Title 40 CFR Part 191
Compliance Certification
Application
for the
Waste Isolation Pilot Plant

Appendix DEF

United States Department of Energy
Waste Isolation Pilot Plant

Carlsbad Area Office
Carlsbad, New Mexico

Deformation

CONTENTS

FIGURES

TABLES

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ACRONYMS

AEC	Atomic Energy Commission
DOE	U.S. Department of Energy
EEG	Environmental Evaluation Group
ERDA	U.S. Energy Research and Development Administration
MB	marker bed
OD	outer diameter
ORNL	Oak Ridge National Laboratory
SHS	salt-handling shaft
SNL	Sandia National Laboratories
SPIV	Site and Preliminary Design Validation
TD	total depth
WIPP	Waste Isolation Pilot Plant

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APPENDIX DEF

DEF.1 Introduction

The Salado Formation in which the Waste Isolation Pilot Plant (WIPP) is located is an evaporite unit comprised primarily of halite and anhydrite interbeds. The Castile Formation which underlies the Salado is also comprised of halite and anhydrite interbeds. Above the Salado, the Rustler Formation includes halitic mudstones, carbonate units, and anhydrite beds. Two processes are of concern in the assessment of a site in this type of geological environment: the rheological properties of halite allow it to deform at lower stresses than other rock types, and the solubility of halite and other evaporite minerals can lead to dissolution. Because of these concerns, the U.S. Department of Energy (DOE) has undertaken a site characterization program to assess the extent of any deformation in the region of the WIPP, and to determine the potential for dissolution to affect the performance of the disposal system.

This document describes the structural features of the Castile (Section DEF.2), the extent of dissolution in the region around the WIPP (Section DEF.3), and identifies the boreholes in the vicinity of the WIPP that have penetrated the Salado (Section DEF.4).

DEF.2 Gravity-Driven Structure in The Castile

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

DEF.2.1 Background Information

For a number of years, it has been known that parts of the Castile Formation are deformed. Cross-sections of the basin geology through its margins have shown some evidence of deformation. Jones et al. (1973) provided a map of the isopachs of part of the Castile that clearly show much thicker portions in some areas along the northwestern to northern Delaware Basin, just inside the margin of the Capitan Reef. Very little information had been collated concerning deformation within the Delaware Basin until studies were initiated of the Delaware Basin as a possible site for radioactive waste disposal. Jones et al. (1973) is probably the clearest early presentation of this information, though the dissertation by Snider (1966) and the paper by Anderson et al. (1972) also reflect thicker sections in some Castile units adjacent to the reef.

In 1975, Sandia National Laboratories (SNL) drilled a third borehole, called U.S. Energy Research and Development Administration (ERDA)-6, at a site (Figure DEF-1) that had been partially investigated by Oak Ridge National Laboratories (ORNL) during 1974. Two boreholes Atomic Energy Commission ((AEC)-7 and AEC-8) were drilled in 1974 by ORNL before SNL was assigned to carry out the task of investigating this site for radioactive waste disposal under programs that preceded WIPP. Formation boundaries and marker beds in ERDA-6 were structurally high compared to AEC-7 and 8, and the degree of deformation increased downward. At about 2,711-feet (826-meters) depth, ERDA-6 began to produce pressurized brine and gas. The hole was tested extensively to determine the nature and origin of the brine. Beds within the Castile were displaced structurally upward, apparently by hundreds of feet (Jones 1981; Anderson and Powers 1978), and some of the lower units may have actually pierced upper units (Anderson and Powers 1978). Because of the desire for structurally uncomplicated units to simplify mining for a repository, the site under investigation at ERDA-6 was abandoned in 1975, and in 1975-76 the current site was initially selected and investigations began (Powers et al. 1978). As part of the selection criteria, a zone about 6 miles (10 kilometers) wide inside the Capitan Reef was avoided because it included known deformed Castile and Salado (Griswold 1977). This is the first instance in which the site investigations were directly influenced by discovery of deformation in the Castile and lower Salado.

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

The first new drillhole within the area encompassed by the disturbed zone was WIPP-11, and it was located about 3 miles (5 kilometers) north of the center of the WIPP site. Long and Associates (1977) examined proprietary petroleum company data in 1976, and identified

