occurred after the accumulation of about 250 feet (76 m) of sand where there is an influx of caliche clasts. A major collapse event occurred after the last high lake level and produced the present San Simon sink. This event actually occurred in stages, as reflected in soil levels and stratigraphic units within the sink and in continuing collapse activity. Collapse since the last high lake stand and within the sink amounts to about 120 to 150 feet (39 to 46 m), or about one fifth of the total depression in the swale.

A preliminary estimate of the age of San Simon swale and sink features can be made at this time, subject to verification by more complete investigation. The sink itself post-dates the 8000 to 9000 year high lake stand. Sediments associated with this saline phase of lake development occur above the clay-rich horizon between 160 to 220 feet (49 to 67 m), which in all probability represents the last full pluvial climatic episode. Correlation with Lake Estancia events and with Lake Lahontan would place this interval at about 18,000 to 20,000 years B.P., or equivalent to Late Lake Estancia

(Bachhuber, 1971). It is conceivable that the pluvial interval could represent early Lake Estancia time and be as old as 60,000 years but this seems unlikely if the diatomaceous beds prove to be 8000 to 9000 years old. The lower unconsolidated sand appears to be part of the same depositional environment as the sand above the pluvial clays and resembles the surface sand now accumulating in the swale. Although the sands are quite thick, they do not necessarily represent a long period of deposition and are probably no older than early Wisconsin.

Localized Dissolution Features:

A variety of collapse structures of a smaller scale than the large dissolution depressions previously described are to be found in different parts of the basin and along the reef margin. In some cases, these structures may differ from the dissolution depressions mainly in scale and the extent of associated dissolution and may merely be different expressions of the same feature. It is convenient, however, to describe these structures separately and according to their position in the basin.

Deep-Seated Sinks in the Deformed Basin Margin

Jones (undated map) recognized that a 6 mile (10 km) belt adjacent to the reef and around the margin of the basin had been subjected to deformation and the development of anticlinal structures. Anderson and Powers (1978) also illustrate this zone and attributed the structures to the flowage of salt. A number of deep-seated sinks are associated with the salt anticlines and are expressed as thin or missing sections of Halite I and Halite II salt and structural depression of the overlying stratigraphic units (see Figures 4, 5, and 16). The sinks generally appear to develop between the anticlinal structures but lack of control makes a determination of the true relationship difficult.

Deep-seated dissolution also occurred at several horizons along the upturned flanks of the anticline at ERDA #6 borehole locality (Anderson and Powers, 1972). This dissolution was associated with flowing brine and H_2S gas. A similar association of brine and gas under pressure associated with an anticlinal structure occurs at the Belco oil field locality in Sec. 1 T 23 S, R 30 E., and at other localities in the basin.

Deep-Seated Sinks in the Mid-Basin Area

The mid-basin sinks, as those in the deformed margin, have thin or missing Castile halite units and depressed structure contours of overlying units. Most of the sinks can be seen as thin areas on the Halite I isopach map (Figure 4) or as thin areas on the other isopach maps (Figures 5-10). Not all of the localized thin halite units have a matching structural depression and some thin halite beds are found above Halite I and II so that no one isopach or structure horizon depicts all of the suspected deep collapse features. A summary of the deep collapse structures encountered at different stratigraphic horizons in this survey is given in Figure 16.

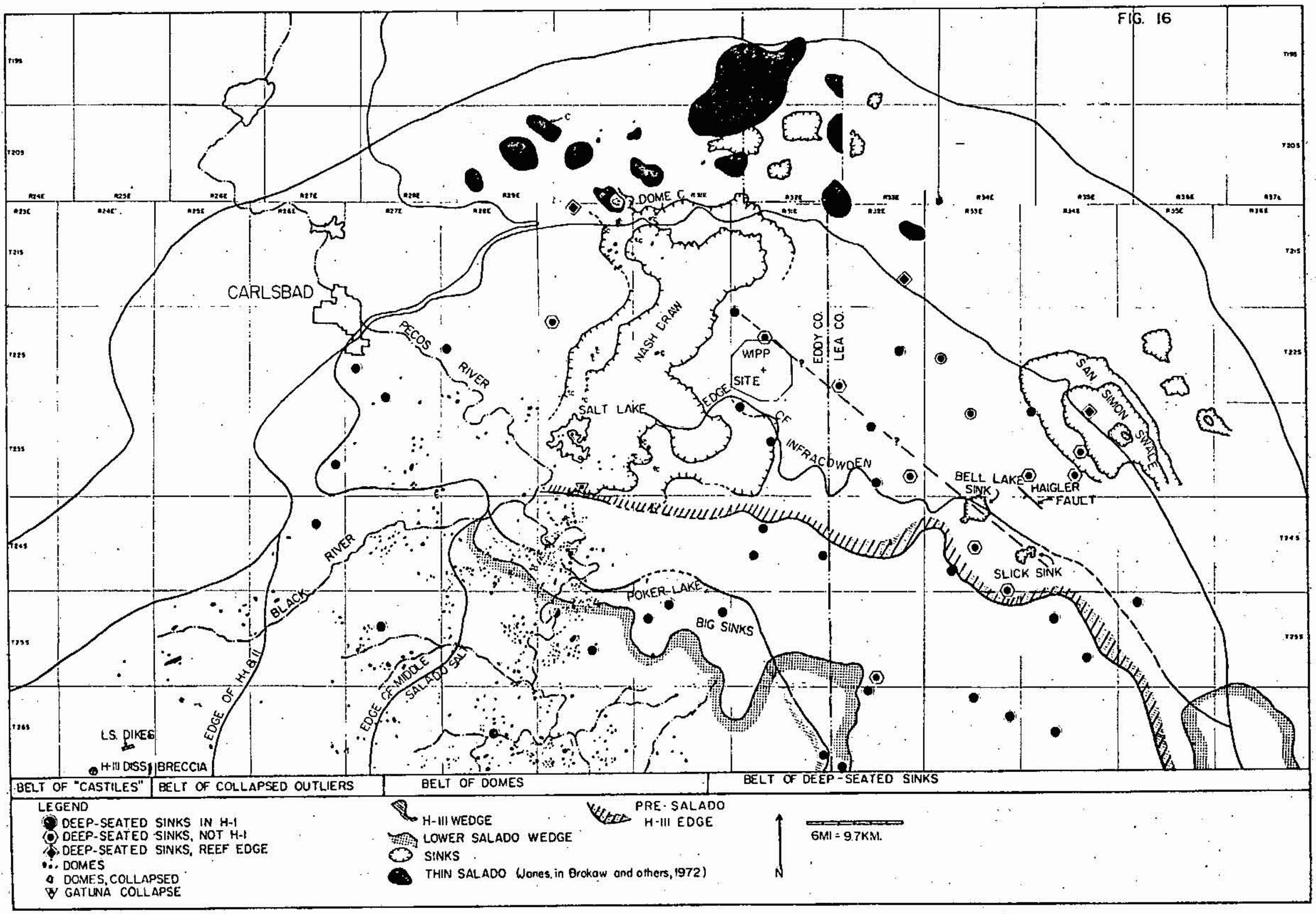
The deep-seated sinks in the basin can be divided into two groups: those that are associated with anticlinal structures and those that appear to be isolated, with no closely related anticline. There appear to be about 10 isolated sinks in the mid-basin area but the lack of association with anticlines may be partly due to lack of log control. About 5 sinks in the mid-basin area are definitely associated with anticlines.

The salt beds over and adjacent to the anticlines have responded to deformation or dissolution in several ways that can be seen by comparing the isopach maps of Halite I and Halite II (Figures 4 and 5). In some of the larger anticlines, particularly in the deformed zone, Halite II has been cut out of the section above the anticline. At Poker Lake, in the basin, both Halite I and Halite II have thickened in the axis of the fold. Three sinks have a thick sequence of Halite II above a thin Halite I and most of the mid-basin sinks have thin intervals of both Halite I and Halite II.

Most of the sinks associated with anticlines occur on the regional down-dip side of the structures but two occur on the up-dip side. Where well control and spacing is close, the true scale of some of the collapse sinks can be seen, but even in these cases the low areas appear to be comprised of several individual sinks. For most of the localities noted, only one data point is available so the true size of the structures is

Figure 16. Summary map of deep seated dissolution features in the northern Delaware basin. Note that western dissolution wedge terminates where it joins salt edge of middle Salado in T 24 S, R 28 E. Note also that distribution of Halite III and Infracowden salt are mutually exclusive and that dissolution features occur in north-south trending belts across the basin.

FIG. 16



CARLSBAD
PECOS RIVER
NASH DRAW
SALT LAKE
WIPP SITE
EDDY CO.
LEA CO.
DOME C
EDGE OF INFRACOWDEN
SAN SIMON SWALE
BELL LAKE SINK
HAIGLER FAULT
SLICK SINK
POKER LAKE
BIG SINKS
BLACK RIVER
EDGE OF H-II
EDGE OF MIDDLE SALADO SALT
LS. DIKES
H-III DISS. BRECCIA
BELT OF "CASTILES"
BELT OF COLLAPSED OUTLIERS
BELT OF DOMES
BELT OF DEEP-SEATED SINKS
LEGEND
DEEP-SEATED SINKS IN H-I
DEEP-SEATED SINKS, NOT H-I
DEEP-SEATED SINKS, REEF EDGE
DOMES
DOMES, COLLAPSED
GATUNA COLLAPSE
H-III WEDGE
LOWER SALADO WEDGE
SINKS
THIN SALADO (Jones, in Brokaw and others, 1972)
PRE-SALADO H-III EDGE
N
6MI = 9.7KM.

not really known. On the basis of the number of sinks in areas with close well control, at least 100 deep-seated sinks probably exist at the present time in the New Mexico part of the basin.

The mid-basin sinks appear to have some preferred distribution with a clustering in an area that roughly parallels the reef edge along a regional sag in the 124 bed structure contour (Figures 11, 16). This is also an area that contains two large surface sinks (Bell Lake sink and Slick sink). Neither of these sinks is in a place where boreholes are present to determine the depth of collapse. Both are associated with blowouts of gypsum dunes above the sink floor. The soils in the area do not appear capable of being a source of the gypsum and other sinks in the area are gypsum free, suggesting that sulfate-rich waters rose up to the sink through fractures at least as deep as the Rustler Formation and perhaps deeper. A water well was drilled in Bell Lake sink to a depth of 150 feet (46 m) and abandoned because it was too salty for cattle (C. Johnson, personal communication). A line connecting Slick sink, Bell Lake sink, and the two mapable depressions in the 124 bed (Figures 11 and 16) parallels the eastern basin margin about nine miles from the eastern edge and may be the site of a fault or fracture zone. A fault that penetrates the Base of the Delaware Mountain group with about 200 feet (61 m) of displacement downthrown on the basin side occurs about 1 1/2 miles (2.4 km) east of this inferred line (Haigler, 1962, p. 3). This same trend extends through the northwestern lobe of Nash Draw and aligns with an exceptionally deep area of dissolution in the Salado above the reef (see Brokaw and others, 1972, figure 9), (see also Figure 16).

Breccia Pipes and Domes

Vine (1960) and Reddy (1961) mapped and described a number of domes in a north-south belt approximately corresponding to the area of Rustler outcrop in the west-central part of the basin. Many of these domes have been breached by erosion to reveal cores of collapsed Gatuna. Rustler, and Triassic beds. A number of these domes were visited and mapped in order to help clarify their relationships and origin (see appendix D). The domal structures can be classified into unbreached simple domes that give no clue as to their internal structure, breached domes which show evidence of circular faults, collapse and brecciation of the overlying beds, and some breached domes (in the Queen Lake area, Reddy, 1961) where the central core appears to be higher stratigraphically than adjacent beds.

The domal structures in the area that could be observed in the field or on aerial photographs were plotted (Figure 16) and the orientation of the long axis of the domes plotted on a rose diagram (Figure 17). Those domes that were visited and where actual collapse and brecciation could be verified are plotted on Figure 16 with a different symbol than unclassified domes.

The upper surface of the domes is most commonly veneered with a layer of Mescalero caliche. This upper surface has been draped over the collapsed and brecciated core of the dome where breaching has exposed the relationship. In some cases, elongate domes are underlain by more than one center or core of collapse. This can be seen at the dome in the southeast corner of Sec. 24, T 23 S, R 30 E. Hence, the bearing or direction of orientation of some of the larger domes may represent several structures. The rose diagram shows a preferred orientation at

Figure 17. Rose diagram of orientation of domes in northern Delaware basin (see Figure 16 for distribution of domes). Data concerning frequency and orientation of domes as follows:

Unoriented (± circular) domes 318

NE-SW oriented domes . . . 201
NW-SE oriented domes . . . 146
Oriented domes. 347

Questionable domes. 38
Total number of domes 702

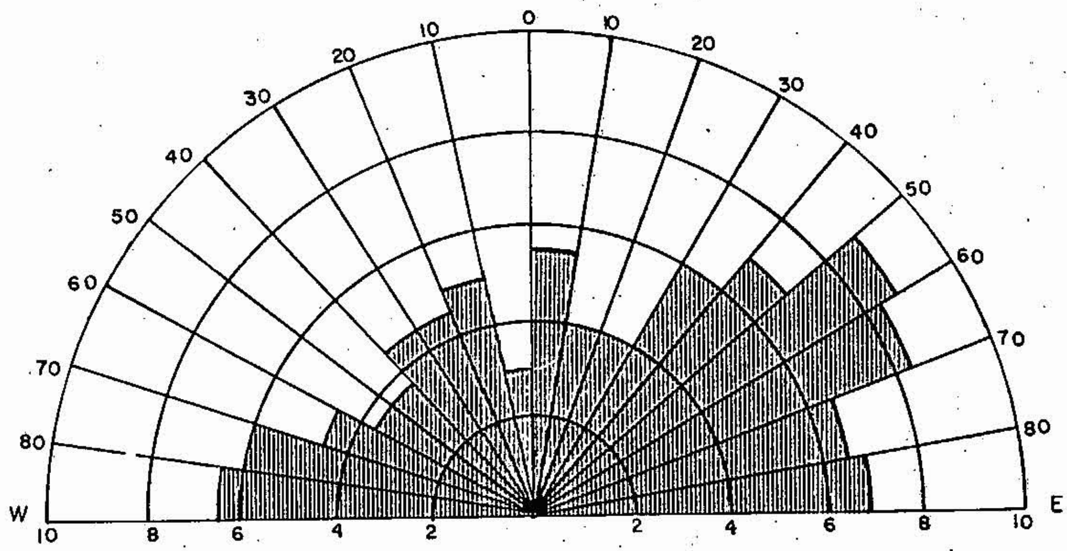


FIG. 17 ORIENTATION OF DOMAL AND COLLAPSE STRUCTURES, EDDY CO., N.M.

about N 62° E and a lesser cluster at about N 80° W, which is approximately the orientation of known fracture systems in the basin.

