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The Geologic Structures Observed in Drillhole DOE-2 and Their Possible Origins: Waste Isolation Pilot Plant

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THE GEOLOGIC STRUCTURES OBSERVED IN DRILLHOLE DOE-2 AND THEIR POSSIBLE ORIGINS: WASTE ISOLATION PILOT PLANT

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Abstract

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

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

ACKNOWLEDGEMENTS

J. W. Mercer (SNL), R. P. Snyder (USGS), and M. Wilson (F&S) performed the bulk of the work during the initial drilling and core logging at drillhole DOE-2. R. P. Snyder provided invaluable assistance in the detailed description and interpretation of the structures observed in the DOE-2 core. F. E. Hensley helped with core slabbing and photography on numerous occasions. W. Casey (SNL) is thanked for his thoughtful review of this report.

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INTRODUCTION

Since the early site characterization studies (Powers et al., 1978) of the Waste Isolation Pilot Plant (WIPP), geologists have been aware of a structural depression 2 mi north of the WIPP site center, within the evaporite sequence at WIPP. This depression has been named informally after a shallow borehole, FC-92. During the spring of 1985, DOE drilled hole DOE-2, largely to investigate the structures associated with the FC-92 depression. Mercer et al. (1986) document the drilling history and core description of units encountered in DOE-2. The objectives of this report are to describe mesoscopic structures observed in the drillcore and to relate these structures to their possible origins and to the FC-92 depression in general.

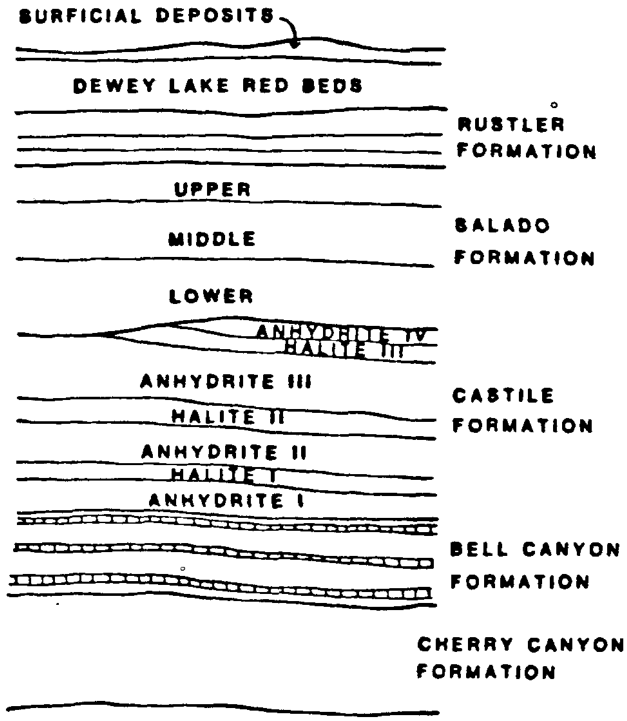

Figure 1. Stratigraphic Section of WIPP Facility Lithologic Units (adapted from Lambert, 1983).

Geologic Setting

The Delaware Basin of southeastern New Mexico contains layered evaporites (see Figure 1). An area in the northern part of the basin has been selected for the WIPP site (see Figure 2). Rock units of interest in this report are Ochoan, with the exception of the underlying Delaware Mountain Group (DMG). The oldest Ochoan unit is the Castile Formation, which overlies the Bell Canyon Formation of the DMG. Locally, the Castile consists of three anhydrite units separated by two halite units. Above the Castile stratigraphically is the Salado Formation, which consists of halite, anhydritic and/or polyhalitic halite, and argillaceous halite. Overlying the Salado is the Rustler Formation, which contains siltstones, anhydrites, dolomitic siltstones, dolomites, and halite.

Evaporite units display deformation structures such as salt anticlines and synclines within portions of the Delaware Basin adjacent to the WIPP site. Workers within the area call this area of deformation, the "Disturbed Zone" or DZ (e.g., Powers et al., 1978; Borns et al., 1983). The extent of the DZ is presently delineated from borehole data and seismic reflection studies up to 1983 (Borns et al., 1983). These structures are important in understanding the evolution of the Delaware Basin from deposition to present.