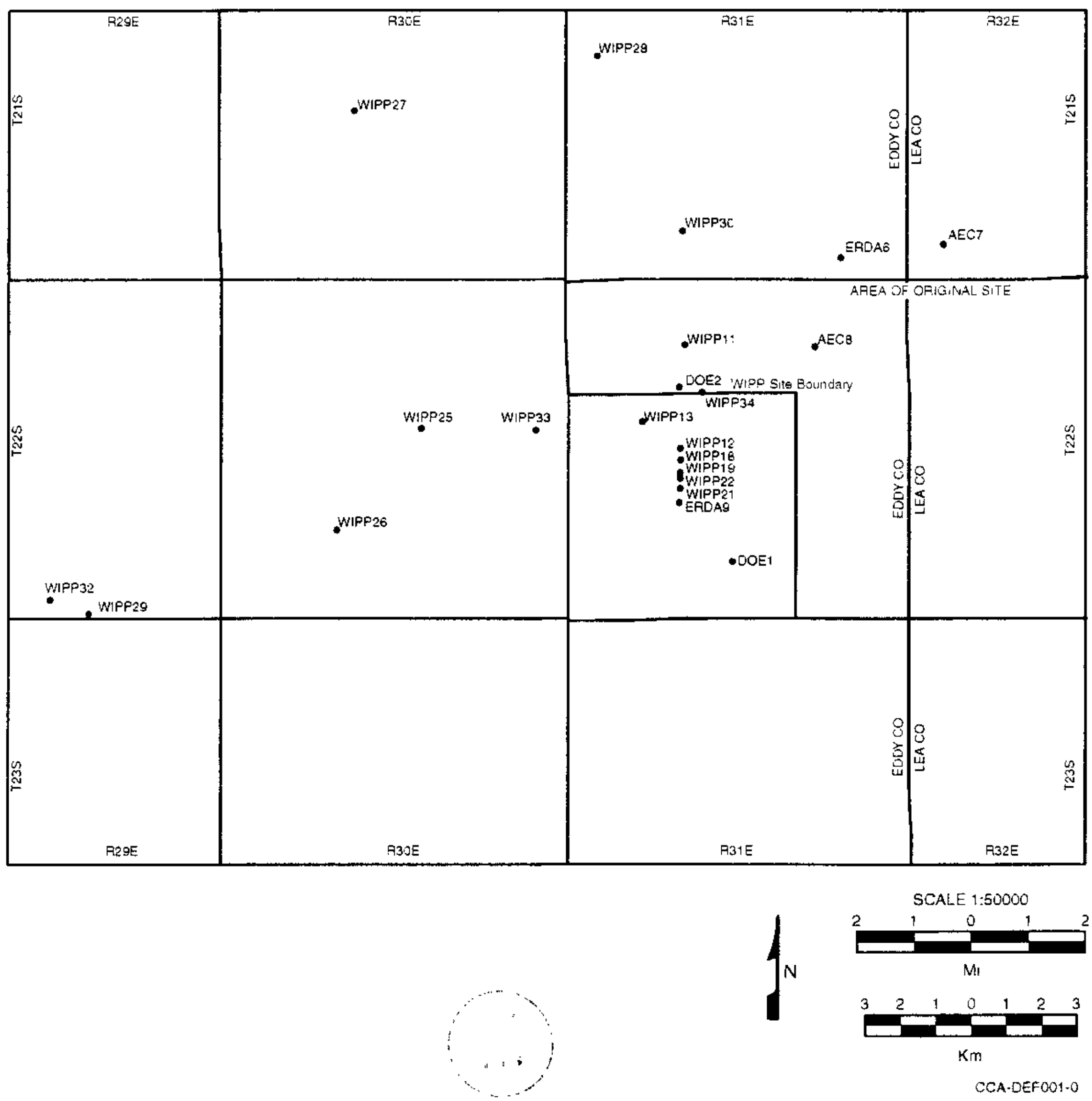

Figure DEF-1. Location of Main Stratigraphic Drillholes

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anomalous areas around the WIPP site, including the structural anomaly at the WIPP-11 location. Seismic reflection data acquired in 1977 indicated possible salt flowage within the Castile and a structure that could be similar to that at ERDA-6 (Sandia National Laboratories and U.S. Geological Survey 1979). WIPP-11 was drilled early in 1978, demonstrating the extensive deformation within the Castile and extending upward into the Salado. WIPP-11 did not encounter any brine or gas flows.

Seismic reflection data acquired in 1977 not only showed a zone of steepened dip of the Castile north of the site center, it also showed a possible fault offsetting parts of the Salado and Rustler Formations. A series of five boreholes was planned to provide detailed information on the structure of the Rustler/Salado contact. Four boreholes (WIPP 18, 19, 21, and 22) were required to demonstrate that there was no detectable offset on that contact in the area interpreted from 1977 seismic reflection data (Figure DEF-2). Later epochs (1978 and 1979) of seismic data in the same area, along with the drilling, continued to show generally poor resolution or uninterpretable data in the area of the disturbed zone. These studies generally showed that the acoustic velocity of the upper section changes laterally, complicating further the interpretation of the deeper Castile structure. Through the WIPP 18-22 drilling program, the upper Salado and Rustler were determined to be fundamentally undisturbed over the southern margin of the disturbed zone where the Castile appears to dip to the south (Sandia National Laboratories and U.S. Geological Survey 1979).