The domal structures range in size (diameter) from less than 50 meters to more than 500 meters. The domes are associated with areas of relatively recent regional surface salt dissolution and are more common along the course of the main drainages in the area. The doming itself appears to be related to this regional removal of salt. The smaller domes occur most commonly in the areas of the main drainages or active subsidence (Figure 16).

Domes with collapsed cores of Gatuna Formation and Magenta (Rustler) dolomite occur in the southern and central part of Nash Draw. The breached domes at the north end of Nash Draw contain brecciated cores of Triassic rocks. These domes were described by Vine (1960). Vine's Dome C was subsequently mined under at the 1200 foot (366 m) level by Mississippi Chemical Company. The mine tunnel encountered a core of brecciated rock directly beneath Dome C. The breccia consisted of blocks of coarsely banded (Salado type) anhydrite and halite ranging in size from centimeters to several meters. Zones of gray clay 10-20 cm wide occurred near the walls of the pipe and some of the breccia blocks were also sheathed in clay. The clay was relatively pure and was apparently emplaced by seeping fluids. The sides of the pipe at the level examined were dipping outward at an angle of about 60°. Marker beds in the mine tunnel gradually began dipping toward the pipe at a distance of about 200 feet (61 m) from the edge of the pipe. A few meters from the pipe, these same marker beds dipped in and downward toward the pipe at an angle of about 20° where they were terminated by the collapse structure (<u>see</u> Figure 12).

Two other breccia pipes have been encountered in the general basin area. One of these (Weaver pipe) lies north of Dome C above the reef. This feature was drilled to a depth of about 800 feet in collapsed material and then abandoned. Another breccia pipe was encountered in the northwestern part of T5, Blk 60, in western Culberson County, Texas, by R. Y. Anderson during research investigations. This core began stratigraphically near the upper part of the Castile Formation and consisted of brecciated Castile gypsum and anhydrite fragments to a depth of 435 feet (133 m). The location was abandoned at about the stratigraphic level of Anhydrite III or Halite III. The entire core was breccia. The pipe at Dome C and other domes at the North end of Nash Draw lie above the inner reef margin, Weaver pipe is above the reef according to the outer reef boundary as figured by Hiss (1975), and the Culberson County pipe is near the center of the basin (Fig. 1).

Collapsed Outliers

Numerous collapsed outliers of Rustler Formation, mostly Culebra Dolomite, occur in the area of the basin west of the domes and where salt has been completely dissolved from the evaporites. The position of the outliers is shown in Figure 16 and some outliers are depicted on the geologic map compiled by Kelley (1971). The Rustler outliers have been derived from overlying units and now are surrounded by the gypsum of the Salado and Castile formations. The features are circular to elongate to somewhat irregular in outline and of about the same diameter as the domes. One of the collapsed outliers in the southeastern part of T 26 S, R 26 E is bounded by a ring structure with a brecciated margin and a collapsed center.

A large collapse structure is well exposed along U.S. Highway 62/180 about 1 3/4 miles (2.8 km) north of the New Mexico-Texas State line (Locality 1 of Kirkland and Evans, 1976). This outlier contains Rustler beds (Kelley, 1971) and laminated Salado Gypsum as well as blocks of tan conglomeratic sandstone which have tentatively been identified as an equivalent of the Cretaceous Cox Formation in the Apache Mountains. The gypsum beds have been replaced along fractures by biogenic calcite of the type found in the replacement limestone buttes (Castiles) farther to the west and south on the Gypsum Plain. Another outlier containing Cretaceous fossils has been reported north of this locality and scattered cretaceous fossils have been found to the south (Lang, 1947).

Replacement Limestone Masses

Groups and clusters of replacement limestone buttes (Castiles) occur on the Gypsum Plain to the west and south of the collapsed outliers (Kirkland and Evans, 1976). The main body of the buttes consists of biogenic calcite which has replaced the gypsum or anhydrite. Some of the buttes are actually collapse structures with brecciated cores which apparently helped provide access for the solutions accompanying the replacement process. The diameter, scale, and distribution of these features is similar to that of the collapsed outliers farther to the east.

The replacement limestone masses occur mainly in Texas in the lower part of the Castile Formation. The collapse outlier with biogenic calcite near the State line occupies a higher stratigraphic position than most of the Castiles on the Gypsum Plain. Just south of the outlier, there are several dike-like bodies of replacement limestone that intersect the Highway (Figures 1, 16). The trend of the fractures along which replacement has taken place is the same as for the solution troughs in the western Gypsum Plain (Olive, 1957). This is the same trend as the limestone replacement mass which was controlled by faulting of the lower Castile anhydrite and Delaware sand described by Smith (1978; see appendix C).

Other Collapse Structures

Many sinks are present in the Delaware basin and most of these are associated with active near-surface salt dissolution, such as along the Pecos River and in Nash Draw. Some of these sinks, such as the one in Sec. 6, T 23 S, R 30 E, show evidence of recent collapse. In this example, gypsum dunes bordering the sink have had their slip faces steepened to about 60° by deepening and further subsidence of the sink. Other collapse structures representing earlier episodes of sink development can be found above the levels of existing sinks in the Willow Lake area, suggesting several generations of relatively young sinks.

Below the Mescalero caliche, there are collapse structures in the Gatuna Formation that have not acted as resistant plugs to produce the later doming and arching of the overlying caliche. One of these structures (no association with doming can be demonstrated here) has dips of 40°-60° and involves more than 200 feet (61 m) of Gatuna section and appears to be a synclinal structure plunging northeastward. This particular structure is exposed in the bed of the Pecos River at the Pierce Canyon crossing east of Malaga (Figure 16). Another pre-Mescalero structure is located at the southern edge of Nash Draw in Secs 33 and 34, T 23 S, R 29 E (Figure 16). At this locality two episodes of collapse during Gatuna deposition (one may be post-Gatuna) produced a sink structure that was not involved in later doming.

Origin of Deep-seated Dissolution:

The large dissolution depressions along the reef margin, breccia pipes lying above the reef edge, deep-seated sinks in the basin, collapsed outliers, and brecciated limestone buttes share a common relationship. The origin of all these features can be explained by their association with fracture systems that have communicated with underlying aquifers. (The western wedge of dissolution, which has undercut the salt beds for great distances, requires a different explanation.) In the course of this investigation a concept of deep-seated dissolution by means of brine density flow has been developed that explains why such features are common in the Delaware basin. These ideas are presented in the context of the individual examples or features of deep-seated dissolution.

Origin of Reef-associated Dissolution

Several observers have noted the absence of halite adjacent to and above the reef in the eastern and northeastern part of the basin (see summary by Hiss, 1975). In addition to Hiss, Adams (1944, p. 1623), and Adams and Frenzel (1950, p. 301) have recognized that flexuring and fracturing of the Artesia Group and impermeable anhydrite, that accompanied uplift and tilting of the basin, allowed waters to gain access to the overlying and superjacent salt near the reef resulting in its subsequent removal. One problem with this explanation, and with other explanations for lateral and subsalt dissolution, has been providing for a circulating hydrologic system. It is not sufficient to place undersaturated water in contact with salt because it will soon become saturated and dissolution will stop. Water must continually be circulated to and from the salt body.

Douglas W. Kirkland (Mobil Research and Development, Dallas, Texas) has suggested a mechanism of brine density flow to account for the removal of salt under these circumstances. Using this suggestion, I constructed a brine density flow model in the laboratory that simulated the hydrologic flow system in the Delaware basin (see appendix A for a more complete description of the model and the experimental results). In the brine density flow process, undersaturated waters, under artesian pressure, rise in open fracture systems until they encounter a salt body. Once in contact with the salt body these waters soon become saturated and dense. The heavy, saturated waters descend through the more open fractures as a density current or flow and are replaced by lighter undersaturated waters under artesian pressure to complete the circulation cycle. The dense brine enters the underlying aquifer where it is removed by mixing with flow through the aquifer. In this manner a continuous flow of water travels to and from the salt to accomplish continuous dissolution.

The laboratory model (see appendix A) showed that undersaturated "fresh" waters rose in a constricted passageway, connecting an underlying aquifer with an overlying salt body, toward the potentiometric surface. Upon encountering the salt, the water became saline and dense and the brine descended through a more open passageway to the underlying aquifer. At the same time, undersaturated water moved up the more constricted passageway to contact the salt and establish a continuous brine flow cycle. The dense brine, upon entering the simulated aquifer, moved down and out of the system. The opening in the simulated system that carried the brine downward and away from the salt body had a diameter of 2 mm. Circulation in the tube, driven only by brine density flow, moved at a rate of about 5 cm per second. This flow in the tube dissolved salt in the overlying chamber at a rate of 1 g per minute.

In the Delaware basin the potentiometric surface above the reef is near the surface (Figure 14) and the high artesian pressure would be more than adequate to raise waters through fracture systems to initiate the cycle. The volume of water flow through the Capitan aquifer is many times more than needed to carry away the brine derived from dissolution depressions overlying the reef. It is probably the permeability of fractures that limits salt dissolution near the reef.

The brine density flow mechanism helps explain how deep depressions above the reef, with no external surface drainage, could have developed at the observed horizons of dissolution at the base of the evaporite sequence (upper Halite III and lower Salado). Once a chamber in the salt above the aquifer had developed and collapsed, the resulting faults and fractures would have allowed communication between surface waters and the aquifer through the fractured evaporites. The surface waters would then have contributed to the brine-dissolving mechanism as they contacted the salt, became saturated, and descended through the leaky collapse depression into the aquifer. In this manner surface drainage would have contributed to enlarging the original depression and salt beds throughout the section in the depression would ultimately have been subjected to dissolution. The large eastern reef-margin depressions described by Malley and Huffington (1953) are thought to have originated in this way.

San Simon sink and swale may represent an early stage of deep-seated reef margin dissolution in the northeastern part of the basin but sufficient evidence is not yet available to demonstrate this conclusively. The following review summarizes the principal relationships:

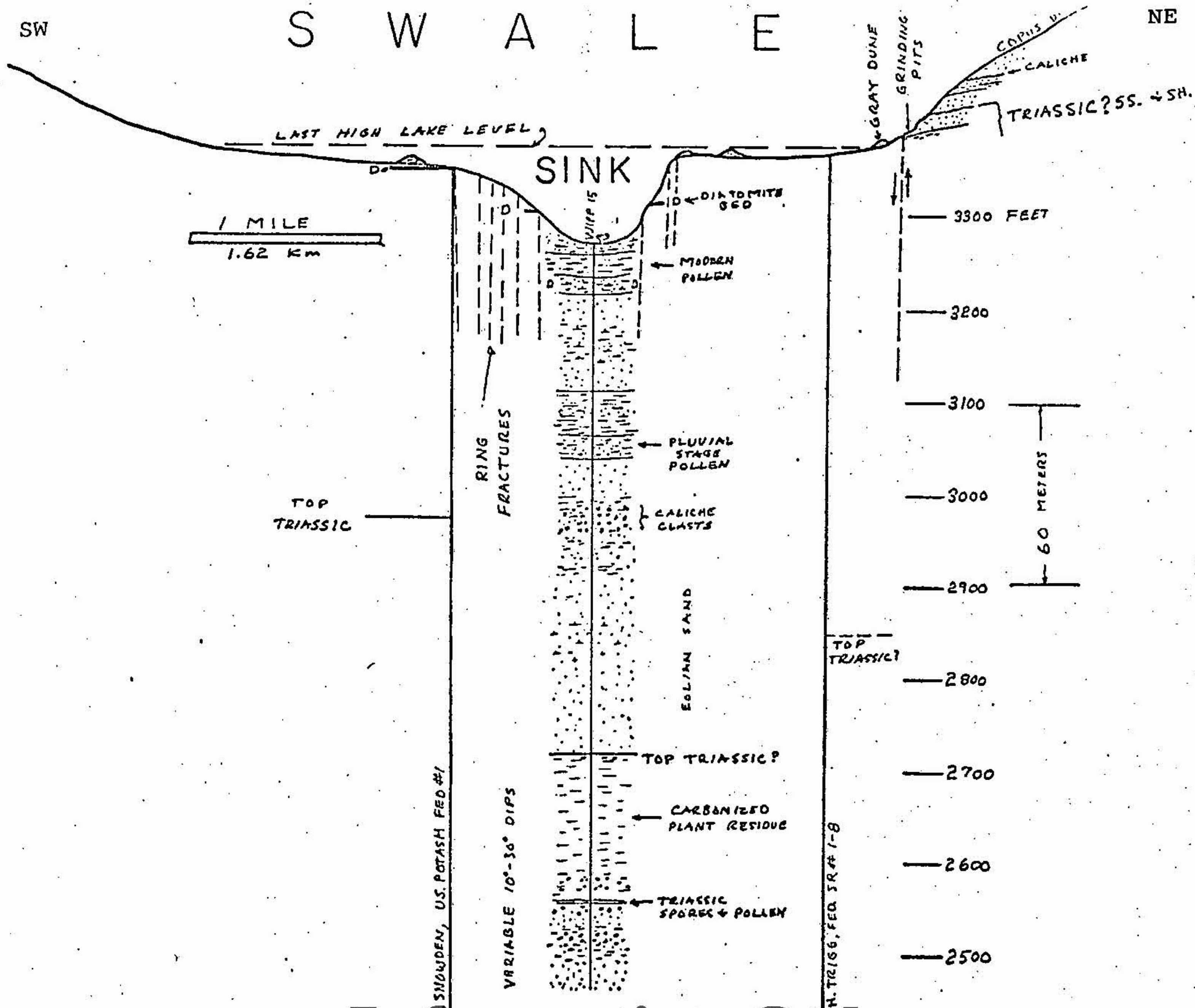
Nicholson and Clebsch (1961, p. 44) suggested that San Simon swale once may have been an early Tertiary river valley and drained southward. They also suggested that the swale could have formed from coalescing sinkholes. Subsequently, Bachman and Johnson (1973, p. 32) interpreted the swale, as well as the deep eastern reef-margin depressions of Malley and Huffington (1953) as the result of dissolution along a major abandoned tributary to the Pecos River. They concluded that dissolution of the Rustler Formation beneath the red beds was responsible for the collapse of San Simon sink within the old stream course.