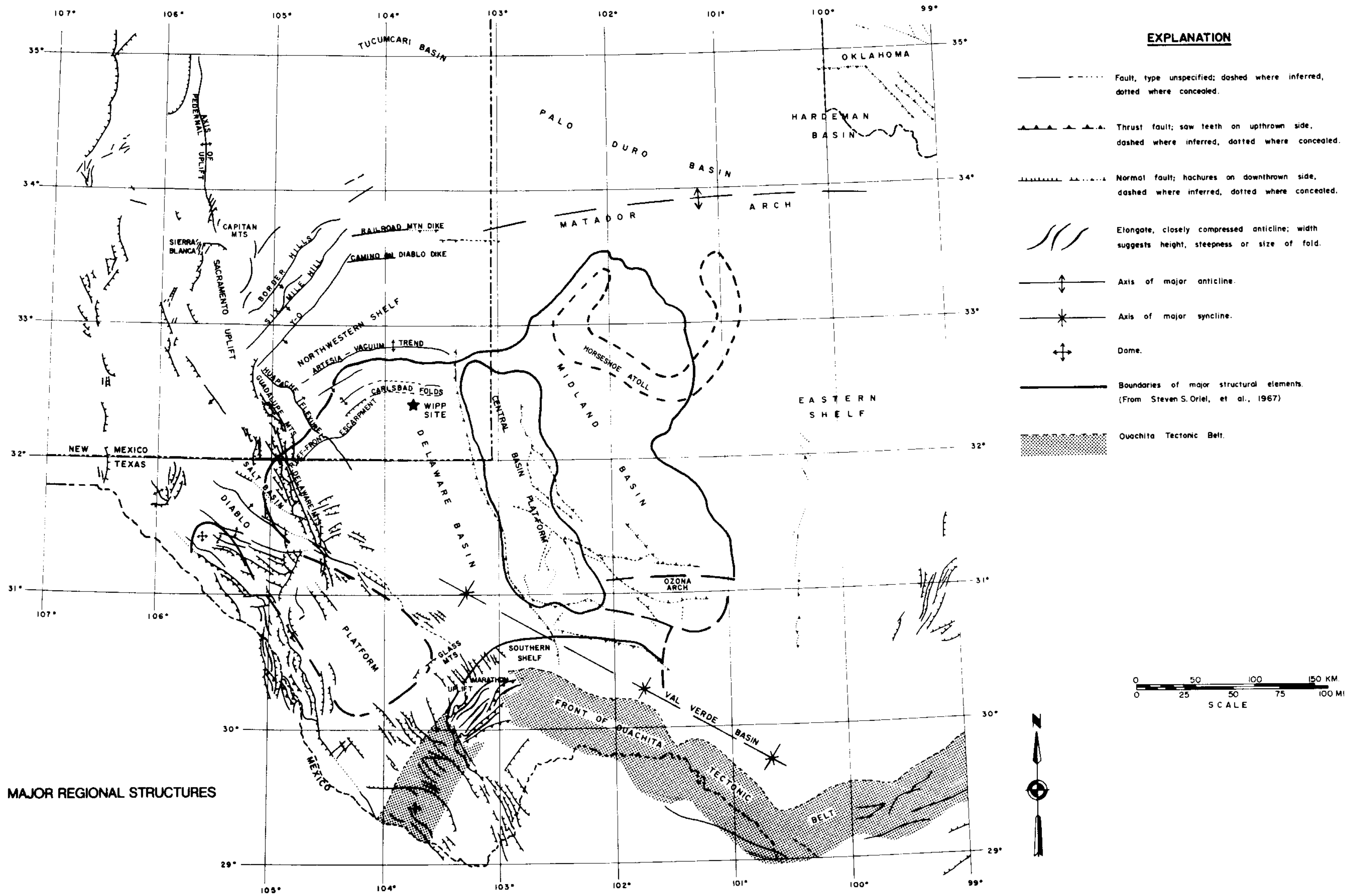

Figure 2. Location of the Delaware Basin and the WIPP Site.

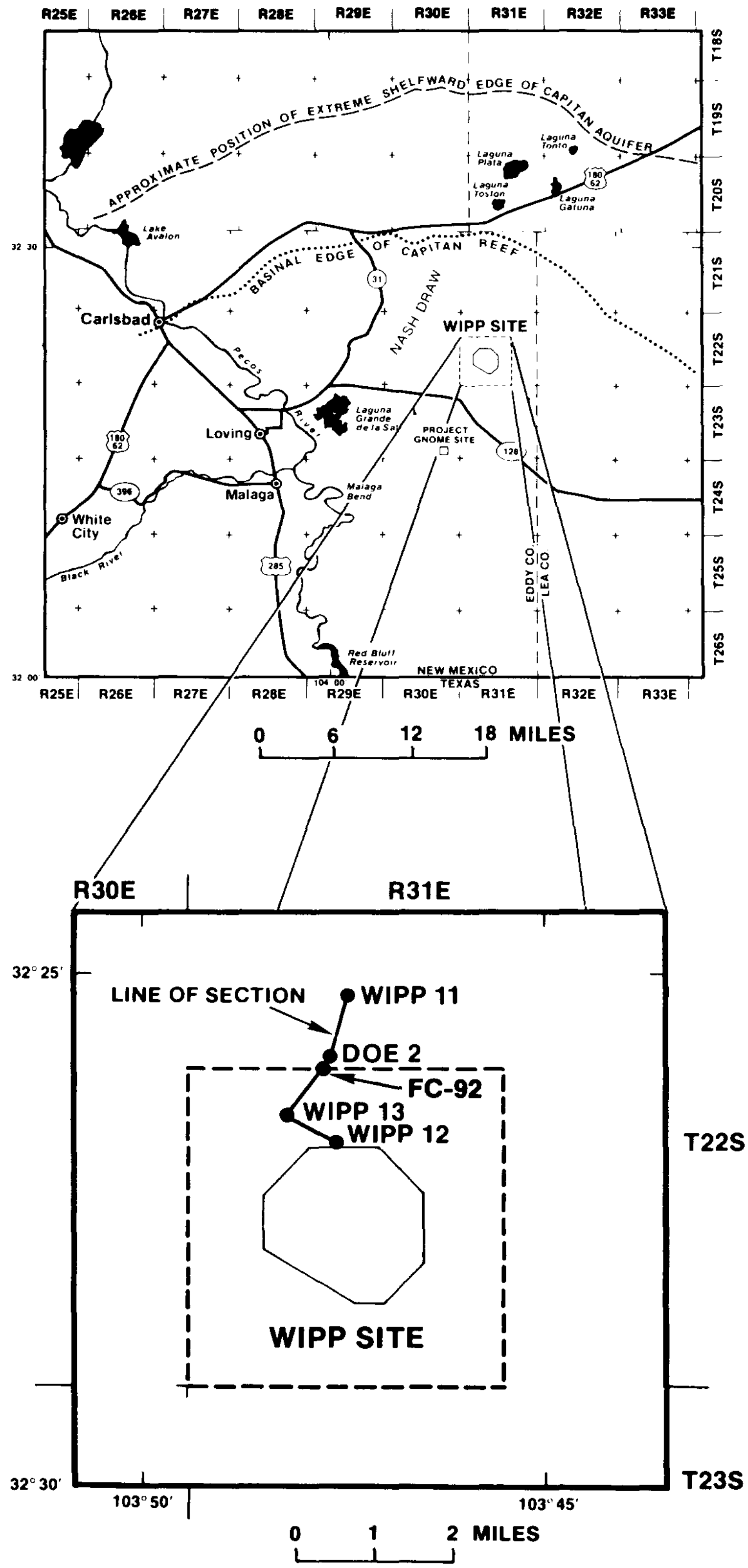

Figure 3. Location of Noted Drillholes at the WIPP Site.

Processes of Interest for Origin of Deformation

Prior to the drilling of DOE-2 (Figure 3), several processes were suggested as possible origins for the FC-92 depression. These suggested processes can be summarized as follows:

- o Dissolution--subsidence of Salado markers due to dissolution removal of halite at the base of the Salado or within the Castile (Anderson, 1978)
- o Gravity-driven deformation--flow of salt related to the development of anti- and synclines in response to halokinesis or gravity sliding (Borns et al., 1983)
- o Syndepositional basins--Salado infill basins formed by dissolution or erosion at the top of the Castile (Borns et al., 1983).

In the sections below, I will discuss the background and history of these processes.

Dissolution: Processes and Evidence in the Northern Delaware Basin

Anderson (1978) concluded that 50% of the original salt in the Delaware Basin was removed by dissolution. He also stated that most of this dissolution occurred within the Salado. Earlier workers in the area such as Bachman (1974) recognized dissolution features in the region, but Anderson suggested that dissolution is the major active process in the area and the process with the most ramifications for the siting of the WIPP.

Dissolution is inferred from several surface features such as the karst terrane along the east side of the Pecos River (Bachman, 1983), the Nash Draw collapse features (Lambert, 1983), and breccia pipes (Snyder and Gard, 1982). Other traces of active dissolution are the salinity gradients in the Bell Canyon, which increase to the northwest within the basin (Wood et al., 1983). The presence of dissolution in the Delaware Basin is not questioned, but the extent, timing, and process of dissolution are a matter of debate.