WIPP-12 was located approximately 1 mile (1.6 kilometers) north of the site center to test the amount the Castile was elevated (Figures DEF-1, DEF-2). It was drilled late in 1978 to the top of the Castile and detected approximately 160 feet (50 meters) of structural elevation compared to ERDA-9 and the center of the site (Sandia National Laboratories and D'Appolonia Consulting Engineers 1982c). The amount of disturbance of the Salado was not considered an impediment to underground development, though the underground storage facility was later reoriented from this northern area to an area south of the site center (see Section DEF.2.1). From drilling WIPP-12 and the WIPP 18-22 series, the southern margin of the disturbed zone was considered to be much more gentle in structure, while the seismic character and WIPP-11 indicated much more severe deformation of the Castile farther to the north.

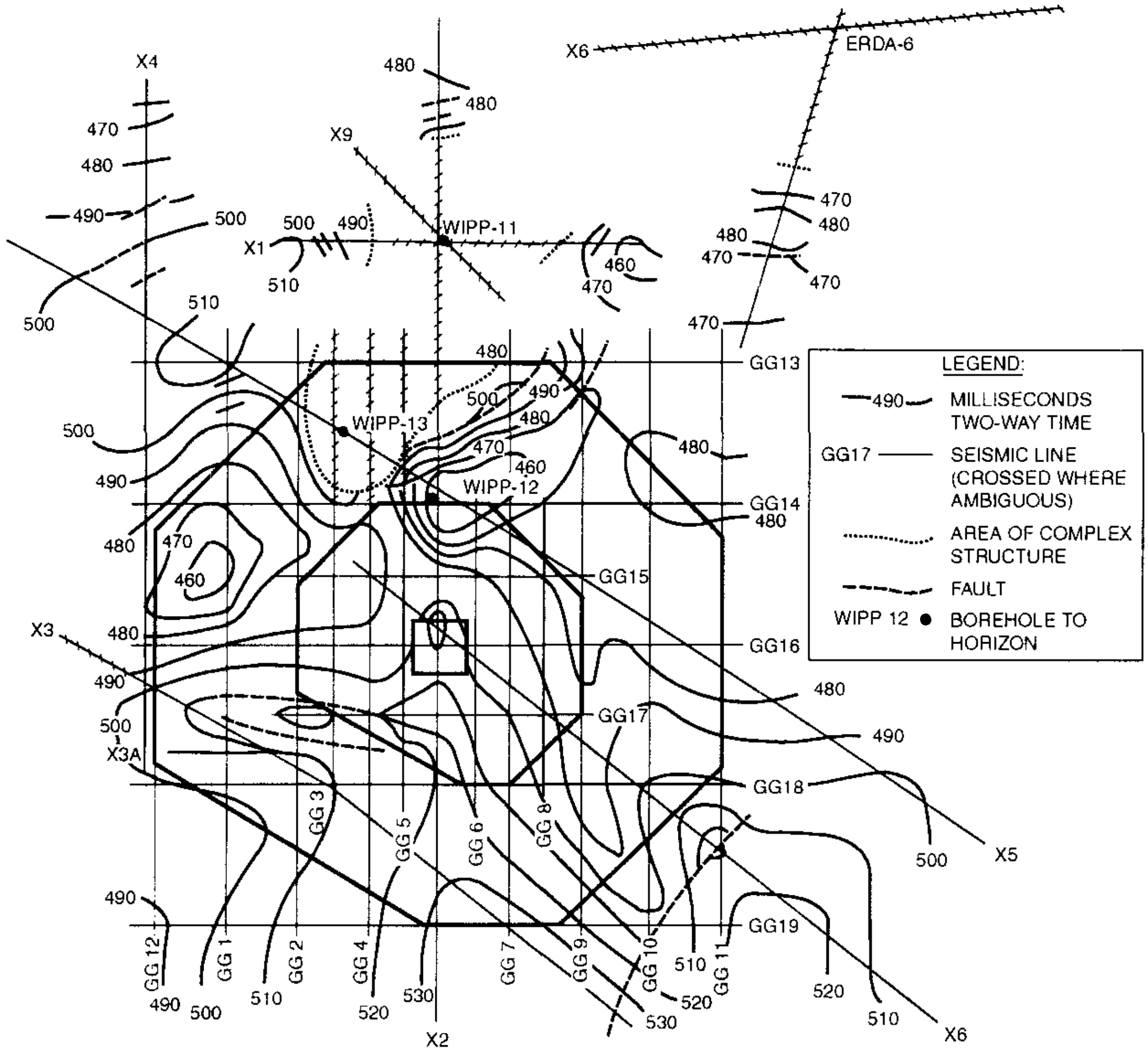
Two additional phases of seismic reflection data were acquired in 1978 and 1979. These data mainly concerned the immediate site area (about 4 square miles [10 square kilometers]) and the southern edge of the disturbed zone. They indicated much the same problems and margins associated with the disturbed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