The preliminary information obtained from the W.I.P.P. 15 core does not support the concept of an ancient stream channel. No stream deposits were observed beneath the lake sediments and the thick sequence of water-deposited dune sand indicates that ponding took place shortly after the development of the swale. The sill level in Triassic bedrock for the lake-deposited sediments in the swale is about 425 feet (129 m) above the base of the sand and the floor of the swale, eliminating the possibility of through-flowing drainage accompanying swale development (note: Nicholson and Clebsch's map suggested the possibility of drainage, but this was based on an erroneous interpretation of the elevation of top of the red beds). The youthful age of the sediments in the swale would also preclude their deposition in a long-abandoned tributary to the Pecos.

The W.I.P.P. 15 core did not penetrate deep enough to provide specific information about the horizon of dissolution responsible for the collapse. The variable dips in the underlying bedrock indicate some distortion and tilting but the absence of brecciation shows that a chimney or pipe of breccia does not extend to the pre-collapse surface in the center of the sink. The swale appears to have formed as a downdropped unit about 2 miles (3.2 km) across. The Triassic? outcrop and the fault and fractures along the western edge of San Simon ridge suggest that most of the depression took place close to the swale margin (Figure 18). At least 500 feet (152 m) and possibly as much as 700 feet (213 m) of vertical displacement has occurred across an area less than 2 miles (3.2 km) wide. This amount of displacement, if translated to volume of salt dissolution, indicates that the salt would have to have been removed from the entire Rustler Formation as well as a good part of the upper Salado by localized ground water flow, mostly during the last pluvial episode of the Pleistocene. Estimates of the volume of ground water flow at the top of the evaporites could determine if this is a reasonable possibility. Clearly, some means of focusing or concentrating ground water movement in the San Simon area would be needed to account for salt removal at the top of the sequence in the time-frame available.

An alternative to a collapse origin for the swale by means of dissolution at the top of the evaporites, is to assume relatively recent tectonic movement along the swale margins and the development of a graben-like structure. This interpretation would be contrary to the conclusions of Haigler (1962) and other workers regarding the age of faulting in the basin but cannot be entirely ruled out at this stage of the investigation. This explanation would account for the existence of a nearly normal, regional amount of salt in the Rustler and upper Salado in the two boreholes within the swale (see Figure 18). Faulting of the evaporites beds has been reported by Griswold (1977) and the age of this faulting has yet to be determined.

Figure 18. Diagrammatic cross section of San Simon sink and swale.


SW
SWALE
NE
LAST HIGH LAKE LEVEL
SINK
GRAY DUNE
GRINDING PITS
CALICHE
TRIASSIC? SS. + SH.
DIATOMITE BED
1 MILE
1.62 Km
3300 FEET
3200
3100
3000
2900
2800
2700
2600
2500
60 METERS
MODERN POLLEN
RING FRACTURES
PLUVIAL STAGE POLLEN
CALICHE CLASTS
TOP TRIASSIC
EOLIAN SAND
TOP TRIASSIC?
CARBONIZED PLANT RESIDUE
TRIASSIC SPORES + POLLEN
VARIABLE 10°-30° DIPS
SNOWDEN, US. POTASH FED #1
J.H. TRIGG, FED SR #1-8

San Simon swale and sink can also be visualized as the latest and northernmost of the series of deep-seated dissolution depressions that have formed along the eastern margin of the basin. The zone of flexuring along the axis of the swale and the margin of the basin, as depicted in Figure 11 and on Hiss' (1975) map of the top of the Rustler Formation, would have provided permeability and access of reef water to the overlying salt beds. Water under artesian pressure would have contacted the salt and the salt removed by brine density flow. It is possible that some water under artesian pressure may have risen along faults and fractures to mix with surface waters in the swale. A diatom flora with saline affinities was reported by Bradbury (Appendix B) and this could possibly be due to brine mixing. J. Mercer (personal communication, 1978) performed a preliminary conductivity test on fluids flowing from the lower sands in the swale under weak artesian pressure and obtained during coring operations. He reported no measurable salinity. This artesian system, however, is probably related to sink configuration and not of deep-seated origin.

Of the three possibilities for the origin of San Simon swale, I favor deep-seated collapse related to removal of salt from the base of the evaporite sequence because this horizon has demonstrably been the source of collapse and active dissolution elsewhere along the reef edge. Also, the youthfulness of the depression is to be expected at that locality if it formed by the same process as other reef margin depressions. In addition, there are analogs of similar collapse structures in other evaporite basins.

The dissolution depression about 14 miles (23 km) northeast of Carlsbad (Figure 1) along the inner reef margin that contains about 700 feet of fill is another feature that may have originated from deep collapse. Piper (1973, p. 21) citing the pressure head in the Capitan aquifer, concluded that if the conduits above the aquifer in that area had sensible transmissivity then the amount of upward movement may have been sufficient to dissolve the evaporites. Cooley (in Brokaw and others, 1972, p. 62), referring to the area northeast of Carlsbad, cites evidence that such upward movement of waters has taken place.

To my knowledge, no cores of the evaporites overlying the reef margin in areas of collapse depression in the Delaware basin have been taken or are available. Closely analogous collapse structures in the Prarie evaporites of Saskatchewan, however, have been cored. The collapse depressions in the Prarie Formation also occur where a fringe reef is overlapped by evaporites (de Mille, and others, 1974). The reef in that area has influenced dissolution along a 200 mile (324 km) trend and it was concluded by de Mille and others (1974) that irregular compaction over the reef (fractures) aided the movement of waters which dissolved the overlying salt in the evaporites. The Saskatchewan area that was subjected to dissolution contains several large depressions analogous to the reef-margin depressions in the Delaware basin. These depressions have structural lows on overlying units of up to 600 feet (183 m). One of these structures was cored to the base of its collapse and brecciation was present in the evaporites above the reef

(Gorrel and Alderman, 1968, p. 311). The Canadian example indicates that the situation in the Delaware basin is not unique. The brine density flow mechanism can also probably be applied to the Canadian occurrence.

The breccia pipe under Dome C described by Vine (1960), and the cluster of related domes and collapse structures at the north end of Nash Draw that lie above the reef margin, can also be explained by the mechanism of brine density flow. The diagrammatic cross section (see Figure 12) shows that the domes and known pipe sit above the reef margin in the zone of flexure and fracturing suggested by Hiss (1975). The breccia pipes can best be visualized as the precursors or the incipient stage of development of larger collapse depressions and have probably developed above the most open fracture systems.

A circulation system related to brine density flow is probably the mechanism for the lateral and westward extension of dissolution at the Halite III and lower Salado horizons (eastern dissolution wedge). In this model, saturated brine moved down dip from the actively dissolving salt edge to be removed by the lower part of the reef aquifer. The dense brine was replaced by undersaturated waters moving through fractures above the brine-conducting horizon and under artesian pressure from the upper part of the reef aquifer. Originally, the undersaturated water may have gained access to the salt laterally along the permeable horizon. Subsequently, the breccia produced by collapse over dissolved salt layers would have provided additional permeability.

Origin of Deep-seated Dissolution in the Basin

General Considerations: The similarity in scale, geometry, and distribution of domes and collapse structures along the reef margin and in the basin suggests that these structures have a common origin. Also, each type of localized collapse feature, from the brecciated Castiles in the west, to collapsed outliers, to collapsed domes, to deep basin sinks in the east, has its own particular area or belt of expression in the basin, suggesting that these features represent different levels of exhumation as erosion has progressed from west to east across the basin. This explanation seems particularly appropriate when one notices the similar scale of the features and the clustered patterns of distribution. A unifying mechanism that can explain the deep-seated origin of the collapse associated with these features can be found in the removal of salt from localized areas near the base of the evaporites. The alternative is to assume that somehow surface waters have maintained circulation vertically through fractures in the evaporites and that the plastic properties of salt at depth were not sufficient to close the fractures. Another alternative is to transmit the dissolving waters down dip through fractures in the anhydrite beds over great distances. A final alternative is to assume that each of these collapse structures developed as a unique response as dissolution progressed to different levels in the evaporite. This alternative could be invoked to explain some of the collapse structures in the western part of the basin, but it cannot explain the deep-seated nature of the sinks in the central and eastern basin areas, the brecciated Castiles, or the known breccia pipe.

It seems most likely that the many evidences of localized collapse in the lower part of the evaporites can best be explained by the same mechanism and processes that produced deep collapse around the reef margin. This means that a different aquifer and different fracture systems were involved in bringing waters to and from the salt than for the reef margin.

For the basin area, the underlying aquifer is the upper part of the Delaware Mountain Group where the Delaware sand is the most permeable unit. The impermeable unit above the aquifer is the lower anhydrite (Anhydrite I) of the Castile Formation and the salt bed subject to initial dissolution is the lower halite (Halite I) of the Castile. The geometry and hydrology of this system was examined to determine if dissolution by means of brine density flow is an acceptable explanation.

Hydrologic Potential for Dissolution: The basin aquifer is tilted eastward at 100 feet per mile (19 m per km) and the potentiometric surface rises to slightly above the ground surface east of the Pecos River. The artesian pressure is more than adequate to raise water in fractures in the lower anhydrite, should they have suitable permeability. Evidence for permeability is found in the limestone buttes in the western part of the Gypsum Plain where biogenic limestone has replaced anhydrite along fractures in the lower anhydrite unit and where small-scale faulting of both the Delaware sand of the overlying anhydrite has occurred (Smith, 1978; see appendix C).

The salinity of the water within the aquifer shows that the natural recharge area is in the western part of the basin, and that the water in the aquifer picks up salt (increases salinity) as it moves eastward and down-dip through the aquifer (see Hiss, 1975, map 4). The salinity increases to a maximum where the aquifer lies adjacent to the reef. The potentiometric surface for the reef is lower than for the basin aquifer indicating that the brines are escaping into the reef aquifer. The salinity of the water in the basin aquifer is greater than for the water in the permeable units at greater depth in the basin, (McNeal, 1965, figures 8-13). This indicates that dissolved brine from the overlying evaporites is entering the upper Delaware units and increasing salinity beyond that of the other waters in the basin.

The hydrologic information compiled by Hiss (1975) can be used to estimate the volume of water and salt moving through the basin aquifer. Using the equation

$$a = \frac{Q}{A} = \frac{Kdh}{dI} \quad [LT^{-1}]$$

from Lohman (1972, p. 10), and the permeability of 0.0049 m/day (Hiss, 1975, p. 154) and a final salinity in the aquifer before discharge into the Capitan aquifer of 150g/l (Hiss, 1975, map 4), the upper 100 feet (30.5m) of the basin aquifer has the potential to transport NaCl at a rate of $14 g/m^2$/day. This rate is sufficient to carry away the salt dissolved by brine density flow from 100 collapse chambers (50 x 100 x 100 m) in the southern three townships of the Delaware basin in New Mexico in a period of 30,000 years. If a thicker aquifer is used the dissolving potential is much greater. Hence, it would appear that the limiting factor to brine density flow is not the capacity of the aquifer to remove the brine but the fracture systems in the lower anhydrite.

Deep Basin Sinks and Salt Anticlines: A number of isolated deep-seated sinks in the central and eastern basin area can be explained by dissolution from below, through sets of intersecting fracture systems. This is particularly true for the southeasterly trending trough in the 124 bed (Figure 11) where several deep-seated sinks appear to be aligned along an inferred fracture system parallel to the reef edge and where faults beneath the evaporites may have made recurrent movement during Cenozoic uplift and tilting.

Several sinks in the basin, however, lie next to salt anticlines and the relationship of the sinks to the anticlines or the anticlines to the sinks is difficult to determine. It seems likely that dissolution and sink development may have preceeded anticline development. The overburden above the lower salt bed, which is generally the salt bed that has produced flowage, is inadequate to account for the temperature and pressures required to cause salt flowage under ordinary geological conditions of differential vertical stress (Anderson and Powers, 1978). The dissolution of a collapse chamber and subsequent collapse of the overlying units can be expected to increase differential stress in a relatively short time period. This stress differential may have been adequate to cause the movement of salt, in which case, the structure of the salt anticlines at depth may be quite complicated as salt may have tended to move into collapsed areas. This may account for the few structures where Halite II was observed to thicken above thin areas of Halite I (Figures 4 and 5).

The salt anticlines around the deformed basin margin are also associated with deep-seated sinks. Either sink development and subsequent anticline formation was greater near the basin margin or sagging of the basin during tilting and uplift created greater differential stress in this area. In either case sink development and salt movement are closely related and this problem deserves further consideration.

Domes and Collapse Structures: The doming over collapsed and brecciated pipes is clearly a superficial process related to the removal of salt from around collapsed structures. The pipes are more resistant to the effects of near surface dissolution on a regional scale. The sheathing of the breccias in the pipes by clay, as observed in the Mississippi Chemical Company mine under Dome C (Figure 12), may have protected the brecciated core so that it remained as a spine over which caliche was draped during the general lowering of the surface by dissolution. Evidence for this is found in Sec. 18, T 23 S, R 30 E where circular ring fractures have lowered successively lower sections of caliche around a resistant central plug.

The doming over collapsed brecciated structures implies that the pipe beneath the dome extends below the general surface of dissolution in the upper Salado, which in all but the most active areas of dissolution near the Pecos River is 500 feet (152 m) or more beneath the surface. Some collapse structures that have involved the Gatuna Formation (Sec. 24, T 23 S, R 29 E) have not developed doming over the collapse indicating that structures of both deep and shallow origin are present.

Reddy (1961) recognized three different types of domes in the Queen Lake area; simple uncollapsed domes, collapsed structures with circular faults and brecciated centers, and domes with pushed up centers of lower stratigraphic units. Some of the domes in the Queen Lake and Willow Lake area appear to have been formed as high areas remaining after the collapse of surrounding sinks. In any case, many of the smaller domal features in the basin, especially in areas of most recent and active dissolution associated with the main drainage systems, may not have brecciated cores.

<u>Sequence of Collapse Development</u>: The different localized collapse features in the basin occur in north-south trending belts across the basin that correspond to different depths of erosion. It seems apparent that these are different manifestations of the same general process being seen at

different levels of exhumation. Although individual structures may depart from the general pattern, it is possible to diagrammatically reconstruct a composit collapse structure (Figure 18) based on known structures in the basin, and describe a sequence of events to explain how such structures are formed.