Anderson's (1978) primary line of evidence for dissolution was the interpretation of well logs from the basin. From these, he believed he could trace units into regions of the basin where major portions of the section were missing. He attributed this removal to deep dissolution. Lambert (1983) and Borns and Shaffer (1985) discuss the ambiguities of well log interpretation with special reference to the delineation of dissolution structures. Generally, Anderson's structures do not have unique basin-wide interpretations; e.g., he did not consider original facies variation, for which there are core and mine data in the Ochoan sequence (Holt and Powers, 1986). Also, some of Anderson's structures such as the Poker Lake anticline and syncline pair are not as extensive as originally thought (Borns and Shaffer, 1985). Still, a sequence of structures that Anderson delineated suggests the partial removal of the Salado after deposition. This sequence is the same as the terrane along the east side of the Pecos described by Bachman (1983). Bachman also concludes that this terrane, which begins around Poker Sink and extends southward along the Pecos, represents karst and extensive dissolution by waters of the ancestral Pecos River. The fluids penetrated the Salado from the surface, and the dissolution front remained perched on the aquitard formed by the upper Castile anhydrite. Thus, dissolution is envisioned in a portion of the basin within the Salado and is also seen in the advance of Nash Draw within the Rustler and upper Salado to the west of the WIPP site. Borns and Shaffer (1985) stated that dissolution was not evident within 10 to 15 km of the WIPP site, referenced to the location of the structures along the Pecos River and Nash Draw. However, Davies (1983) has interpreted a series of depressions centered on Drillhole FC-92, 2 mi north of the WIPP site (see Figure 3). The geometry of these depressions of marker beds in the upper Salado is comparable to numerical models for dissolution that Davies produced. He therefore attributedd the stacked depressions to dissolution in the Salado, well within the area of interest to the WIPP site.

If dissolution is present in the basin, the important consideration becomes the rate at which a dissolution front can advance vertically and laterally. Anderson (1978) assumed that essentially all of his salt removal (50%) occurred in the last 4-6 million years (ma), which he believes corresponds with the major stage of uplift for the basin. Bachman (1983) and Lambert (1983) have pointed out that more than one period of dissolution has occurred since deposition of the evaporite units in the basin. Hence, dissolution may be integrated over a 250-ma period. For example, Bachman (1983) reported episodes of dissolution as follows:

- Syndepositionally with the Castile-Salado transition.
- At the close of Salado deposition and beginning of the Rustler deposition, the west edge of the sequence was uplifted and truncated. This process left a series of solution valleys that are infilled with Rustler sediments.
- In the Triassic, troughs and karst terrane formed in response to the ancestral Pecos River.
- During the Tertiary, troughs up to 400 m deep formed in Texas.

The complexity of deciphering which dissolution process was active in a given rock unit is apparent. Anderson's mass removal of salt in the last several million years gives an upper bound on the rate of advance. But if Bachman's sequence of troughs is related to the ancestral Pecos, the process and rate are not applicable to the rest of the basin. In terms of the WIPP site, the rate of advance for Nash Draw becomes the concern.

Gravity-Driven Deformation

In other salt basins, such as east Texas and the Gulf Coast, gravity-driven deformation is manifest, ranging from salt pillows to diapirs (Seni and Jackson, 1983). Borns et al. (1983) demonstrated in a numerical model that gravitational instability would arise within the evaporite stratigraphy of the WIPP site. Many observations have been made of flow fabrics on both the meso- and microscopic scales (Borns, 1983a; Borns et al., 1983). However, such flow textures may also be associated with dissolution structures, especially at slower dissolution rates (Davies, 1983). The distribution of structures both areally and vertically, (i.e., whether a structure is an anticline or a syncline) may distinguish between the dissolution and gravity-driven mechanisms. Lambert (1983) pointed out that anomalous structures in the northern Delaware Basin are distributed as both highs and lows. In a dissolution model, the associated anomalies are expected to be lows.

The timing of gravity-driven deformation is not precisely known. Jones (1981) and Borns et al. (1983) suggested that such deformation has occurred over the past 70 ma and may be active at present. Evidence for such time brackets are the deformation of Gatuna sediments at Drillhole ERDA-6 (Jones, 1981) and current gravitational instability of the Castile density stratification (Borns et al., 1983). The age is also inferred from the initiation of basin uplift over the past 70 ma with a resurgence in the last 6 ma.

<u>Syndepositional Basins</u>

Snyder in Borns et al. (1983) observed that the halite units of the lower Salado thinned over structural highs (e.g., Borehole WIPP-11) and thickened over structural lows (e.g., Borehole B-10JR) in the Castile. However, Snyder noted exceptions such as Borehole ERDA-6, where the Salado was not thinned over a Castile high. Still, Snyder put forth the concept that the Salado was deposited during the deformation of the Castile or closely thereafter. In this hypothesis, the lower Salado structures resulted from accumulation in forming basins, which had been filled in or ceased to be active by the time that the middle Salado was deposited.

SALADO AND CASTILE FORMATION STRATIGRAPHY IN BOREHOLE DOE-2

<u>Salado Formation</u>

The presence of the structural depression, as discussed in the objectives of the borehole, was confirmed by the drilling project. The distinctive marker beds of the Salado are lower relative to depths in adjacent boreholes WIPP-11, -12, and -13 (see Figure 4). The amount of relative displacement in depth for these marker beds in DOE-2 increases with depth compared to adjacent holes. Between the downwarped marker beds within the Salado, the halitic units thicken with depth relative to the same section in adjacent holes. Hence, the borehole penetrated a structure in the Salado that results in a marked downwarp of marker beds, which is accompanied by thickening of the interlayered halitic section of the Salado Formation.

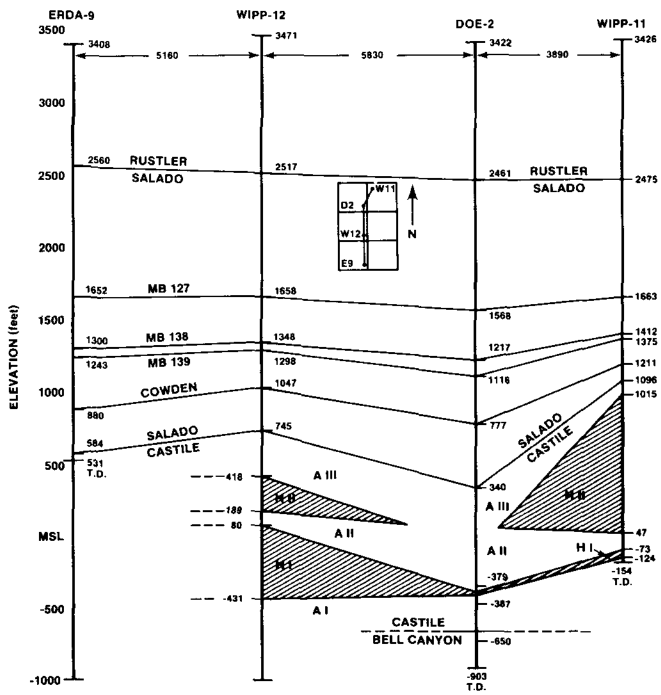

Figure 4. Fence Diagram Using DOE-2 and Adjacent Holes.