A microgravity survey of the site area was conducted to determine if the structure within the disturbed zone could be partially resolved by that method (Barrows et al. 1983; Barrows and Fett 1985). The large differences in density of halite and anhydrite might cause detectable differences in the gravity field locally if the units were displaced and/or thickened relative to the surrounding areas. The microgravity survey covered an area of normal stratigraphy from south of the WIPP site center to the area of WIPP-11 (Figure DEF-3). As interpreted by Barrows et al. (1983), the microgravity does not resolve the larger scale deformation within the Castile Formation. Based on the interpretation of probable shallow disturbance of the gravity field, WIPP-14 and WIPP-34 were drilled about 2 miles (3 kilometers) north and about 0.5 mile (0.8 kilometer) east of the site center (Figure DEF-1). These boreholes encountered normal stratigraphy within the Rustler and upper Salado; Sandia National Laboratories and U.S. Geological Survey 1981) with some slight structural depression made apparent mainly by the deformation northeast of this area around ERDA-6 (Holt and Powers 1988). Barrows et al. (1983) attributed the gravity anomaly around WIPP-14 to decreased density within parts of the Rustler Formation, mainly from the difference in density due to anhydrite versus gypsum in WIPP-14. The overall difference in mass was attributed to karst processes by Barrows et al. (1983), rather than to deformation of any of the units associated with the disturbed zone.

During the mapping of the first shaft drilled at the WIPP site Salt Handling Shaft (SHS), Marker Bed (MB)139 was observed to have a few inches of relief on the basal contact and 2 to 3 feet (0.6 to 0.9 meter) of relief on the upper surface. Jarolimek et al. (1983) interpreted the internal structure on these high points of MB139 as showing a radial structure due apparently to gypsum growth textures and subsequent crushing, indicating a fundamentally depositional origin to the relief, rather than any structural disturbance related to the disturbed zone. Borns (1985) conducted an investigation of additional cores and holes drilled through MB139, because EEG was concerned that the apparent structure was related to the disturbed zone. Borns (1985) also concluded that the relief was not due to structural deformation, but mainly to erosion processes that carved part of the relief found on the top of the marker bed. From either point of view, the difference in relief on the upper and basal contacts of MB139, in such a thin unit, were convincing evidence that a form of tectonic deformation was not involved.

In late 1981, WIPP-12 was deepened to test for the possible presence of brine and/or pressurized gas within the structure in the Castile Formation (D'Appolonia Consulting Engineers, Inc. 1982). The probability of producing brine and/or gas from WIPP-12 was considered reasonably low at the time, because most known pressurized brine and/or gas was associated with much more deformed units than the Castile at WIPP-12. Fractured anhydrite in the upper Castile did begin to yield pressurized brine and gas when intercepted late in 1981, and WIPP-12 and ERDA-6 were further tested. Later geophysical work (Earth Technology Corporation 1987) suggests that the brine may underlie part of the WIPP facility, beyond the area usually included in the disturbed zone.

Though the DOE and EEG agreed that neither brine nor structure constituted a threat to health and safety, the proposed underground facilities were reoriented south of the site center, avoiding longer haulage and the slight structure encountered at the facility horizon (see



NOTES:

1. CONTOUR INTERVAL 10 MILLISECONDS. DATUM 3350 FEET ABOVE SEA LEVEL.
2. CONTOUR INTERVAL IN FEET WOULD BE APPROXIMATELY 75 FEET BASED ON AN AVERAGE SEISMIC VELOCITY OF 7620 FT./SEC. AVERAGED OVER THE ENTIRE STRATIGRAPHIC INTERVAL FROM GROUND SURFACE TO THE MIDDLE OF THE CASTILE FORMATION.