After uplifting and tilting of the basin and erosion to expose the western reef, meteoric waters began moving slowly down dip through the basin aquifer. At the same time, hydrocarbons (mainly gas, Kirkland and Evans, 1976) migrated up dip. Both the meteoric waters and the hydrocarbons moved upwards into fractures in the lower anhydrite and, infused with a bacterial culture, replaced the anhydrite in the walls of the fractures with biogenic calcite. There is a 10 percent volume reduction in the replacement process so that the biogenic activity increased the permeability of the fractures. In the more open systems of intersecting fracture sets, the undersaturated waters came in contact with the salt and developed a circulation system of brine density flow. Continued dissolution enlarged a chamber in the lower salt which subsequently collapsed to form a breccia chimney, sometimes penetrating to the surface. Meteoric waters, hydrocarbons, and bacterial populations moved upward in the collapsed chimney to replace brecciated anhydrite at higher stratigraphic levels. Some of the evolving H_2S gas from the biogenic activity became trapped and reduced to form sulfur deposits that are associated with collapse from below (Hinds and Cunningham, 1970, p. 11).

Probably not all of the collapsed chimneys penetrated to the surface, especially in the deeper eastern part of the basin. Those that did in the

Figure 19. Diagrammatic illustration of a composit collapse structure originating from dissolution above Bell Canyon (Delaware) aquifer. Note: not all structures will show the combination of all features.

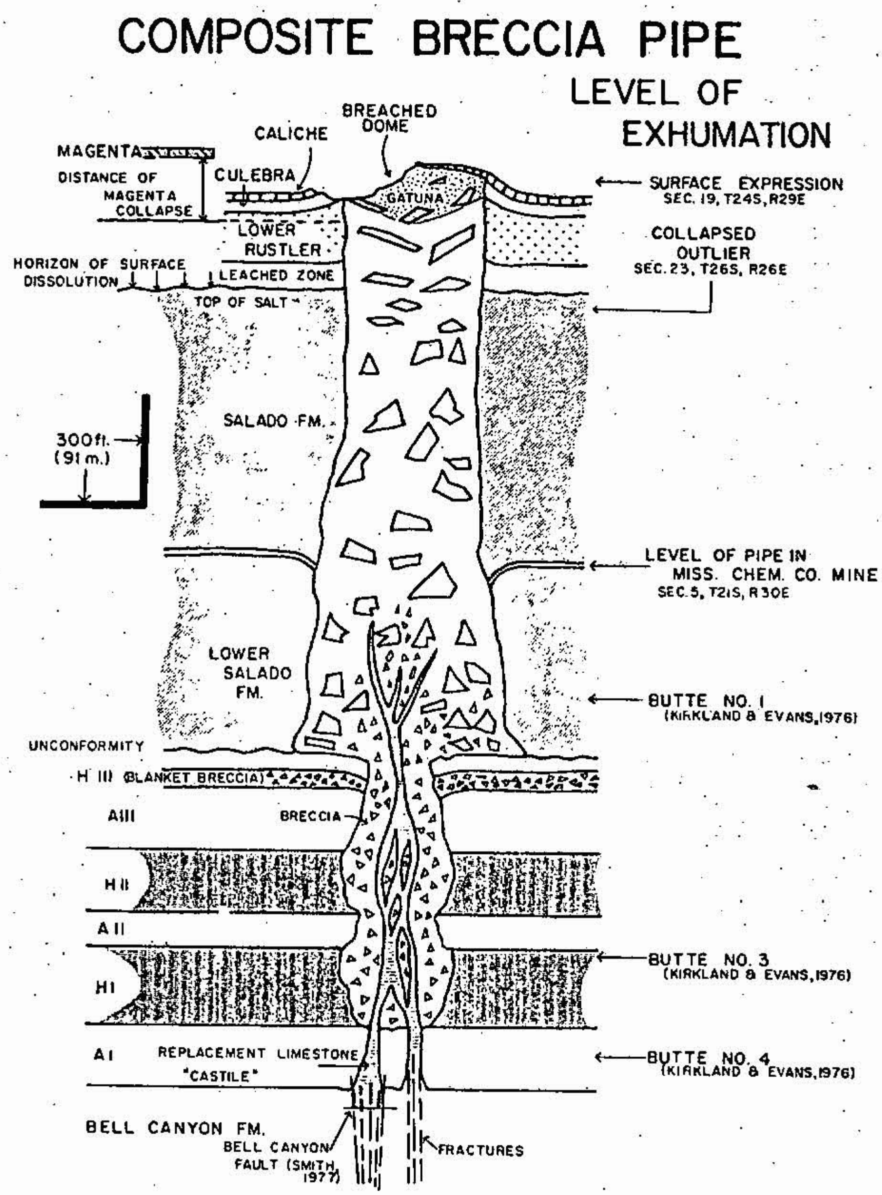

COMPOSITE BRECCIA PIPE
LEVEL OF EXHUMATION
BREACHED DOME
CALICHE
MAGENTA
DISTANCE OF MAGENTA COLLAPSE
CULEBRA
GATUNA
SURFACE EXPRESSION
SEC. 19, T24S, R29E
LOWER RUSTLER
COLLAPSED OUTLIER
SEC. 23, T26S, R26E
HORIZON OF SURFACE DISSOLUTION
LEACHED ZONE
TOP OF SALT
SALADO FM.
300ft. (91 m.)
LEVEL OF PIPE IN MISS. CHEM. CO. MINE
SEC. 5, T21S, R30E
LOWER SALADO FM.
BUTTE NO. 1
(KIRKLAND & EVANS, 1976)
UNCONFORMITY
H III (BLANKET BRECCIA)
A III
BRECCIA
H II
A II
H I
BUTTE NO. 3
(KIRKLAND & EVANS, 1976)
A I
REPLACEMENT LIMESTONE
"CASTILE"
BUTTE NO. 4
(KIRKLAND & EVANS, 1976)
BELL CANYON FM.
BELL CANYON FAULT (SMITH, 1977)
FRACTURES

FIG. 18

west were filled with downdropped blocks of Rustler and Gatuna and a thick calcic soil (Mescalero caliche) developed over the filled collapse structures. Finally, regional near-surface dissolution removed salt from around the pipes and sagging around the pipes produced domes.

The process described above cannot be assumed to have affected the entire basin simultaneously. Brine density flow can be expected to be most efficient where salinity differences between the underlying aquifer and the overlying saturated brine are greatest. This means that the area of optimum development of collapse structures is probably slowly moving from west to east across the basin.

Origin of the Western Dissolution Wedge

The geometry of the western wedge and its location in the basin provide some clues as to the controls that were operating to produce the feature. The wedge occurs along almost the entire western margin of the basin, indicating that it is not a local feature and that it is in some way related to the general stripping, erosion, and dissolution that followed uplift. The fact that the leading edge of the wedge is developed in the lower Salado Formation and the upper part of Halite III indicates that this was the horizon of greatest permeability and that it was more susceptible to dissolution. (This same horizon along the eastern side of the basin is also the most susceptible to dissolution). As the western reef was exposed and the reef became an aquifer, a dissolution wedge probably developed at the susceptible horizon. This would hardly explain, however, the presence of the wedge some 70 miles (113 km) from the western margin of the basin.

As the surface of the evaporites in the west was lowered by erosion, the permeable and susceptible horizon became directly exposed to surface infiltration. The extensive development of gravels along the western edge of the basin testifies to abundant surface water in contact with the exposed evaporites. The discharge from these eastward flowing streams may have been the vehicle for the further dissolution of the wedge. In this case, the water moving through the wedge would have flowed parallel to the axis of the wedge and approximately parallel to the present axis of most of the Pecos River. The Pecos valley sits above or behind the leading edge of the wedge in much of the basin suggesting that deep dissolution in the wedge has controlled the position of the Pecos during its later history. The ancestral Pecos probably migrated eastward across the basin, occupying a valley behind the leading edge of the wedge.

The margin of the wedge turns westward to the north of the Big Sinks and Poker Lake dissolution depressions and terminates adjacent to the large reentrant in the Capitan reef southwest of Carlsbad. This reentrant also marks the northern limit of extensive development of gravels from eastward flowing streams. The loss of relief to the north and the reentrant appear to have combined to delay dissolution in the area to the north of the present position of the wedge.

The leading edge of the western wedge at the present time is directly associated with the large dissolution depressions described by Malley and Huffington (1953) in the central basin area (see Figure 1). The deepest parts of these depressions contain collapse structures that penetrate to the lower basin aquifer. It is conceivable that salt dissolved in the wedge found access to the lower aquifer through the collapse structures and that this was the path of escape of the brine from the basin. One can estimate the volume of salt that might have escaped by this route from the capacity of the aquifer to conduct water. With a head of 100 ft per mile (19 m per km) and a permeability of 0.0049 m per day, using the Bell Canyon aquifer to transmit the brine, only about 20-30 percent of the salt in Halite III and the lower Salado that is now missing from the basin could have been removed through the lower aquifer since the uplift of the basin. Hence, the brine derived from these units must have found a way out of the basin by some other means, at least during the early stages of dissolution of the wedge in the basin.

Later in the history of the basin, however, some of the waters from the Pecos may have found their way through to the lower aquifer by moving down gradient into the collapse depressions and enlarging them to their present size. Collapse features of the scale of the Big Sinks or Poker Lake dissolution depressions have the potential of having substantial amounts of brine drained from them through the lower aquifer. A collapse depression with an area of about 10 mi^2 (26 km^2) and with a 100 foot (30.5 m) thick aquifer collecting the brine from over a distance of 4 miles (6.5 km) can have its brine removed in about 40,000 years.

This explanation seems particularly appropriate to the dissolution depression around Poker Lake anticline. The floor of the collapse at the level of the Rustler Formation is some 1000 feet (305 m) below the level of the Rustler at the Pecos River which lies about 6 miles (10 km) to the west. The dissolution depression at Poker Lake is much larger than the small sink adjacent to the anticline, which in turn appears to consist of several collapse structures. Surface waters, including some from the

Pecos, might have enlarged the original depression by contacting the salt and by having the brine removed through the lower aquifer.

The development of the western dissolution wedge has been a complex process, most easily visualized if divided into three stages. The first stage was initial wedge development adjacent to the reef. The second stage was the undercutting of the overlying salt beds by waters moving through the permeable horizon from surface streams flowing eastward from the Guadalupe Mountains. The third stage is related to the enlargement of dissolution depressions east of the axis of the Pecos River. Examples of the first stage of development of the wedge can still be seen operating around the eastern and northern margins of the basin. Remnants of the second stage can still be seen but it was probably most active during the early dissolution of the western part of the basin. The third stage is active today. All three stages, although representing somewhat different processes, have the development of a wedge-like dissolution front in common. This can best be explained by the potential for greater dissolution at the Castile-Salado permeable horizon and unconformity.

Rate of Cenozoic Dissolution

Determining the rate of both surface and deep dissolution in the basins depends largely on the time and rate of uplift of the Delaware and Guadalupe mountains to the west. It is generally agreed by most workers that the major uplift took place beginning in late Pliocene or early Pleistocene time (King, 1948). Low fault scarps have displaced gravels in the western foothill areas of the mountains indicating some movement in late Pleistocene time. Leveling surveys across the graben to the west of the mountains indicate that this area is tectonically active at the present time. How fast the salt was dissolved depended upon the pace of the uplift.

One can roughly say that the main episode of Cenozoic dissolution was accomplished in the past 4-6 m.y., or after the removal of the Ogallala Formation. A younger limit for some of the dissolution has been set by Bachman (1974) by correlating the Mescalero caliche surface with surfaces of similar development in other areas. If Bachman's correlation is correct, then most of the dissolution in the basin had been accomplished by about 1/2 m.y. ago. This period of Mescalero stabilization was followed by renewed dissolution which is active at the present time.

Extrapolations of the rate of dissolution from such meager information are of limited value because they do not take into account the rate of change over time. In geomorphic terms, the dissolution stage of the Delaware basin, with 50 percent of the salt removed, can be considered mature and the basin probably has a maximum development of dissolution features. We do not know how much faster salt dissolves during the initial, intermediate, or later stages of dissolution of a basin. If we assume 4 m.y. for the initiation of the western dissolucation wedge, then it has progressed eastward across the basin at a rate of about 20 miles per m.y. If we assume 8 m.y. as the starting point and a lesser distance of travel across the basin then the rate may be as little as 5 miles per m.y. Neither of these two figures is significant because the wedge probably developed in stages from different controls with different rates.

The central-basin dissolution depressions and the eastern and northern reef-margin dissolution depressions contain Conozoic fill which would be considered post uplift (Ogallala) and hence Pleistocene in age. The reef-related depressions, as well as the basin depressions along the Pecos River, probably did not develop simultaneously but followed a progression. One could expect the southermost depressions to develop first because they would be up the salinity gradient and erosion has progressed from southwest to northeast across the basin. This would agree with the observation that the relatively young, still-active San Simon sink represents the most recent stage in this process. Similarly, the reef margin dissolution depression northeast of Carlsbad could be expected to be older than San Simon sink and swale. This means that other dissolution depressions and an associated wedge will ultimately develop along the northeastern corner of the basin. San Simon swale and sink are young geologically and probably developed under the influence of pluvial climate. We can expect enlargement of the sink and swale and perhaps the development of additional similar features around the northern basin margin during subsequent pluvial episodes.

The effect of pluvial climate on the rate of dissolution is unknown but can be assumed to be significant. Extrapolations of the rate of dissolution under Nash Draw by assuming a constant rate of dissolution since the development of the Mescalero surface are of limited value because most of the salt may have been dissolved during pluvial stages and significant collapse of Nash Draw could be as late as the Wisconsin.

Age of Localized Dissolution in the Basin

The domes and collapse structures in the west-central part of the basin have Gatuna cores and Mescalero caliche draped over the top. This means that the collapse structures developed before 1/2 m.y. ago and the doming since that time, if the correlation of the Mescalero caliche in that area is correct. The model of brine density flow predicts that the development of collapse structures in the salt overlying the aquifer will be a function of the salinity gradient between brine in the dissolution chamber and the water in the underlying aquifer (assuming equal fracture development). The salinity maps of Hiss (1975) and McNeal (1965) show that essentially fresh water is contained in the aquifer in the part of the basin west of the salt cover and that the salinity gradient gradually increases eastward to the margin of the basin. This means that as the basin is eroded, the most effective salinity gradients will gradually migrate eastward. As the gradient moves, weaker fracture systems can be expected to be activated. Application of the brine density flow model to the Delaware basin means that the development of collapse structures is an ongoing and developing process.