Castile Formation

The Castile section as observed in DOE-2 departs distinctly from the stratigraphy exhibited in adjacent boreholes WIPP-11, -12, and -13. The upper anhydrite that was encountered in DOE-2 was 1.5 to 2 times thicker than in neighboring boreholes (see Figure 4). In contrast, only one halitic unit was observed within the Castile at DOE-2. This unit was less than 3 m thick and, therefore, significantly thinner than in adjacent holes. This halite unit was markedly clear, with no observable relics of the anhydrite stringers that are observed in Halite II and I in other holes. Below the halite unit, the lower anhdrite unit of the Castile appears to be a normal section of Anhydrite I relative to the adjacent holes.

MESOSCOPIC STRUCTURES

Salado Formation

Other than the correlated downwarp of marker beds and the thickening of the halitic section, mesoscopic structures such as small-scale (second-order) folds and extension fractures are not evident in the upper and middle portions of the Salado Formation. In the lower Salado, extension fractures of near vertical orientation are observed in clay and anhydrite interbeds. Such fractures are infilled with cross-fiber halite. We have been unable to determine whether this halite is original or a pseudomorph of gypsum. The lowermost subunit of the Salado is the Infra-Cowden Halite, which thickens significantly in Borehole DOE-2. Laminar markers in this halitic unit can be traced through overturned fold hinges with sub-horizontal axes. These laminar markers display a range of dips from 90 to 0^{o}. Smaller (<1 cm wide) anhydrite stringers in the halite exhibit pull-apart structures and ptygmatic folding.

Castile Formation

The upper 3 m of Castile anhydrite penetrated by Borehole DOE-2 are characterized by several zones of near-vertical laminated anhydrite. The steeply dipping laminae change abruptly to a horizontal orientation. Tight folds or sharp changes in orientation of banding can be seen in Figures 5 and 6 (3082 and 3233 ft, respectively). As mentioned by Borns (1983a) in the state-line outcrops of deformed Castile Formation (Kirkland and Anderson, 1970), several generations of structures may be present, including products of syndepositional deformation. The apparent fold structures of these two plateswith their evidence of truncation of fold limbs and absence of similar structures in the interval immediately below suggest such syndepositional soft-sediment deformation. The occurrence of brecciated laminae (Figures 7 and 8, 3168 and 3169 ft) may also be evidence of interstradal deformation during deposition of the unit. Basically, these observations do not prove a syndepositional origin for these structures, but do suggest that the structures are not all halokinetic or tectonic in origin.

However, there exist meso- and microstructures, as observed in the core of DOE-2, that are characteristic of deformation considered halokinetic in neighboring holes (e.g., WIPP-11 and WIPP-13) (Borns et al., 1983). The polyharmonic folds of finely laminated anhydrite (Figure 9, 3798 ft) are typical of such structures. With folding, pull-apart structures develop and are infilled with secondary anhydrite, which forms subparallel

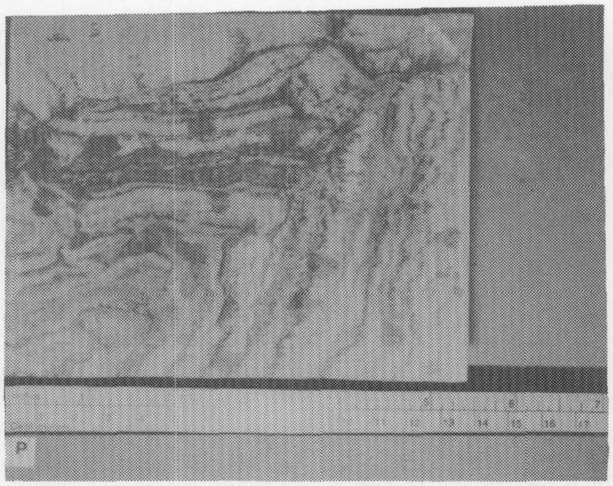

Figure 5. P: 3082.4-3082.8, Tight Fold of Anhydrite Laminae (secondary anhydrite aligns perpendicular to the original banding; circular darker grey spots are glauberite overgrowths).

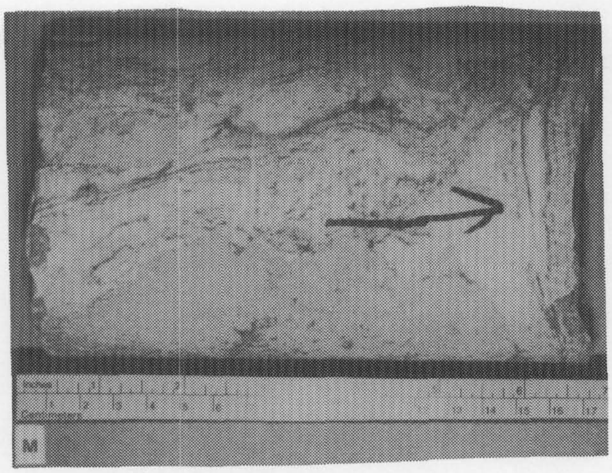

Figure 6. M: 3233.4-3233.9, Sharp Fold Hinge in Banded Anhydrite (dip of fold limbs goes from vertical to horizontal at bottom of the core slab; large patches of glauberite [darker grey] replaced anhydrite).

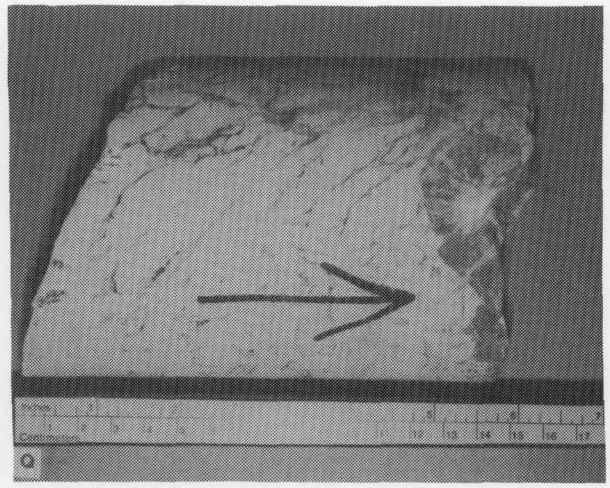

Figure 7. Q: 3168.1-3168.6, Brecciated Dipping Laminae of Anhydrite.