Figure DEF-2. Seismic Time Structure Middle Castile Formation

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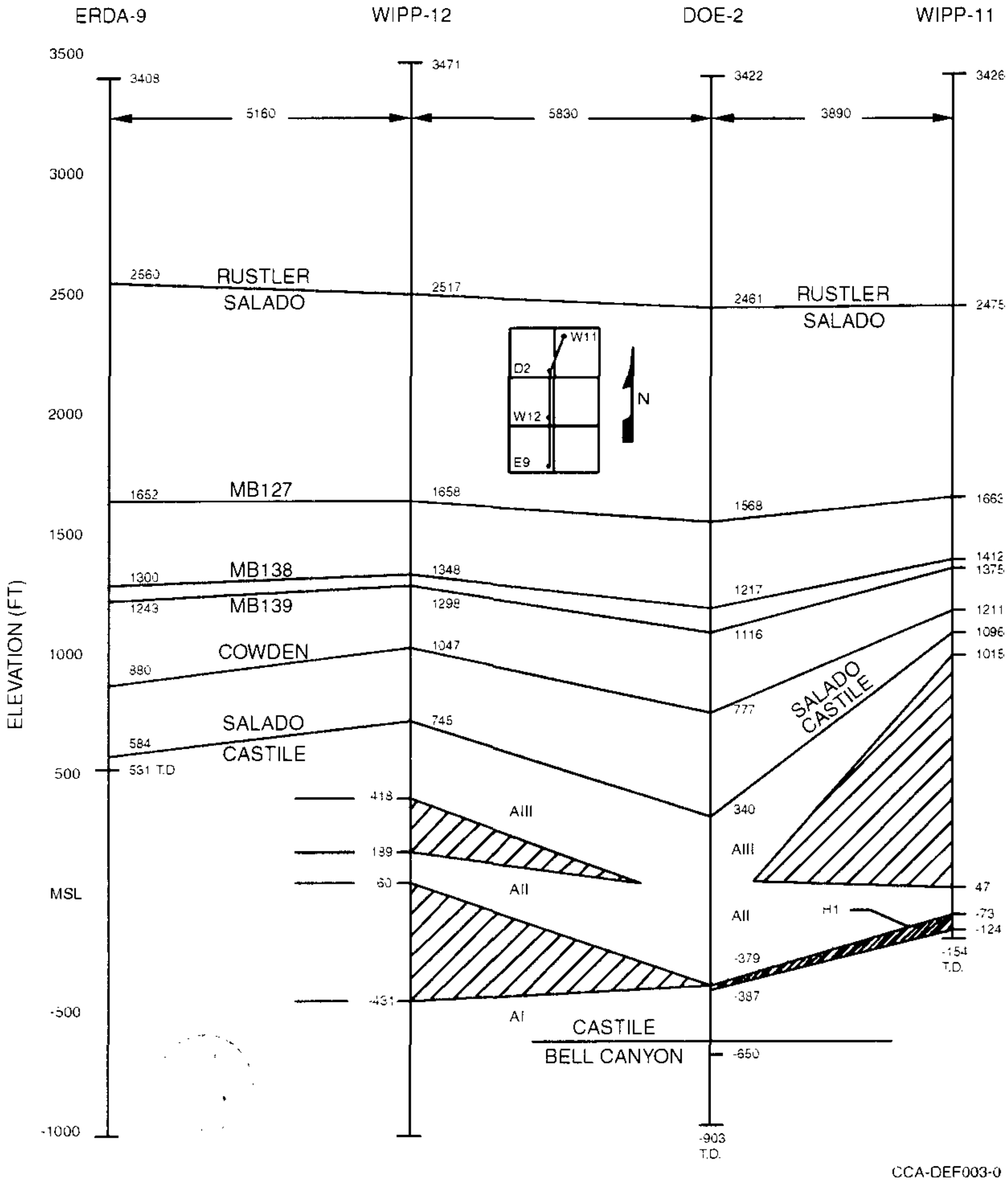

Figure DEF-3. Fence Diagram Using DOE-2 and Adjacent Holes

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Section DEF.2.1). As a consequence of the deepening and testing of WIPP-12, the link between structure and pressurized brine and gas was strengthened.

The last direct investigation of the disturbed zone was a by-product of another investigation. DOE-2 was drilled approximately 2 miles (3 kilometers) north of the center of the WIPP site to investigate the origin of a modest depression on MB124 (Griswold 1977; Powers et al. 1978) that was detected in a corehole drilled by a potash company. DOE-2 was principally a test of the hypothesis that the depression was caused by ductile flow of halite in response to deep dissolution of halite by water from the Bell Canyon Formation (Mercer et al. 1987).

Halite layers in the lower Salado were thicker than usual, indicating that part of the sequence had not been dissolved, and the Castile was very deformed. The Castile stratigraphy was not normal; the second halite was apparently squeezed out of the area during deformation. The stratigraphy in DOE-2 is apparently the result of processes that caused the disturbed zone and is not the result of any dissolution (Borns 1987; Mercer et al. 1987).