Climatic changes during the pluvial episodes can be expected to have increased the artesian pressure in the aquifer and shifted the salinity gradient eastward in the basin. This means that the development of collapse structures in a particular area may be an episodic, climatically controlled process. The above considerations mean that no one age can be assigned to the collapse structures that have already formed in the basin. Certain times may have been more favorable to the development of the structures than others, and the structures to the west, in general, are older than the structures to the east. Bell Lake sink and Slick sink are relatively young features that may represent the most recent episode of deep-seated collapse in the eastern part of the basin.

POTENTIAL GEOLOGIC HAZARDS FROM DEEP-SEATED DISSOLUTION

(Implications for the W.I.P.P. Site)

Long-term Hazards:

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

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

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

The future course of dissolution in the northern corner of the basin can be predicted from the past history of dissolution elsewhere in the basin. More reef-margin depressions will probably develop and enlarge as water from the Pecos continues to enter the Capitan aquifer and move toward the northeast low area of the basin. Hiss (1975) believes that the basaltic dike that intersects the reef near the Eddy-Lea County line has retarded the flow of water through the reef to the west of the dike. This may have slowed the development of dissolution depressions in the northern reef area. Several potential sites for the development of future dissolution depressions are present along the northern reef edge. The cluster of domes at the north end of Nash Draw is one locality. A thin area of Infracowden salt was noted in Sec. 25, T 21 S, R 32 E that could represent dissolution (Figure 7). Both of these features are about 11 miles (18 km) from the edge of the site. (A low in the structure contour of the Rustler Formation in the northeast corner of T 21 S, R 32 E on the map of Hiss (1976, map 7) is actually a plotting error and not a dissolution feature (Hiss, 1977, personal communication).

The long term hazard to the site would be presented by an advancing dissolution wedge associated with reef-margin depressions. The irregular nature of the margin of the eastern dissolution wedge suggests that deep-seated sinks in the deformed margin area of the basin have influenced the extent and development of the wedge (see map 7 of Hiss, 1976). This means that the sinks to the north and east of the site area may ultimately play a role in bringing dissolution into the area. Three sinks appear to be present within about a 5 mile (8 km) radius of the center of the site (Figure 16). The sink to the northwest originates in Halite I. The deep-seated sink to the east, however, shows no involvement of the lower salt beds (Figure 4), a near absence of Infracowden salt (Figure 7), and a substantial depression in the structure contour of the 124 marker bed (Figure 11). In this case, localized dissolution appears to have developed at the Infracowden horizon and either at present, or sometime in the future, could be associated with reef-margin dissolution. The lack of involvement of deeper beds, however, may be due to inadequate information. The suspected sink on the northern edge of the site area has a depressed structure contour on the 124 marker bed. Seismic profiles show it to be of deep-seated origin and associated with faulting of the Bell Canyon Fm.

The eastern dissolution wedge projects, at places, about 15 miles (24 km) beyond the reef margin and into the basin. Ultimately, as reef-associated dissolution moves into the northern corner of the basin, it can be expected that wedge-like dissolution effects will enter the site area, probably at the Lower Salado horizon. This advancing wedge could represent a long-term hazard to the site if dissolution has already progressed to the sink localities north and east of the site area or if the rate of advance can be demonstrated to be relatively rapid.

A possible long-term hazard may be advancing dissolution related to the western dissolution wedge. The formation and enlargement of deep dissolution depressions east of the Pecos River is the most recent stage in the development of the western wedge. Whether or not this process represents a long-term hazard depends upon an interpretation of the origin of Nash Draw. The alignment of the dissolution depressions along the western salt edge, and the occurrence of Nash Draw as a northern continuation of this trend, implies that Nash Draw is an early stage in the development of a large dissolution depression (Figure 1). Its location to the north of the other depressions, the scale of the feature, and the lobate pattern formed by its margins suggest a genetic relationship. The top of the Rustler Formation is also depressed in the southern Nash Draw area, which is a feature common to the other depressions to the south.

On the other hand, Nash Draw is an area of active near-surface dissolution and its recent subsidence appears to be related to the removal of salt at the top of the Salado Formation rather than from the base. No deep-seated collapse features such as the Poker Lake or Big Sinks depressions appear to be associated with Nash Draw, although, a number of suspected breccia pipes are present in the area of depression.

An examination of the isopach maps and logs of the Salado Formation in the Poker Lake and Big Sinks area (Figures 8, 9, 10), shows that above the wedge in the lower Salado, both the middle and upper Salado have lost about half of their original thickness. This means that development of the wedge and depression was not a simple process of undercutting the overlying evaporites. Rather, dissolution appears to have developed throughout the overlying salt section in the area of the depression.

Dissolution of salt beds, as determined by the comparison of acoustical logs, is a very selective process. Township-size areas have had salt removed at selected horizons throughout the salt section that lies adjacent to areas of deepest dissolution. Apparently, dissolution effects are capable of moving laterally, bed by bed, for distances of several miles (kilometers) from the point of origin of dissolving waters.

The lack of well-log or core control in the part of Nash Draw with the greatest depression does not permit an examination of the effect of selective dissolution beneath Nash Draw. At this point in the investigation, the origin of Nash Draw and the reasons why it has developed its distinctive lobate form and well-defined collapsed margins is not understood. The greatest hazard related to dissolution from the west or southwest may be in the lack of information about the deeper geologic features west of the site. Some of this information for the shallower stratigraphic horizons may exist in the records of potash exploration.

Short-term Hazards:

The common occurrence of localized features of deep dissolution and collapse (breccia pipes, isolated deep sinks, and anticlinal sinks) in the basin presents an unavoidable risk that will have to be weighed and evaluated. In the general site area, there is some evidence that deep-seated dissolution, faulting of evaporites, and anticline development has taken place. Structurally this can be seen as a low in the 124 marker bed contour in the southeast corner of Sec. 9, T 22 S, R 31 E and about 2 miles (3 km) north of ERDA #9 borehole (Griswold, 1977, figure 7). This is the depression that aligns with several deep-seated depressions to the southeast as well as a suspected dissolution feature to the northwest and is associated with a fault in the basin. Anticlinal structures have developed both to the north and south of this sink, along with faults within the Castile Formation that could be associated with the anticlinal structure (Griswold, 1977, figures 8 and 9). Hence, the depression is of the anticline-associated type. The presence of such a structure and the associated sink could present a short-term geologic hazard to the disposal facility for two reasons: (1) Geopressurized brine and H_2S gas may be present in or near the structure and eruption into the mine workings would be an immediate threat to personnel and might bring radionuclides to the surface; (2) brecciated rock may be present in the depression or in other sinks associated with the anticline and, combined with faults and fractures and possible dissolution horizons associated with the anticline, could form a conduit for transmission of brines from the area.

The evidence suggests that dissolution of deep-seated collapse chambers by means of brine density flow has been an active process in the basin. The brine density flow model infers that the development of such chambers will affect different areas of the basin at different times and that it is an on-going process subject to rejuvination during periods of higher artesian pressure, especially during pluvial climatic episodes.

In this respect, there is probably no way of being absolutely certain that fractures or incipient collapse chambers are not present at depth in the site area or that collapse chimneys are present but have not breached the surface. Detection of such small features by geophysical methods is not possible in the present state of the art although larger structures, especially those that have involved collapse to the surface, can be identified. The potential for the formation of such collapse structures in the site area constitutes an unavoidable geologic hazard that is inherent for any site selected in the basin. Studies of the statistical probability of occurrence based on known distributions and on a better understanding of the collapse process will provide estimates of the seriousness of the hazard.

REFERENCES CITED

Adams, J. E., 1944, Upper Permian Ochoa Series of Delaware Basin, west Texas and southeastern New Mexico: Am. Assoc. Petroleum Geologists Bull., v. 28, no. 11, p. 1596-1625.

Adams, J. E., and Frenzel, H. N., 1950, Capitan barrier reef, Texas and New Mexico: Jour. Geology, v. 58, no. 4, p. 289-312.

Anderson, R. Y., Dean, W. E., Jr., Kirkland, D. W., and Snider, H. I., 1972, Permian Castile varved evaporite sequence, west Texas and New Mexico: Geol. Soc. America Bull., v. 83, no. 1, p. 59-86.

Anderson, R. Y., Kietzke, K. K., and Rhodes, D. J., 1978, Development of dissolution breccias, northern Delaware basin, New Mexico and Texas: New Mexico Bur. Mines and Mineral Resources, Circular 159.

Anderson, R. Y., and Powers, D. W., 1978, Salt anticlines in the Castile-Salado evaporite sequence, northern Delaware basin, New Mexico: New Mexico Bur. Mines and Mineral Resources, Circular, 159.

Bachhuber, F. W., 1971, Paleolimnology of Lake Estancia and the Quaternary history of the Estancia valley, central New Mexico: Univ. New Mexico Ph.D. Dissertation, 238 p.

Bachman, G. O., 1974, Geologic processes and Cenozoic history related to salt dissolution in southeastern New Mexico: U.S. Geol. Survey open-file report 74-194, 31 p.

Bachman, G. O., and Johnson, R. B., 1973, Stability of salt in Permian salt basin of Kansas, Oklahoma, Texas, and New Mexico, with a section on dissolved salts in surface water, by F. A. Swenson: U.S. Geol. Survey open-file report (USGS-4339-4), 62 p.

Baltz, E. H., 1959, Diagram showing relations of Permian rocks in part of Eddy County, New Mexico: U.S. Geol. Survey, map TEM 1035.

Brokaw, A. L., Jones, C. L., Cooley, M. E., and Hays, W. H., 1972, Geology and hydrology of the Carlsbad potash area, Eddy and Lea Counties, New Mexico: U.S. Geol. Survey open-file report (USGS-4339-1), 86 p.

De Mille, G., Shouldice, J. R., and Nelson, H. W., 1964, Collapse structures related to evaporites of the Prarie Formation, Saskatchewan: Geol. Soc. America Bull., v. 75, p. 307-316.

Dunay, R. E., and Traverse, A., 1971, Preliminary report on Triassic spores and pollen of the Dockum Group, Texas Panhandle: Geoscience and Man, v. III, p. 65-68.

Gorrell, H. A., and Alderman, G. R., 1968, Eil Point Group saline basins of Alberta, Saskatchewan, and Manitoba, Canada: in Mattox, R. B. ed., Saline Deposits, Geol. Soc. America Special Paper 88, p. 291-317.

Griswold, G. B., 1977, Site selection and evaluation, Los Medanos, New Mexico: Sandia Laboratories Memorandum, 6 p.

Haigler, Leon, 1962, Geologic notes on the Delaware basin: New Mexico Bur. Mines and Mineral Resources Circular 63, 14 p.

Hills, J. M., 1968, Permian basin field area, west Texas and southeastern New Mexico, in Mattox, R. B., ed., Saline Deposits, Geol. Soc. America Special Paper 88, p. 17-27.

Hinds, J. S., and Cunningham, R. R., 1970, Elemental sulfur in Eddy County, New Mexico: U.S. Geol. Survey Circular 628, 13 p.

Hiss, W. L., 1975, Stratigraphy and ground-water hydrology of the Capitan aquifer, southeastern New Mexico and western Texas: Unpub. Ph.D. Dissertation, University of Colorado, 396 p.

Hiss, W. L., 1976, Structure of the Permian Ochoan Rustler Formation, southeast New Mexico and west Texas: New Mexico Bur. Mines and Mineral Resources, Resource map 7.

Jones, C. L., 1954, The occurrence and distribution of potassium minerals in southeastern New Mexico, in Stiff, T. F., ed., southeastern New Mexico: New Mexico Geol. Soc. Guidebook, 5th Field Conf., p. 107-112.

______________, 1973, Salt deposits of Los Medanos area, Eddy and Lea Counties, New Mexico, with sections on Ground water hydrology, by M. E. Cooley, and Surficial geology, by G. O. Bachman: U.S. Geol. Survey open-file report (4339-7), 67 p.

______________, undated, Structure contour map of northern Delaware basin showing distribution of salt structures, Castile brine and possible repository sites: U.S. Geol. Survey (preliminary data).

Kelley, V. C., 1971, Geology of the Pecos Country, southeastern New Mexico: New Mexico Bur. Mines and Mineral Resources Mem. 24, 75 p.

King, P. B., 1942, Permian of West Texas and southeastern New Mexico, Part 2, of DeFord, R. K., and Lloyd, E. R., eds., West Texas-New Mexico--a symposium: Am. Assoc. Petroleum Geologists Bull., v. 26, no. 4, p. 535-763.

______________, 1948, Geology of the southern Guadalupe Mountains, Texas: U.S. Geol. Survey Prof. Paper 215, 183 p. (1949)

Kirkland D. W., and Evans, R. E., 1976, Origin of limestone buttes, Gypsum Plain, Culberson County, Texas: Am. Assoc. Petroleum Geologists Bull., v. 60, no. 2, p. 2005-2018.

Kroenlein, G. A., 1939, Salt, potash, and anhydrite in Castile Formation of southeast New Mexico: Am. Assoc. Petroleum Geologists Bull., v. 23, no. 11, p. 1682-1693.

Lang, W. B., 1942, Basal beds of Salado Formation in Fletcher potash core test, near Carlsbad, New Mexico: Am. Assoc. Petroleum Geologists Bull., v. 26, no. 1, p. 63-79.

____________, 1947, Occurrence of Comanche rocks in Black River valley, New Mexico: Am. Assoc. Petroleum Geologists Bull., v. 31, no. 8, p. 1472-1478.

Lohman, S. W., 1972, Ground-water hydraulics: U.S. Geol. Survey Prof. Paper 708, 70 p.

Malley, V. C., and Huffington, R. M., 1953, Cenozoic fill and evaporite solution in Delaware basin, Texas and New Mexico: Geol. Soc. America Bull., v. 64, no. 5, p. 539-546.

McKee, E. D., and others, 1959, Paleotectonic maps of the Triassic System: U.S. Geol. Survey Misc. Geol. Inv. Map I-300, 33 p. (1960)

McNeal, R. P., 1965, Hydrodynamics of the Permian basin, <u>in</u> Young, Addison, and Galley, J. E., eds., Fluids in subsurface environments: Am. Assoc. Petroleum Geologists Mem. 4, p. 308-326.

Olive, W. W., 1957, Solution-subsidence troughs, Castile Formation of Gypsum Plain, Texas and New Mexico: Geol. Soc. America Bull., v. 68, no. 3, p. 351-358.

Pierce, W. G., and Rich, E. I., 1962, Summary of rock salt deposits in the United States as possible storage sites for radioactive waste materials: U.S. Geol. Survey Bull. 1148, 91 p.

Piper, A. M., 1973, Suberosion in and about the four-township study area near Carlsbad, New Mexico: ORNL subcontract 3745 report, 28 p.