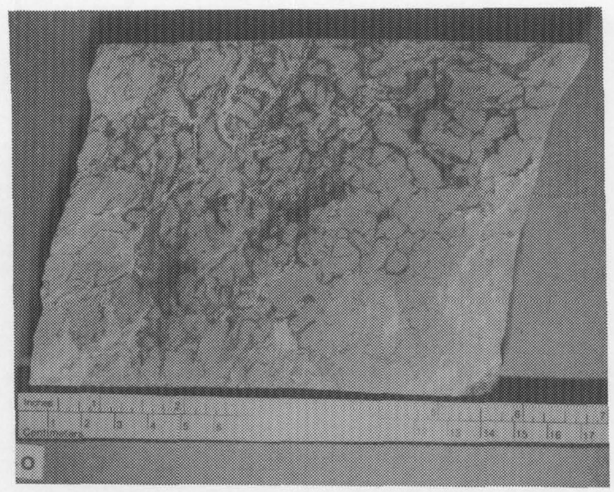

Figure 8. O: 3169.6-3170.1, Brecciated Laminae of Anhydrite (matrix infilled with secondary anhydrite and possible glauberite).

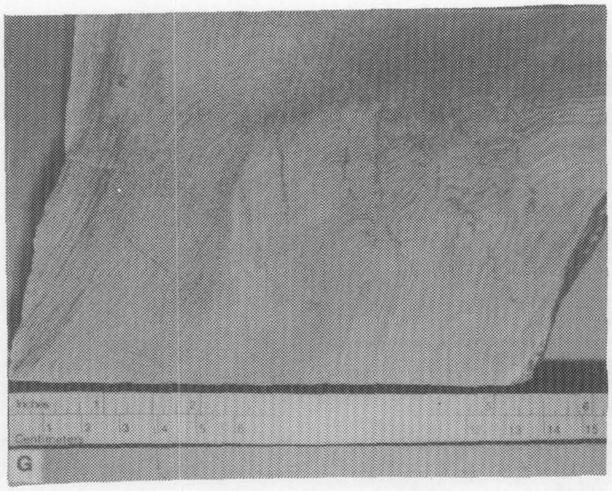

Figure 9. G: 3798.8-3799.3, Polyharmonic Folds in Finely Laminated Anhydrite (pull-aparts of banding formed coeval with folding; anhydrite infills the separation that developed; these infillings cross the laminae at high angles; such textures are typical of deformed Castile Formation units in neighboring drillholes WIPP-11 and WIPP-13).

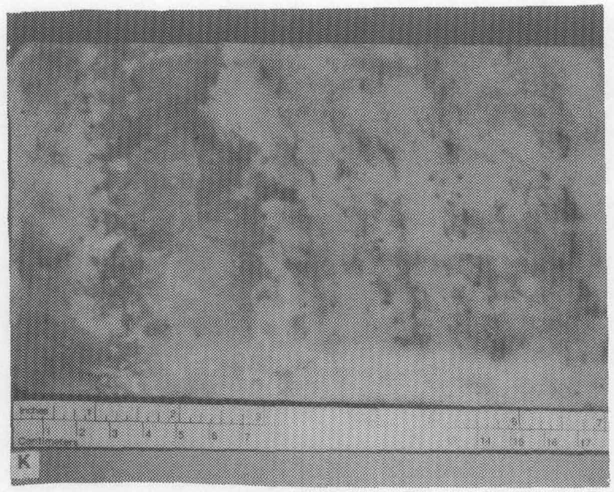

Figure 10. K: 3227.6-3228.3, Near Horizontal Bands of Anhydrite with Glauberite Overgrowths (interlayered with the anhydrite bands are darker dolomitic laminae that show pull-apart textures).

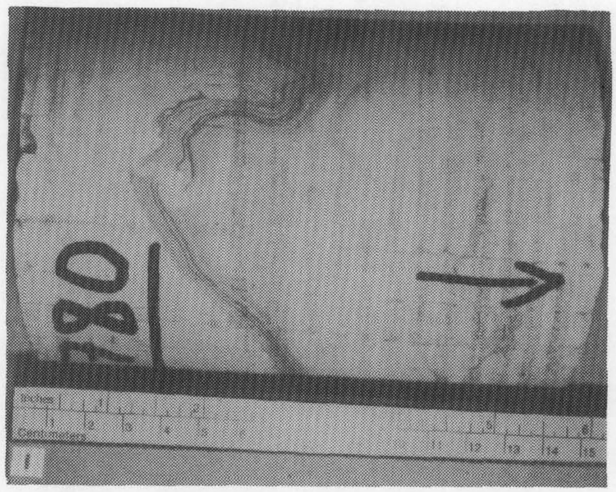

Figure 11. I: 3779.9-3780.4, Folded Dolomitic Laminae in Anhydrite (dolomitic laminae exhibit pull-apart texture; pull-aparts are infilled with secondary anhydrite).

vein networks. These pull-apart structures are characteristic of this style of deformation in the Castile. Figures 10 and 11 (3228 and 3780 ft, respectively) show styles of pull-apart in which dolomitic laminae are extended either in a fold or along a plane. Other pull-apart structures (Figure 12, 3690 ft) open a separation that is infilled with halite. Nearly all these structures suggest some fluid migration during deformation, accompanied by recrystallization or replacement of the mineral assemblage. Such textures are the replacement of anhydrite by glauberite and the development of secondary anhydrite in pull-apart structures. These textures include the development of secondary anhydrite in a parallel fabric at high angle to the primary banding or lamination (Figures 13 and 14, 3082 and 3232 ft, respectively). This second orientation is observed to parallel local fold axes and may represent a form of crenulation cleavage. With depth, the upper anhydrite of the Castile at DOE-2 becomes more massive, except for rare dolomitic laminae. Hence, folds or horizons that were once halite (if either existed) are masked by the now massive anhydrite unit. The contact between this

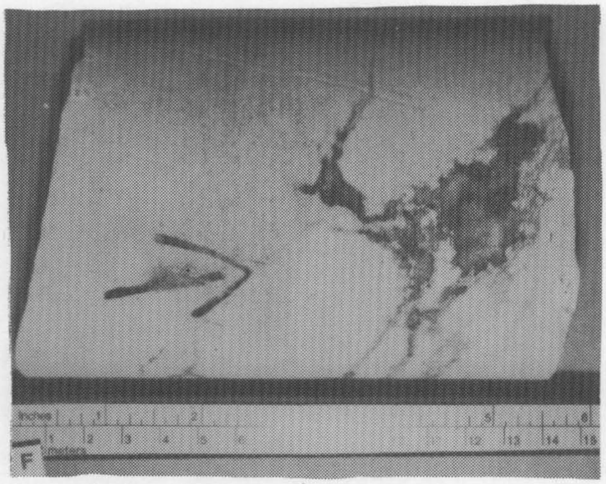

Figure 12. F: 3690.4-3690.8, Anhydrite Bands with Development of Pull-apart Textures (halite infills the separation; some brecciation of the bands can be observed).