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

DEF.2.2 Specific Features of the Disturbed Zone

The first specific feature of the disturbed zone is its boundary. In Section DEF.2.1, the different concepts of the boundary depended on ideas of where the Castile began to change and steepen dip (about 0.5 mile (0.8 kilometer) north of the site center, or where the various epochs of seismic data became unreliable to uninterpretable). Borns et al. (1983) present one diagram (Figure DEF-2) of the seismic time structure for the top of the Castile Formation that illustrates the variously defined boundaries as well as any diagram. The principal part of the disturbed zone is defined by a lobate area (Figure DEF-2) shown as an area of complex structure where the seismic data are considered ambiguous. The structurally-deformed area clearly includes an area about halfway between boreholes WIPP-12 and ERDA-9, as well as a larger area to the northeast. The two-way travel time contoured on the map is a function of depth; as the reflector is nearer the surface, the travel time to the reflector and back to the surface decreases. Thus, the areas enclosed with contours of smaller values should be structurally higher. (The top of Castile in WIPP-12 was 160 feet [50 meters] higher than it is in ERDA-9). The map was not directly converted to depth because the seismic reflection and borehole geophysical logging programs demonstrate clearly that there are also lateral velocity variations within the upper part of the rock section, especially within the Rustler and Dewey Lake Formations. These velocity variations cannot be adequately extracted from the travel times to permit converting the travel time to depth. Nonetheless, the map demonstrates the general best information about the extent of the disturbed zone. The central and southern part of the WIPP site area displays relatively uniform seismic travel time structure and nothing within the geological data contradicts that information to date.

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

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

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

Structure contour and isopach maps of the Salado and Rustler over areas of complicated Castile structure also show that the overlying units are successively less involved in the structure (for example, Section 7.2; Borns and Shaffer 1985; Borns et al. 1983; Holt and Powers 1988). Lower units that are thicker and deformed are overlain by units that are thinner and less structurally involved in the deformation. Under normal geological circumstances, for example, dealing with a rock sequence of carbonates or siliciclastics, the deformation would be considered completed by the time of deposition of the lowermost undeformed rock unit. Here, within a much more plastic set of rocks, the same geological reasoning is of less value, as the rocks may compensate laterally for late deformation effects and produce the same results as seen here.

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

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

DEF.2.3 Hypotheses of Formation of Deformation in Castile

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

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

Halite could potentially be removed from the evaporite section by dissolution and change the form of the evaporites. The density structure could be changed by removing salt near the surface, causing collapse and fill with sediment that is more dense than the removed salt (Anderson and Powers 1978). Borns et al. (1983) reviewed some of the evidence that evaporites were deformed near surficial sinks and concluded that there was certainly some association, but that the pattern of deformation did not match the shallow dissolution. If salt is dissolved from the lower Salado or Castile, then overlying beds should deform in response to the removal of mass. DOE-2 was drilled to test that hypothesis. Recrystallized halite has been offered as evidence of the passage of fluids, but there appears to be no unique relationship between recrystallized halite and deformation. In addition, certain halite sections appear much overthickened, which is clearly not directly due to halite removal. These features generally indicate that the halite can be squeezed and will move laterally. The fact that the Rustler shows no discernible overall structural lowering over the disturbed zone (Holt and Powers 1988) suggests that dissolution of the lower Salado or Castile is not the origin of the deformation. The one area in which the Rustler is structurally affected is around ERDA-6, and there it is warped upward as noted by Jones (1981). Borns et al. (1983) do not believe that the Bell Canyon has been a source for brines in the Castile because of the chemistry (Lambert 1978, 1983) and the small volume.

Gravity sliding in the Delaware Basin could be driven by two physical situations: the general eastward dip, and the dip off the Capitan Reef and forereef into the basin. In contrast to the gravity foundering mechanism, where movement is dominantly vertical, gravity would result in sliding blocks moving mainly laterally as well as downslope in this mechanism. Some of the deformation is adjacent to the reef (Jones et al. 1973), lending some substance to the hypothesis that the reef-forereef slope and facies changes could cause such sliding. Some deformation is in somewhat isolated portions of the basin (for example, Poker Lake; Anderson and Powers 1978; Borns and Shaffer 1985), and these structures were originally interpreted to align along the strike of the basin (Anderson and Powers 1978). Borns and Shaffer (1985) conclude that the data do not uniquely support that interpretation, and these structures may or may not support the concept of gravity sliding within the basin. Borns et al. (1983) also concluded that the timing of the various structures is an important factor in evaluating this hypothesis. As discussed above, neither the age of the various structures, nor the timing of the basin tilt, is well constrained. If tilting of the basin is an important event in forming these structures, the various macro- to microstructures should probably be consistently related. As in gravity foundering, much of the basin area has not reacted to what appears to be widespread similar stresses. Special circumstances, such as an anomalous distribution of water, may be necessary to overcome a threshold for deformation to occur.