Reddy, G. R., 1961, Geology of the Queen Lake domes, Eddy County, New Mexico: Unpub. M.S. Thesis, University New Mexico, 84 p.

Smith, A. R., 1978, Sulfur deposits in Ochoan rocks of southeast New Mexico and west Texas: New Mexico Bur. Mines and Mineral Resources Circular 159.

Vertrees, C. D., chm., 1964, Cross section through Delaware and Val Verde basins from Lea County, New Mexico to Edwards County, Texas: West Texas Geol. Soc. Pub. 64-49, 1 sheet.

Vine, J. D., 1963, Surface geology of the Nash Draw quadrangle, Eddy County, New Mexico: U.S. Geol. Survey Bull. 1141-B, p. B1-B46.

______________, 1960, Recent domal structures in southeastern New Mexico: Am. Assoc. Petroleum Geologists Bull., v. 44, p. 1903-1911.

______________, 1976, Breccia pipes and burial metamorphism in Permian evaporites of the Delaware basin, New Mexico (abs.): Geol. Soc. America v. 8, no. 6, p. 1154.

APPENDICES

Appendix A. Deep dissolution in the Delaware basin by means of brine density flow.

Appendix B. Report on referred fossils from San Simon sink. J. P. Bradbury.

Appendix C. Figures related to Bell Canyon fault and replacement limestone. (from Smith, 1978).

Appendix D. Geologic sketch maps of collapse structures and domes.

APPENDIX A

DEEP DISSOLUTION IN THE DELAWARE BASIN
BY MEANS OF BRINE DENSITY FLOW

Roger Y. Anderson
October, 1977

Deep Dissolution in the Delaware Basin by Means of Brine Density Flow

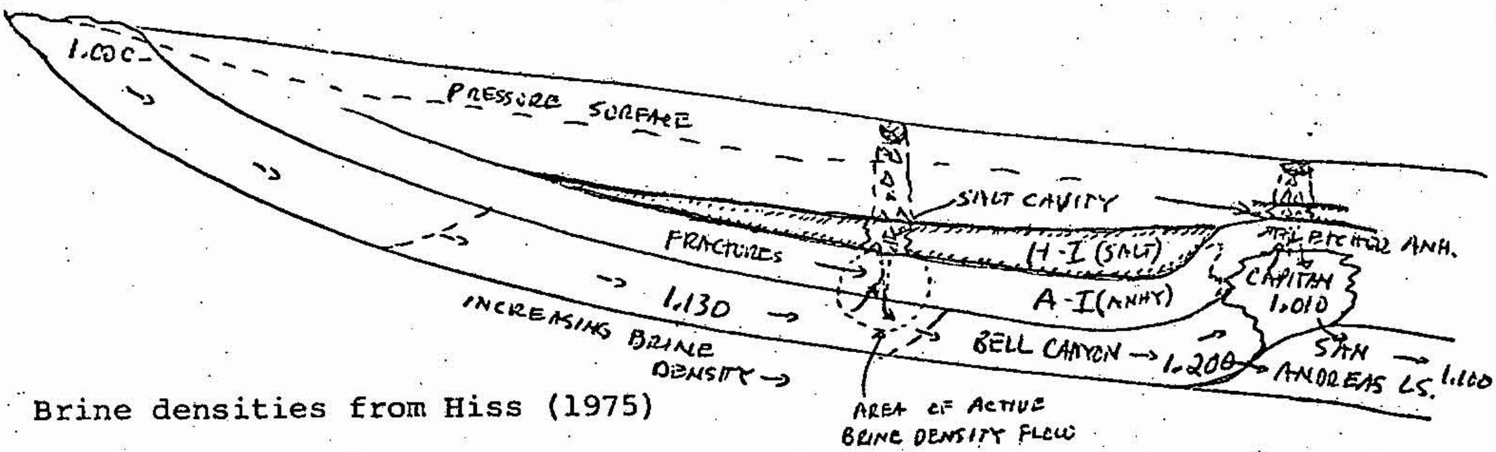
Brine Density Flow:

This concept was suggested by D. W. Kirkland and is related to the mechanism suggested by Kirkland and Evans (1976) for the origin of limestone buttes (Castiles) in the Delaware basin.

The assumption is that undersaturated water from the underlying aquifers (Bell Canyon, Capitan) can gain access to the overlying salt (Halite I, lower Salado) by means of fractures or intersecting fracture systems in the intervening anhydrite (Anhydrite I, Fletcher anhydrite). The contact of the undersaturated water with the salt will increase water density and the brine thus generated will move back down through the fracture system by gravity flow and this downward flow of brine will draw up more undersaturated waters to initiate a flow cycle which will dissolve chambers in the salt bed. Collapse of such chambers will result in a breccia pipe or other collapse structure. The concept is described diagrammatically in Appendix Figure 1.

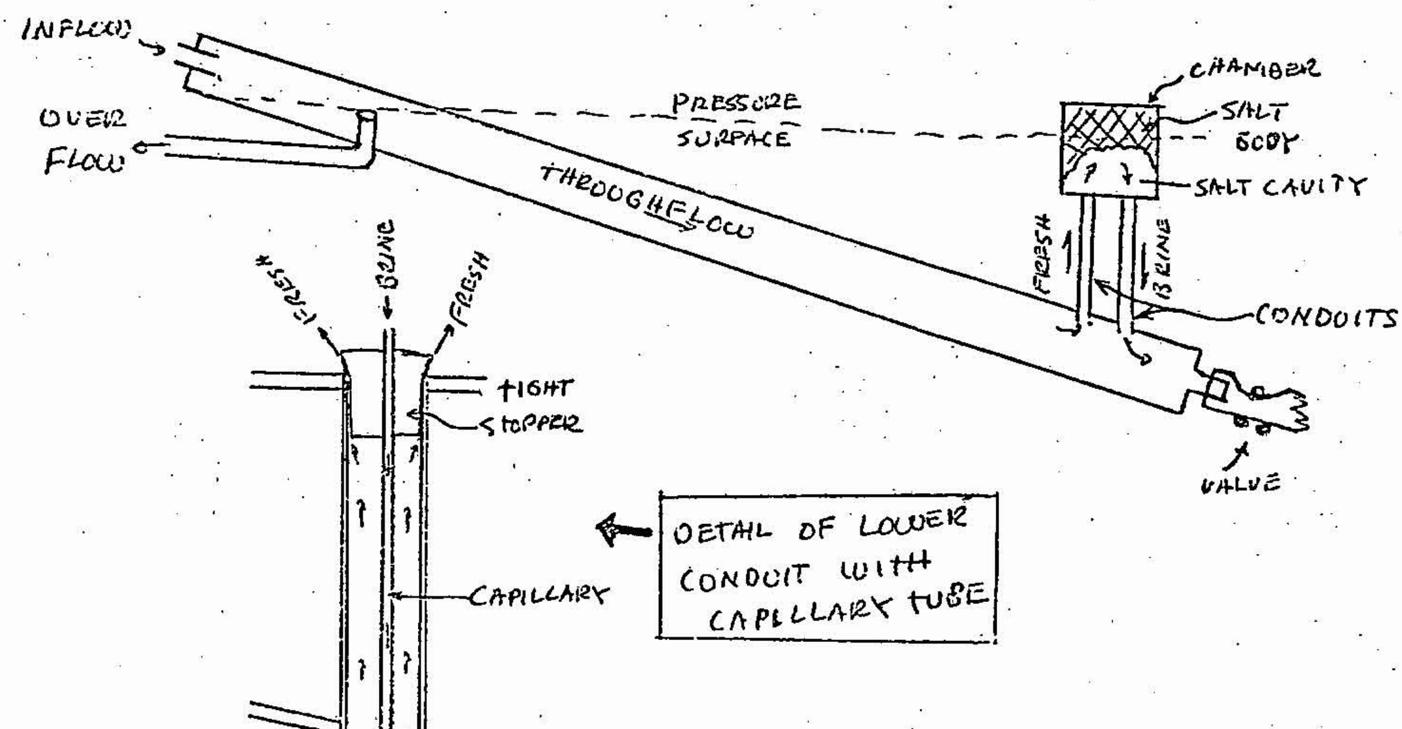
Experimental Model:

An apparatus was built to approximately simulate the hydrologic system described above. It consists of a five foot length of 1 1/2 inch inside diameter pipe mounted at a 25^{o} angle and with the lower end attached to a drain by tubing with a regulating valve (Appendix Figure 2). A constant water level in the pipe (aquifer) is maintained by tubing carrying inflow and overflow to and from the upper part of the pipe. A chamber containing a salt block or salt crystals is affixed to the pipe by means of two 1/2 inch inside diameter tubes of lexan polycarbonate tubing. The polycarbonate tubing is open to both the pipe and the chamber and these openings can be sealed or equipped with stoppers and capillaries to change the diameter of the conduits communicating between the pipe (aquifer) and the chamber (salt body). A constant rate of flow in the pipe is maintained by the regulating valve in the drain tubing.



Brine densities from Hiss (1975)

Appendix
Fig. 1. Diagram of aquifers and salt beds in Delaware basin. Pressure surface raises unsaturated brine through fractures in overlying anhydrite to contact halite. Brine density flow removes salt.



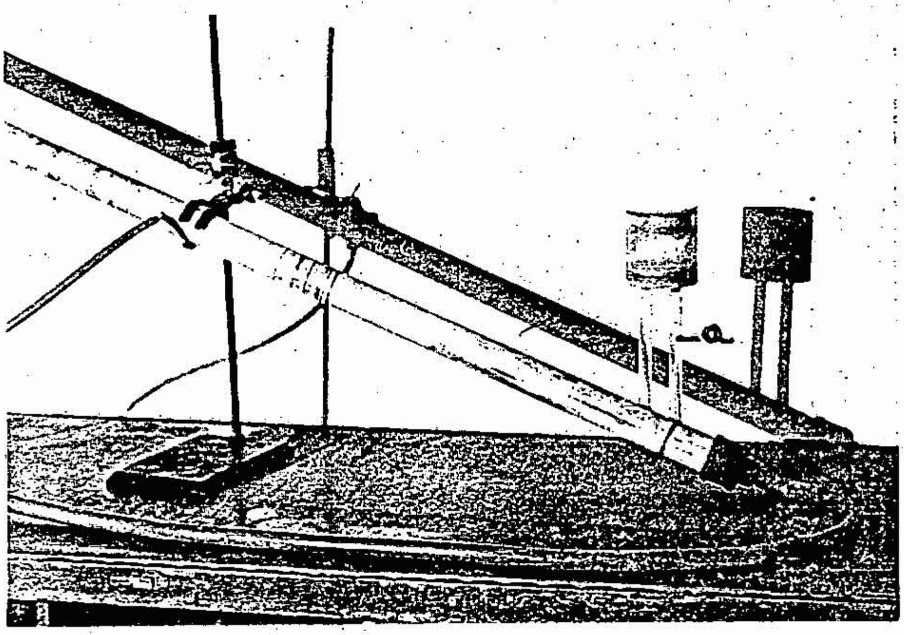
Appendix
Fig. 2. Diagram of laboratory apparatus used to dissolve salt by means of brine density flow.

Summary of Results:

The two open polycarbonate conduits, with a throughflow rate in the aquifer of 0.9 litres per hour dissolved salt at the rate of 10.3 g per minute in the overlying salt chamber. Fresh water moved up one tube and brine water moved down the other tube to form a continuous brine flow. Because of an inadequate overflow drain, siphoning was observed in the tubes that changed the water level in chamber. As the water level was rising in the chamber brine which had developed as a pycnocline in the pipe was drawn up into the chamber through the upper tube. During a phase of falling water level, the brine moved down the lower tube and was replaced by fresh water from above the pycnocline by rising through the upper tube. When throughflow was stopped, the brine and fresh water flows were observed exchanging in the same tube.

The tube system was modified by blocking off one of the 1/2 inch ID polycarbonate mounting tubes and placing a 1/16 inch ID "capillary" in the other tube (Appendix Figure 3) and sealing the sides of the polycarbonate mounting tube with a rubber stopper. The stopper was placed securely in the mounting tube but without a sealant so that "tight" water communication was possible between the sides of the stopper and mounting tube (Appendix Figure 2). This configuration with a throughflow rate in the underlying aquifer of 1 litre per hour dissolved salt in the chamber at a rate of 1.2 g per minute. Current velocity in the capillary of about 5 cm/sec. was observed. The heavy brine moved down the capillary and was replaced by a continuous flow of fresh water passing between the tightly fitting rubber stopper and the polycarbonate mounting tube. The pressure surface in the chamber was maintained at a constant level about 2 cm below the head in the aquifer.

The tube system was further modified by placing a sealant between the rubber stopper and the walls of the polycarbonate tube so that communication could only be maintained in the capillary. This configuration dissolved salt in the chamber at a rate of about 1 g per minute. The single small-diameter passage resulted in feedback system consisting of a filling mode and a draining mode. Brine moved down through the capillary until water level in the chamber was lowered from 0.5 to about 1.5 cm. The flow then reversed itself as fresh water filled the chamber. The cycle repeated indefinitely in an arythmic manner with an average cycle frequency of seconds to minutes. The strongest flows with the shortest frequency occurred with the greatest throughflow rates and the greatest difference in brine density between the chamber and aquifer.



Appendix Figure 3. Photograph of chamber containing salt block connected to lower pipe (aquifer) by means of single capillary (a) inside mounting tube. Water moving only through the capillary dissolved the salt cavity in the chamber above in about 90 minutes.

Conclusions:

1. The access of "fresh" or unsaturated water by means of open conduits from an aquifer below to an overlying body of salt would appear to be a sufficient mechanism for establishing and maintaining water circulation by means of a density flow.

2. Differential flow can probably be expected in different conduits with the viscous brine moving down through the more open systems and the "fresher" water moving up through the tighter systems. Density gradients appear to be sufficient to produce a pulsating flow where only single conduits are available.

3. The rate of brine flow (and dissolution) appears to be controlled by density difference which in turn is controlled by the rate of removal of brine by the aquifer. The geometry of the fracture (conduit) system is also a controlling factor.

APPENDIX B

REPORT ON REFERRED FOSSILS FROM SAN SIMEON SINK

J. P. Bradbury

X

STRATIGRAPHIC RANGE	Pleistocene or Holocene	SHIPMENT NUMBER	0-77-2D
GENERAL LOCALITY	New Mexico	REGION	Lea Co.
QUADRANGLE OR AREA	Oil Center 15 min. quad.	DATE RECEIVED	1/27/77
KINDS OF FOSSILS	Diatoms	STATUS OF WORK	Complete
REFERRED BY	Roger Y. Anderson	DATE REPORTED	11/10/77
REPORT PREPARED BY	J. P. Bradbury		

One sample has been examined for dia oms and assigned USGS Paleobotany locality number D5742. It is from the NE side of San Simon Sink; N 1/2 sec. 18, T. 23 S., R. 35 E., at elevation 3320 feet. Lat. 32 deg. 18 min. 36 sec. N.; Long. 103 deg. 24 min. 21 sec. W.