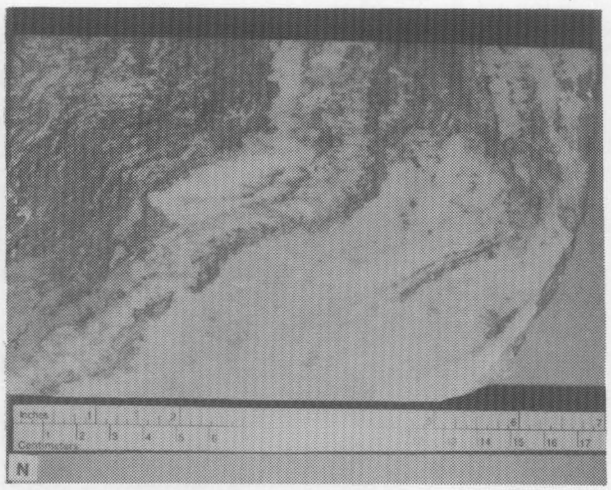

Figure 13. N: 3081.7-3082.3, Folded Anhydrite Laminae (recrystallized anhydrite in laminae aligns parallel to axial plane of folds; recrystallized anhydrite overgrows primary laminae on one fold limb).

anhydrite and the halite below dips 20-30°. Laminae in the anhydrite are conformable to this contact (Figure 15, 3801 ft). Halite at the contact is uniform in grain-size and forms a highly lineated shape fabric that dips parallel to the contact. Below this contact, the halite is the only halitic unit encountered in the Castile. The unit is only 3 m

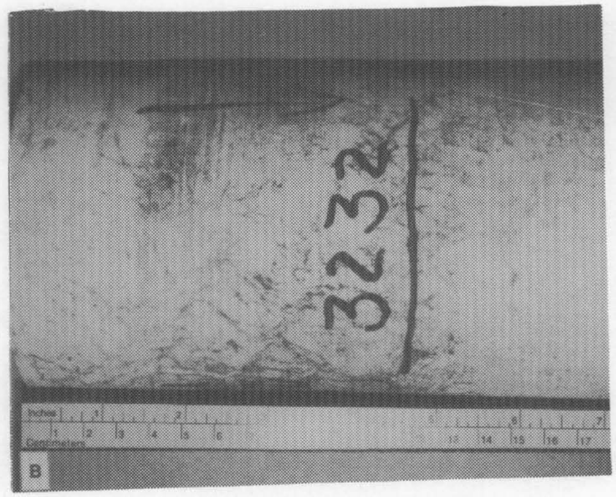

Figure 14. B: 3231.6-3232.3, Banded Anhydrite with Secondary Anhydrite Laminae at High Angles to Original Banding.

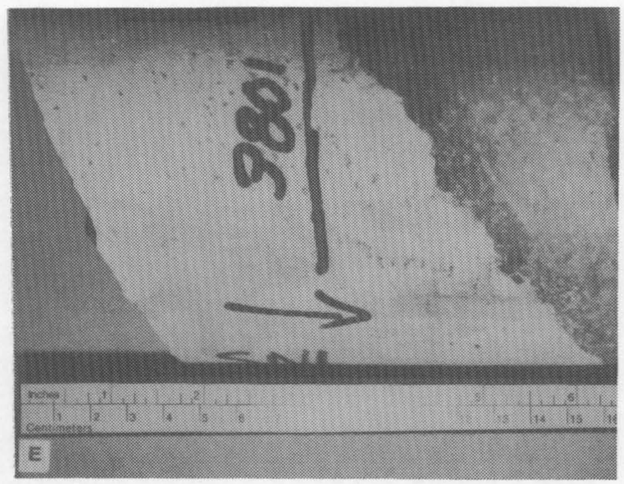

Figure 15. E: 3800.8-3801.2, Upper Contact of Halite Zone in the Castile at DOE-2 (contact is conformable to fine laminae in the anhydrite above; halite at the contact is uniform in grain size and forms a lineated shape fabric parallel to the dip of the contact).

or less thick and represents a major attenuation of halitic units in the Castile. The halite is generally clear and displays a distinct shape fabric as above. The lower contact of the halite dips parallel to the contact above, 20-30°. The laminae in the underlying anhydrite and lineation of the halite above are conformable to the contact (Figure 16, 3809 ft). The anhydrite below the contact correlates to Anhydrite I, complete with laminations with minor crenulations internal to the unit.

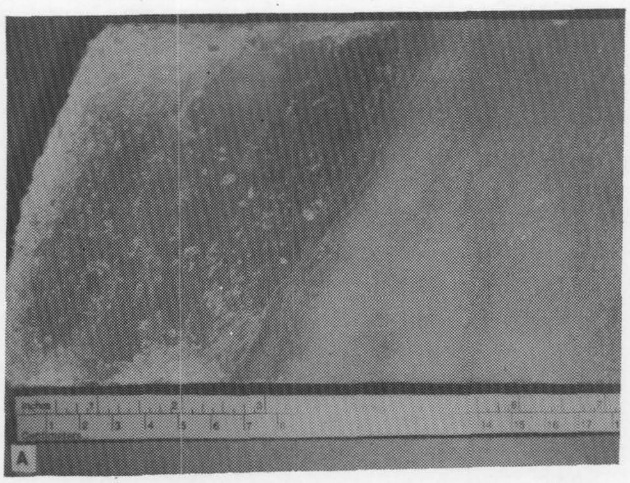

Figure 16. A: 3808.9-3809.6, Lower Contact of the Halite Zone in the Castile at DOE-2 (contact is again conformable to the fine laminae in the anhydrite below [probably Anhydrite I]; lineated shape fabric again has developed in the halite).

Scale and Timing of Deformation

An estimate of the amount of strain due to the formation of the DOE-2 structures can be made by tracing marker beds from adjacent boreholes. The strain can be approximated by calculating the change in radius of a bent beam while assuming a cyclindrical fold shape (Price, 1966). Calculations made for the Salado Castile contact and the top of Anhydrite II at DOE-2 indicated strains of 0.73 and 0.95, respectively. These strains are on the same order as strains determined at ERDA-6 (Anderson and Powers, 1978), but are greater than strains calculated at WIPP-12 (Borns et al., 1983). Borns (1983b) and Jackson and Talbot (1986) have calculated the strain rates for salt pillow growth as being between 10^{-14} and $10^{-15}s^{-1}$. At such rates, the development of the strains in the DOE-2 structures would require 2 to 30 ma.

The upper anhydrite unit of the Castile exhibits complex fold shapes and associated structures (e.g., sharp truncation of fold limbs and sharp changes in orientation at the fold hinge associated with beccia development). These observations raise the question of whether syndepositional processes were active during portions of the recorded deformation. This would follow the hypothesis of Snyder as stated in Borns et al. (1983). In contrast, the development of pull-apart structures with cross-fiber infillings within the Salado and Castile units at DOE-2 is evidence of a postdepositional deformation. Borns (1983a) discusses textures in portions of the Castile that are evidence of both syndepositional and postdepositional deformation within the same outcrop. Hence, with several stages of deformation evident, we must be careful not to place too much emphasis on single structures. Generally, the onset of deformation of the evaporite section in the Delaware Basin is assumed to be related to uplift of the Basin in the last 30 ma (Anderson, 1978; Borns et al., 1983). Borns (1985) pointed out that while the 30-ma uplift is a major event, other significant uplifts occurred during the Mesozoic and at the Cretaceous-Tertiary boundary. Each uplift may have triggered an episode of deformation.