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

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

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

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

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

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

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

DEF.2.4 Timing of Deformation

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

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

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

DEF.2.5 Importance to the WIPP

The structures interpreted from core retrieved from WIPP-12 and ERDA-6 serve as possible analogs to effects of deformation on the WIPP. The DOE and EEG have analyzed the effects of brine and structure at WIPP-12 and the southern portion of the site and concluded the geologic conditions represent no threat to health and safety (see Section DEF.2.1). In addition, both boreholes encountered brine only within the anhydrite units, and that is the experience of all other encounters of these larger brine inflows (Popielak et al. 1983).

Anhydrite supports the fractures that provide porosity for the brine, and the anhydrite/halite units form an effective seal, as the pressurized brines and gas did not escape upward. The principal concern for isolation would be that the deformation, and its associated phenomena, such as pressurized brine and gas, could cause breaching of the repository and provide or make a pathway for the escape of the waste constituents. The period of time expected for development of the structure (700,000 years) is well beyond periods of regulatory concern. In addition, the evidence of the pressurized brine and gas occurrences is that they are confined to these Castile anhydrite layers and do not breach the lower Salado to reach the stratigraphic level of the repository. There is nothing at present to indicate that these features will form in the time period of concern or that they can directly cause a breach of the repository.

DEF.3 Dissolution

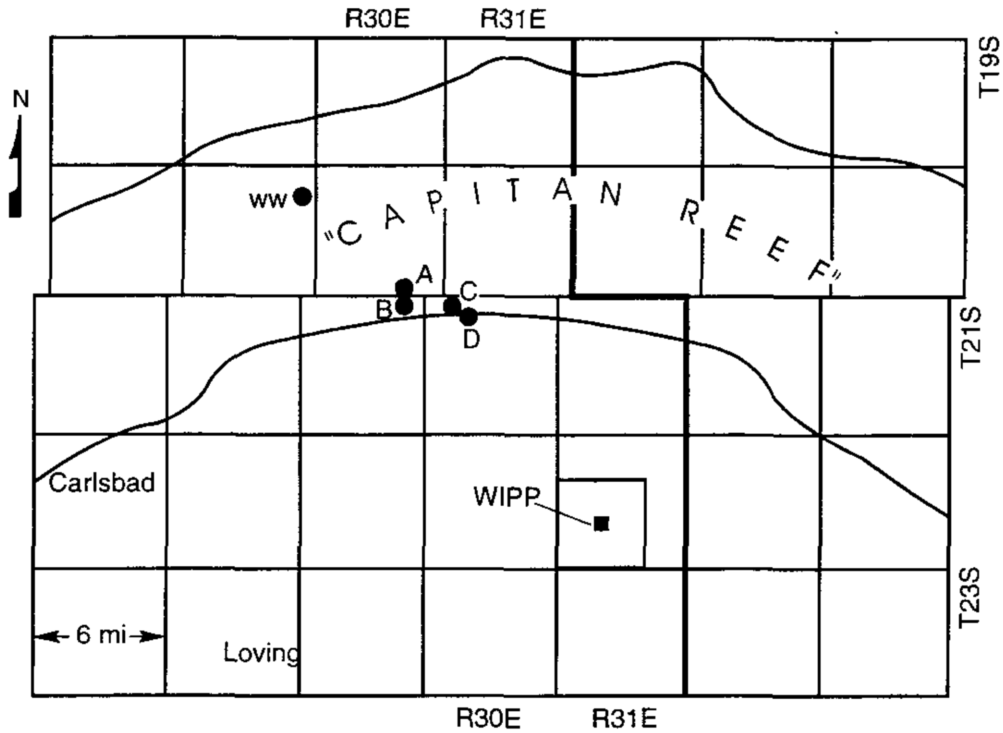
The Permian rocks of the Delaware Basin in which the WIPP is located are dominated by evaporites, and there is a potential for dissolution to change the properties of these rocks. Dissolution will initially enhance porosities, but continued dissolution may lead to compaction of the affected units with a consequent reduction in porosity. Compaction may result in fracturing of overlying brittle units and increased permeability. Extensive dissolution may create cavities and result in the collapse of overlying units. Dissolution has taken place at several stratigraphic levels in the Permian rocks, and has occurred over several periods between deposition and the present-day.

This section describes dissolution features in the region of the WIPP and in other areas of the Delaware Basin. Three broad styles of dissolution have been identified: **deep dissolution,** taking place in the Castile and the base of the Salado; **lateral dissolution**, involving dissolution at the top of the Salado and within the Rustler; and **shallow dissolution**, involving percolation of groundwater and mineral dissolution in the Rustler and overlying units. The known extent of each dissolution style is described, together with an assessment of possible future development and potential impact on the WIPP. A brief history of the investigations undertaken prior to and as part of the WIPP site characterization program is also presented.