The sample contains the following diatom flora:

ACHNANTHES AFFINIS	10 percent
CYCLOTELLA MENEGHINIANA	2
CYMBELLA PUSILLA	11
DENTICULA ELEGANS	48
EPITHEMIA ARGUS	1
MASTOGLOIA SMITHII v. LACUSTRIS	1
MASTOGLOIA ELLIPTICA v. DANSEI	1
NAVICULA HALOPHILA v. SUBCAPITATA	4
NAVICULA OBLONGA	1
NAVICULA CRYPTOCEPHALA	4
NITZSCHIA SUBTILIS	4
NITZSCHIA OBTUSA v. SCHWEINFURTHII	3
NITZSCHIA AMPHIBIA	1
NITZSCHIA DENTICULA	3
RHOPALODIA GIBBA	1
SYNEDRA ACUS?	5

In addition to these dominants, the following species occurred in small numbers:

AMPHIPRORA PALUDOSA
AMPHORA cf. VENETA
ANOMOEONEIS COSTATA
ANOMOEONEIS cf. VITREA v. LANCEOLATA
CAMPYLODISCUS CLYPEUS
COCCONEIS PLACENTULA
CYMBELLA CYMBIFORMIS
FRAGILARIA PINNATA
FRAGILARIA BREVISTRIATA
GOMPHONEMA AFFINE
RHOPALODIA GIBBERULA
SYNEDRA PUCHELLA
SYNEDRA ULNA

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REPORT NOT TO BE QUOTED OR PARAPHRASED IN PUBLICATION WITHOUT A FINAL RECHECK BY THE PALEONTOLOGY AND STRATIGRAPHY BRANCH.

REPORT ON REFERRED FOSSILS

X

98

STRATIGRAPHIC RANGE		SHIPMENT NUMBER	0-77-2D
GENERAL LOCALITY		REGION	
QUADRANGLE OR AREA		DATE RECEIVED	
KINDS OF FOSSILS		STATUS OF WORK	
REFERRED BY		DATE REPORTED	
REPORT PREPARED BY			

This diatom flora is characteristic of alkaline, brackish water. All the species are either tolerant of moderate concentrations of dissolved solids, or prefer such environments. A close analog of this diatom assemblage can be found at Swimming Pool Spring, Sandoval Co., New Mexico which had a salinity of about 7 parts per thousand in 1928; many of the same species were also present in the brackish lake that existed at Zuni Salt Lake, Catron Co., New Mexico in the Late Pleistocene or Holocene. Both Swimming Pool Spring and Zuni Salt Lake are or were partly fed by mineralized springs issuing along fault zones or through subterranean conduits and it seems possible that a similar situation existed at San Simon Sink, where ground water dissolving subsurface evaporites could supply the necessary amounts of sodium, calcium, chlorine and sulfate ions to support the diatom flora.

The diatoms do not provide a firm age for the deposit, but it seems probable that the presence of a diatomite is linked directly or indirectly to increased precipitation. The most recent possibility in this regard appears to be the pre-Altithermal, Lubbock subpluvial period recorded by diatomites at Blackwater Draw, New Mexico and at Lubbock, Texas (Wendorf, 1961; Wendorf and Hester, 1975). This event occurred between 8000 and 9000 years ago (Wenforf and Hester, 1975). The preceding Tahoka pluvials (approximately 10000 and 16,000 years ago) are also possibilities.

The Lubbock sub-pluvial diatom assemblages recorded at these localities contain many of the same species and dominants found at San Simon Sink. Hohn and Hellerman (in Wendorf, 1961) suggest that a correlation exists between the diatom stratigraphies of the Lubbock Site (Texas) and the Clovis-Blackwater Draw site in New Mexico, and that they reflect regional climatic changes. It may be that the diatomite at San Simon Sink can be fitted into this chronology when more samples are analyzed and a biostratigraphy is produced. Despite the general similarity of the diatom assemblages, however, diatoms at San Simon Sink appear to represent more saline environments than those at Clovis-Blackwater Draw and Lubbock. Most likely this reflects a greater input of saline groundwater derived from underlying evaporites at San Simon Sink. @

REPORT ON REFERRED FOSSILS

X

3

99

STRATIGRAPHIC RANGE

GENERAL LOCALITY

QUADRANGLE OR AREA

KINDS OF FOSSILS

REFERRED BY

REPORT PREPARED BY

SHIPMENT NUMBER 0-77-2D

REGION

DATE RECEIVED

STATUS OF WORK

DATE REPORTED

References

Wendorf, Fred, 1961, Paleoecology of the Llano Estacado: Fort Burgwin Research Center Publication no. 1, Museum of New Mexico Press, 144 p.

Wendorf, Fred, and Hester, J. J., 1975, Late Pleistocene environments of the southern High Plains: Fort Burgwin Research Center, Publication no. 9, 290 p.

J. Platt Bradbury

J. Platt Bradbury

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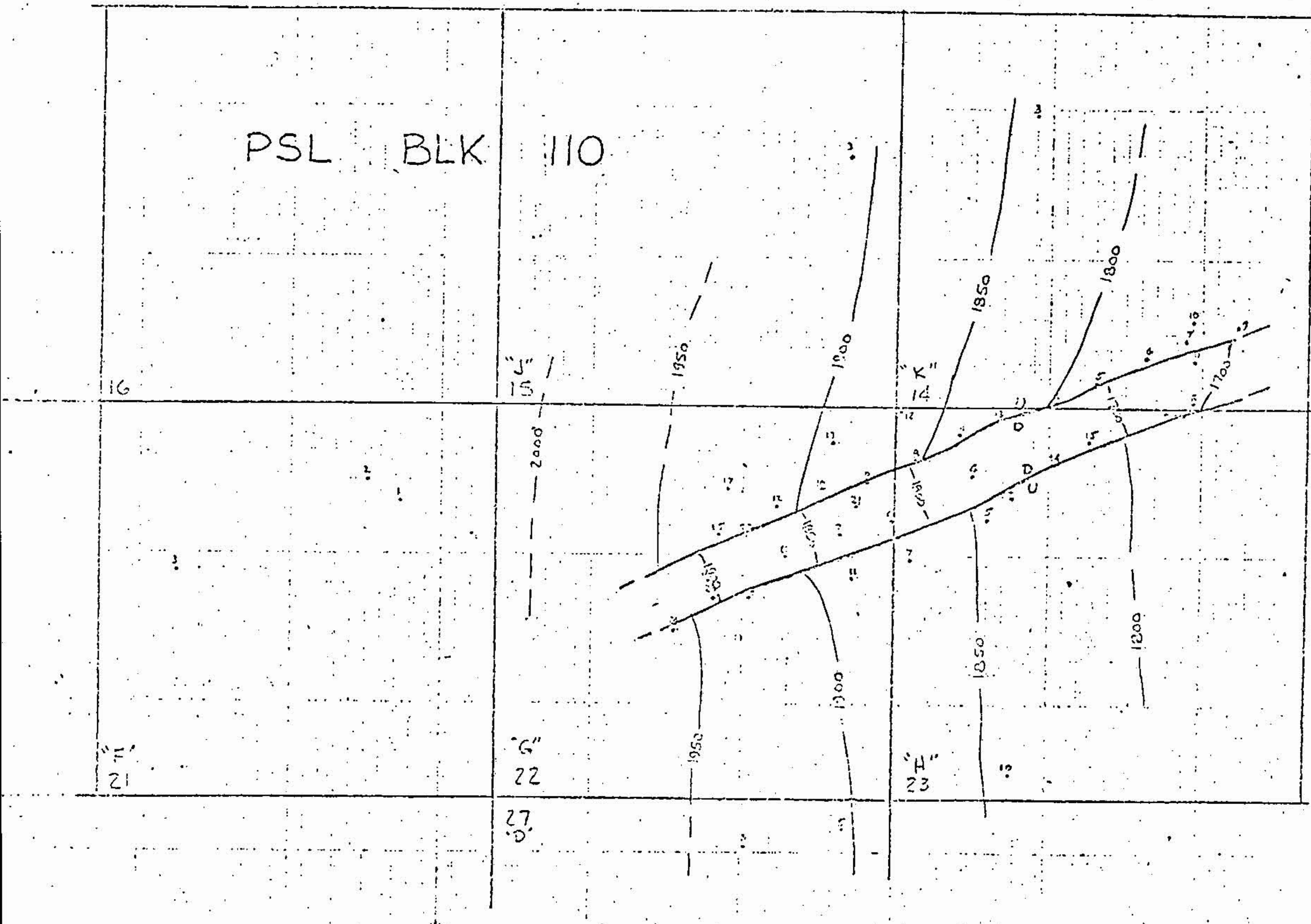
APPENDIX C

FIGURES RELATED TO BELL CANYON FAULT AND
REPLACEMENT LIMESTONE
(FROM SMITH, 1978)

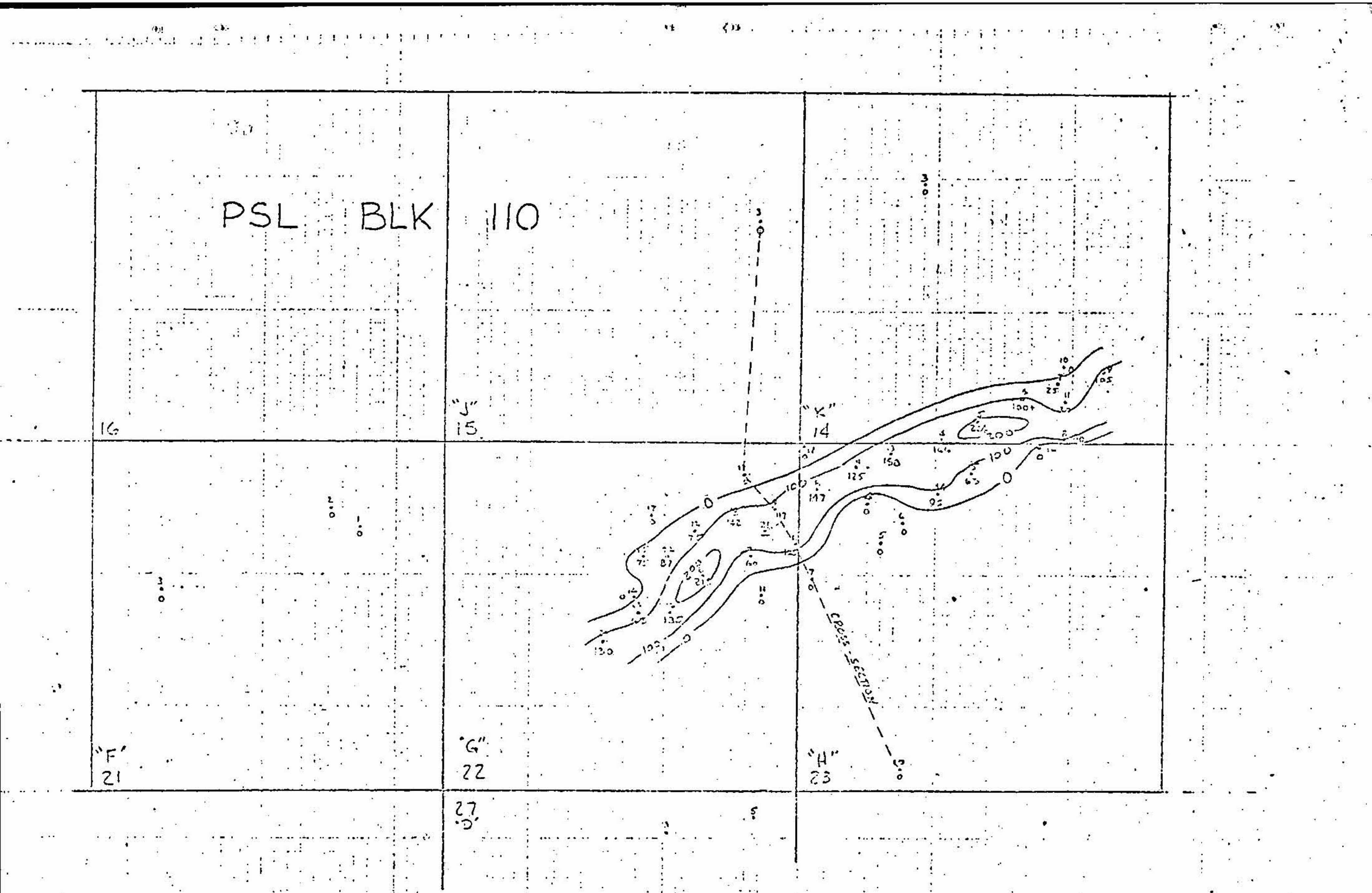


STRUCTURE ON TOP OF
BELL CANYON (DELAWARE)

TEXAS GULF SULPHUR
RUSTLER SPRINGS DEPOSIT
CULBERSON CO., TEXAS

1" = 2000'