DISCUSSION

The stratigraphy of units intersected by Borehole DOE-2 and the structures that developed within them confirm the structural depression indicated by earlier boreholes such as FC-92. In the Salado Formation, this depression is characterized by the downwarp of distinctive marker beds. Thickening of halitic units between marker beds increases downward, accompanying the downwarp. Within the Castile Formation, the stratigraphic and structural relationship are not distinct. The halite units of the Castile are markedly attenuated relative to other holes in the region. Anhydrite I appears to be intact, but the boundary between the upper anhydrites is indistinct. The remnants of Anhydrites III and II are thickened by tight folding and brought into direct contact with each other by deformation.

As mentioned in the introduction, dissolution and gravity-driven deformation are two possible causes of the structural depression at DOE-2. If it occurred at DOE-2 in the last million years, dissolution would be significant relative to the adjacent (2 mi) WIPP site. However, our results indicate it unlikely that the depression was formed by dissolution in the Salado. Dissolution is marked by the removal of salt, but the salt section of the Salado at DOE-2 is thickened. Near absence of halite in the Castile suggests that the dissolution hypothesis be examined. In Halite I and especially Halite II in nearby holes, there are numerous anhydrite stringers 1 cm to 1 m wide (Figure 17). These stringers occur at consistent stratigraphic positions within the halites. If dissolution of Halite II and I occurred, these stringers should remain within the horizon, but not necessarily intact. Examination of the core from DOE-2 has not shown relic stringers or remnants within the Castile.

The only evidence for dissolution is the thinned halite section, but thinning of a halite unit need not be due to dissolution. Halite can also be thinned by deformation. The cross-section of Salado and Castile stratigraphy (see Figure 4) from DOE-2 and adjacent holes shows that the Castile salt is anomalously thickened at Borehole WIPP-11, 1 mi north of DOE-2. Within this portion of the Delaware Basin, the Castile Formation deforms into a series of anti- and synclines (Borns et al., 1983). Salt flow accompanies such deformation. Thickening of salt at WIPP-11 will be accompanied by thinning elsewhere. In some cases, the area of removal is called a salt-removal basin or a peripheral sink (Seni and Jackson, 1983). The structure at DOE-2 may represent a salt removal basin (Figure 18). Salt flowage is consistent with the strongly lineated fabric exhibited by halite remaining at DOE-2. The elongation of the halite grains may represent the direction of flow.

In summary, we conclude that the structural depression intersected at DOE-2 formed in response to gravity-driven salt flow, as suggested by distribution of salt structures within adjacent holes and the distribution of structures within the Castile. Dissolution is not favored, due to the thickening of salt in the Salado and the apparent absence of residues or relics of insoluble portions of the Castile and Salado Formations within the thinned units.

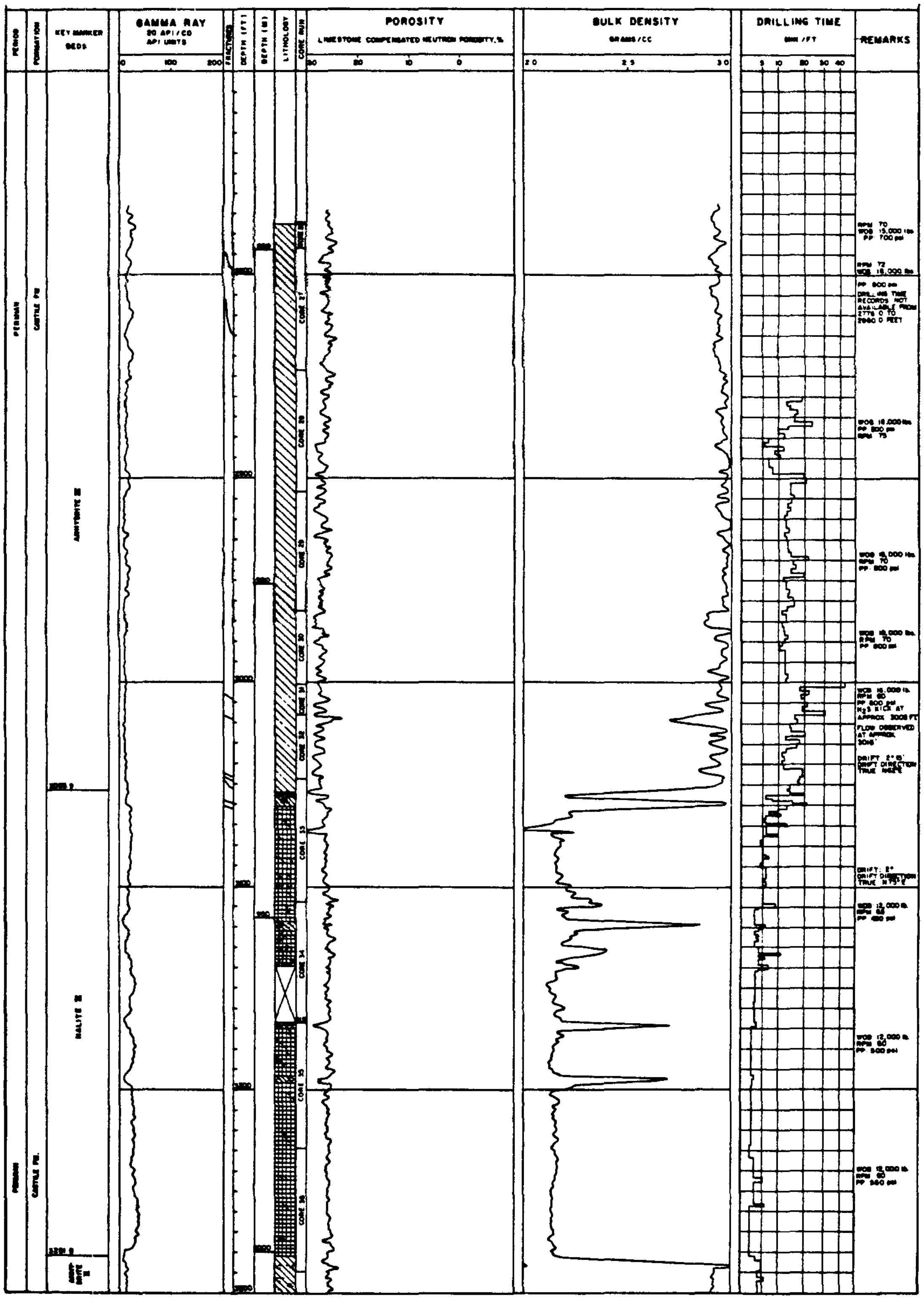

Figure 17. Geophysical Well Logs of the Upper Castile in Boreholes WIPP-12 and -13, Displaying the Set of Anhydrite Stringers Present in Halite Units.