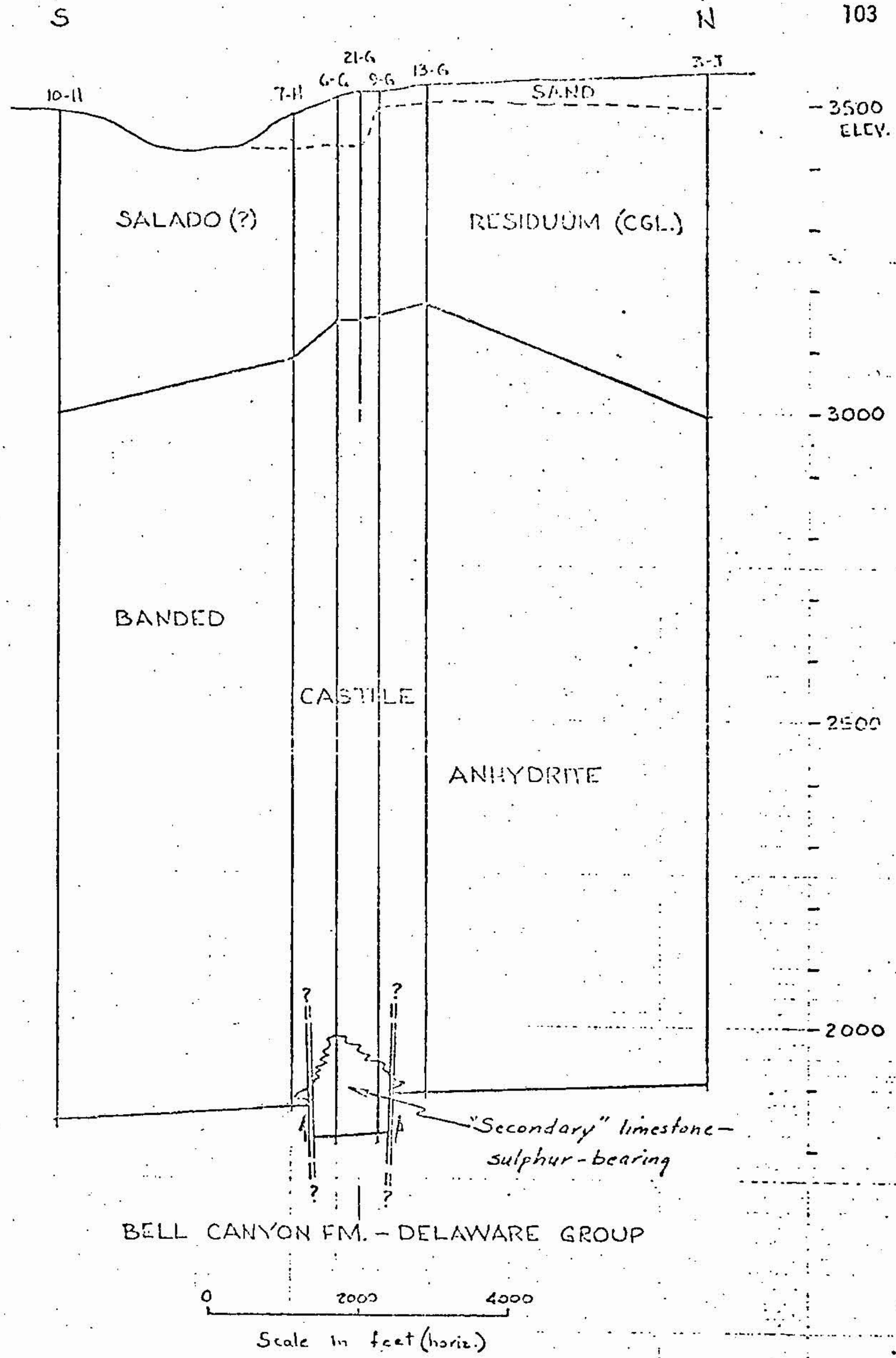
101



ISOPACH OF "SECONDARY"
LIMESTONE IN CASTILE FM.

TEXAS GULF SULPHUR
RUSTLER SPRINGS DEPOSIT
CULBERSON CO., TEXAS

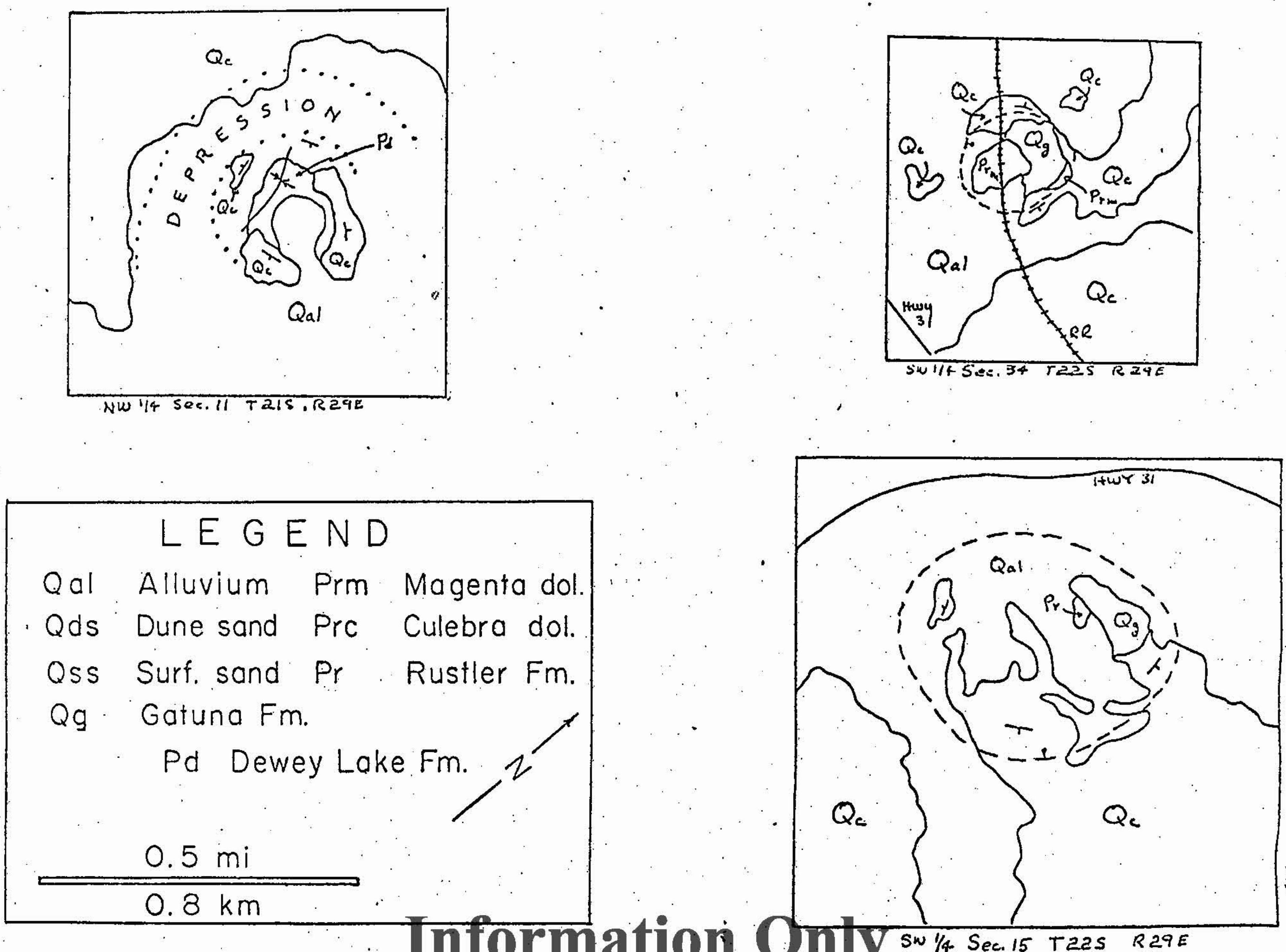
1" = 2000'

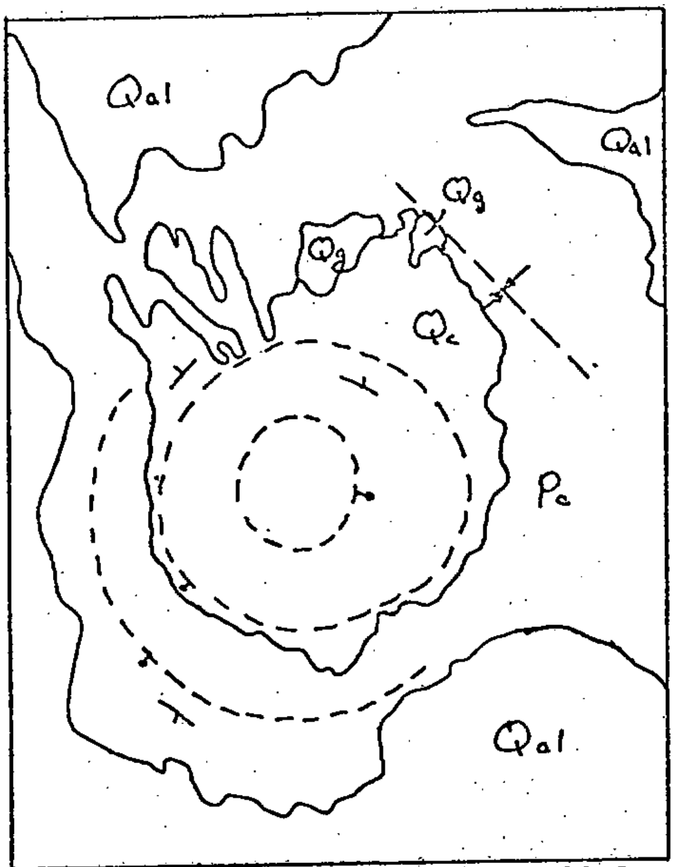


North-south cross-section through Texas Gulf Sulphur Rustler Springs deposit, PSL Blk 110

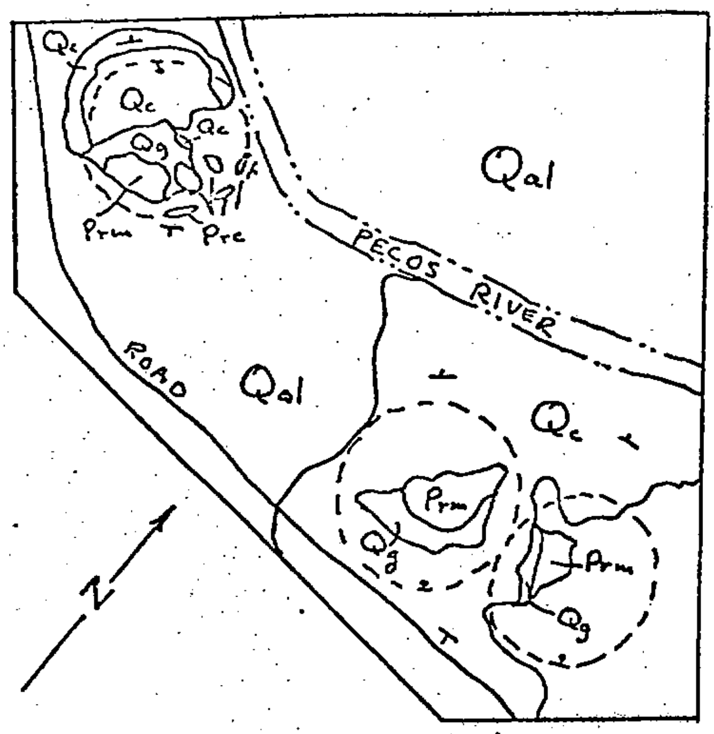
APPENDIX D

GEOLOGIC SKETCH MAPS OF COLLAPSE STRUCTURES AND DOMES

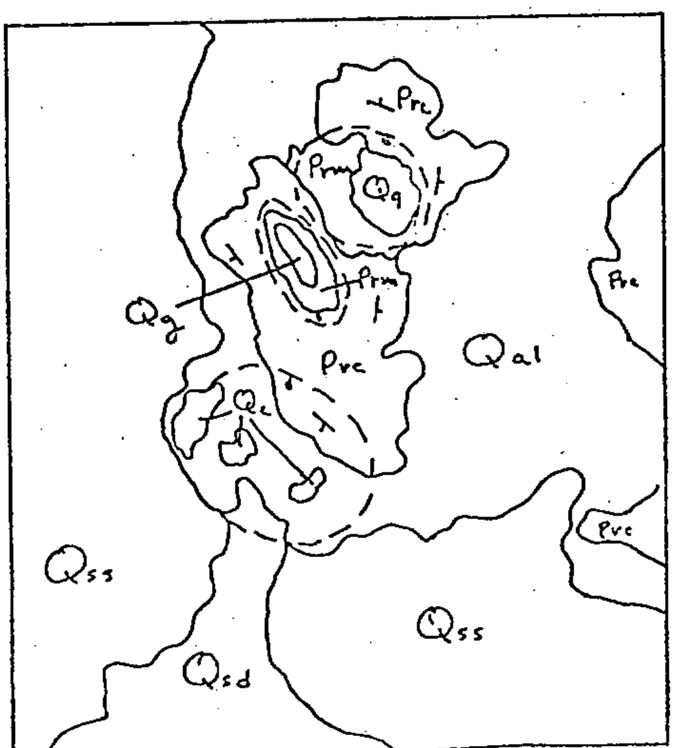

Qc
DEPRESSION
Pd
Qal
NW 1/4 Sec. 11 T21S, R29E
Qc
Qg
Prm
Qal
Hwy 31
RR
SW 1/4 Sec. 34 T22S R29E
LEGEND
Qal Alluvium
Prm Magenta dol.
Qds Dune sand
Prc Culebra dol.
Qss Surf. sand
Pr Rustler Fm.
Qg Gatuna Fm.
Pd Dewey Lake Fm.
N
0.5 mi
0.8 km
HWY 31
Qal
Pr
Qg
Qc
SW 1/4 Sec. 15 T22S R29E



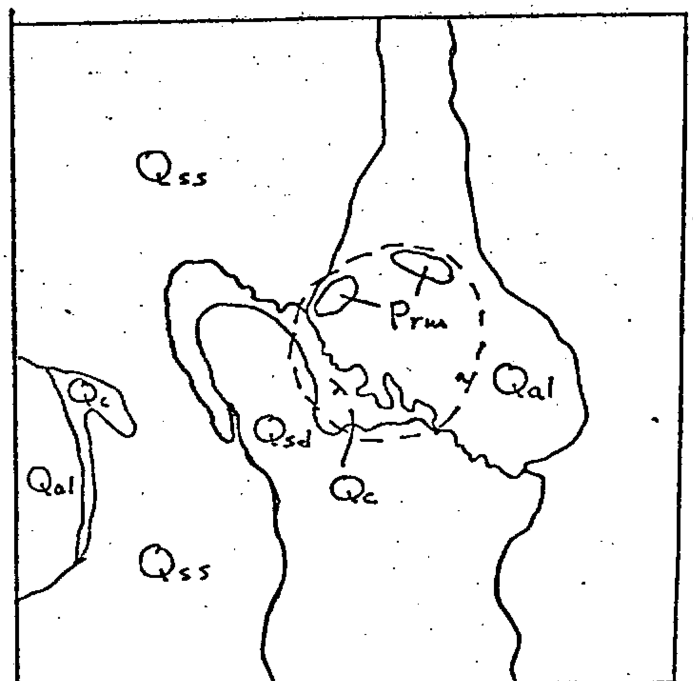
SE 1/4 Sec. 13 T23S, R29E



NW 1/4 Sec. 19
T24S, R29E



SE 1/4 Sec. 24 T23S, R29E



SW 1/4 Sec. 26 T23S, R29E