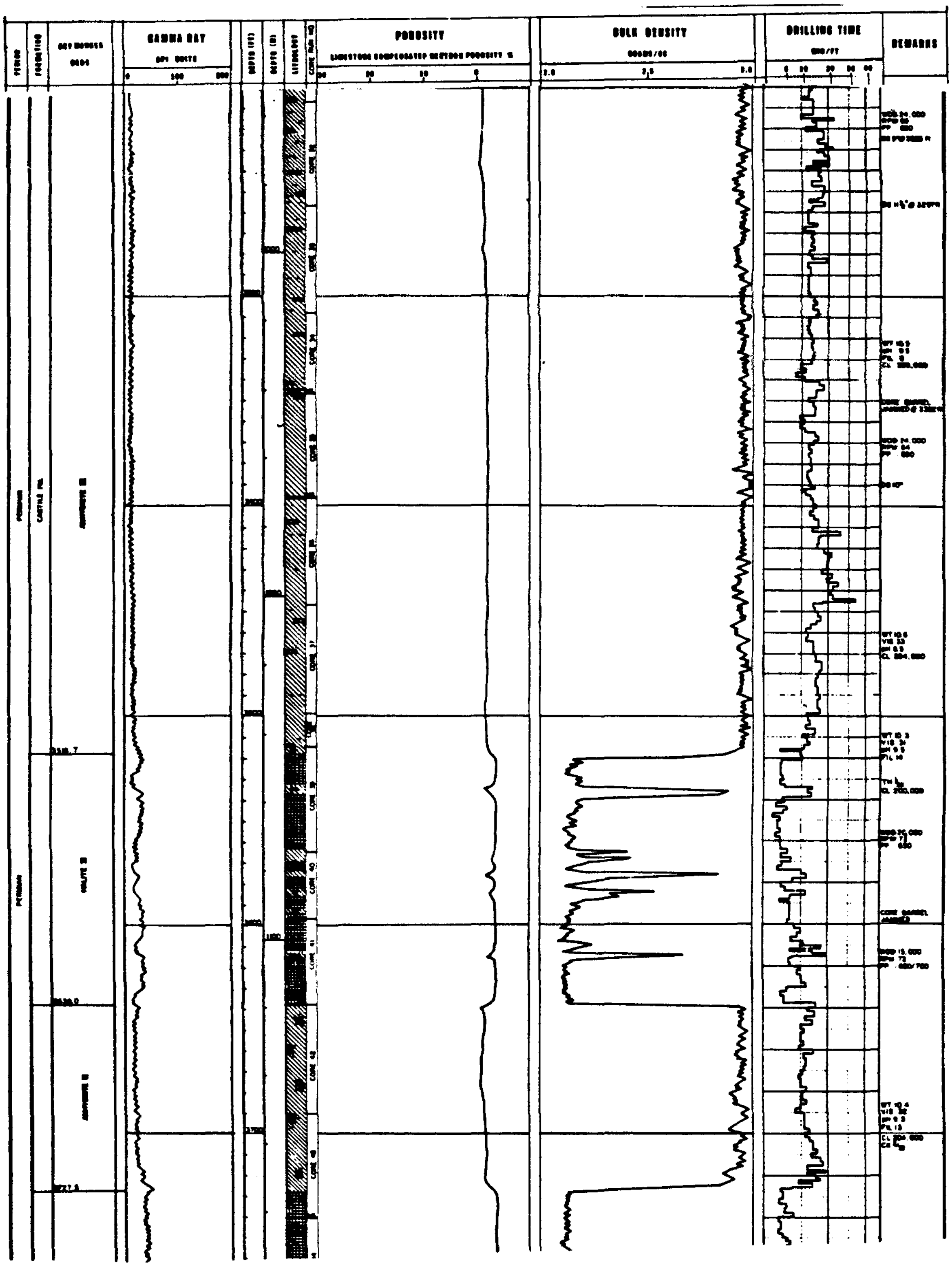

Figure 17 (Continued).

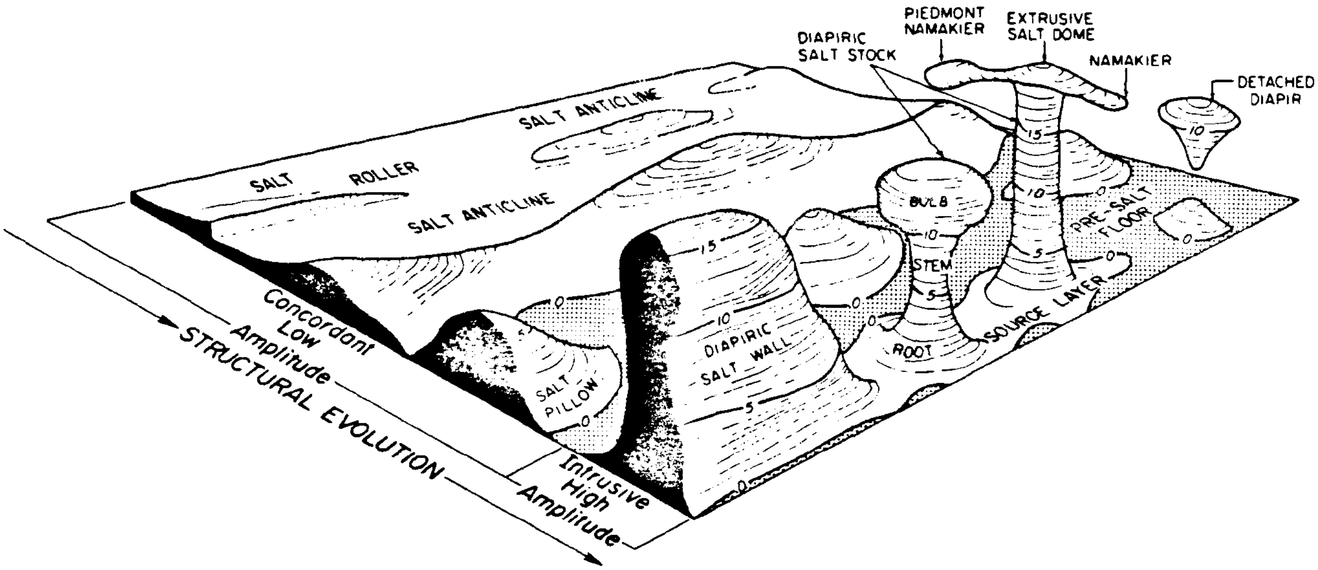

Figure 18. Salt Pillows, Salt Anticlines, and Peripheral Sinks (after Jackson and Talbot, 1986).

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