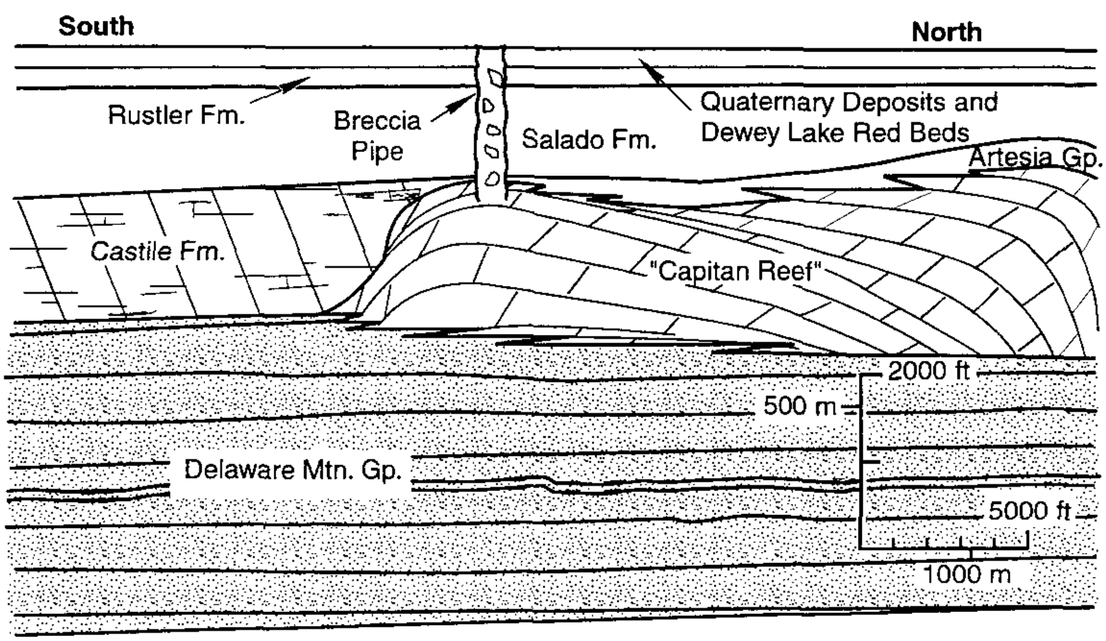
DEF.3.1 Deep Dissolution

Several domal surface features (Hills A-D) are present at the northern end of Nash Draw (Figure DEF-4). These were mapped during investigations for Project Gnome, but were not identified as deep-seated structures at that time (Vine 1960). As part of the early investigations of southeastern New Mexico as a potential site for radioactive waste disposal, geophysical studies were undertaken to test the theory that these domes resulted from salt diapirism. Magnetic studies were not conclusive, but gravity surveys suggested that salt diapirism was unlikely to be the cause (Gera 1974). As a result, Gera interpreted the domes to be the result of shallow dissolution processes.

At the time of the early investigations, potash mining near the northern end of Nash Draw had not encountered any disturbed regions in the Salado. In 1975, however, continued mining



Generalized Location Map



Generalized Cross Section

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Figure DEF-4. Location and Generalized Cross-Section of Localized Deep Dissolution Features

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intersected disrupted beds beneath Hill C, and the domal features were recognized as the surface expression of breccia pipes that affected the Salado.

Although these breccia pipes were some distance from the potential disposal site, there was concern that unidentified pipes elsewhere in the Delaware Basin could pose a threat to a repository. A series of geophysical investigations of the features known to be related to pipes was therefore undertaken to establish a reconnaissance tool for use in other areas. Seismic, electrical, and gravity methods were considered, of which electrical, and specifically resistivity, proved to be most effective in providing consistent indicators over breccia pipes (Elliot, 1976). Based on these results, a large resistivity field program was undertaken in 1977 over an area of about 37 square miles around the WIPP, with a resolution sufficient to identify features similar in size to Hills A-D (Elliot 1977a,b).

The resistivity survey identified an anomaly in Section 17, T.22S., R.31E., with characteristics and an apparent size similar to those of the known breccia pipes. This anomaly was investigated by drilling WIPP 13 in 1978, but no breccia was encountered in this borehole. Mapping of surficial features, conducted during 1978 and 1979, identified an area characterized by unusually thick fill and internal drainage in Section 13, T.22S., R.30E. This area was also characterized by low resistivity, although not by the type of localized anomaly associated with known breccia pipes. WIPP-33, drilled in 1979, showed recognizable marker beds within the upper Salado below this feature, confirming the absence of a breccia pipe. WIPP-32 was also drilled in 1979, in Section 33, T.22S., R.29E., to investigate a possible breccia pipe, but did not encounter displaced or brecciated horizons in the Rustler or Salado.

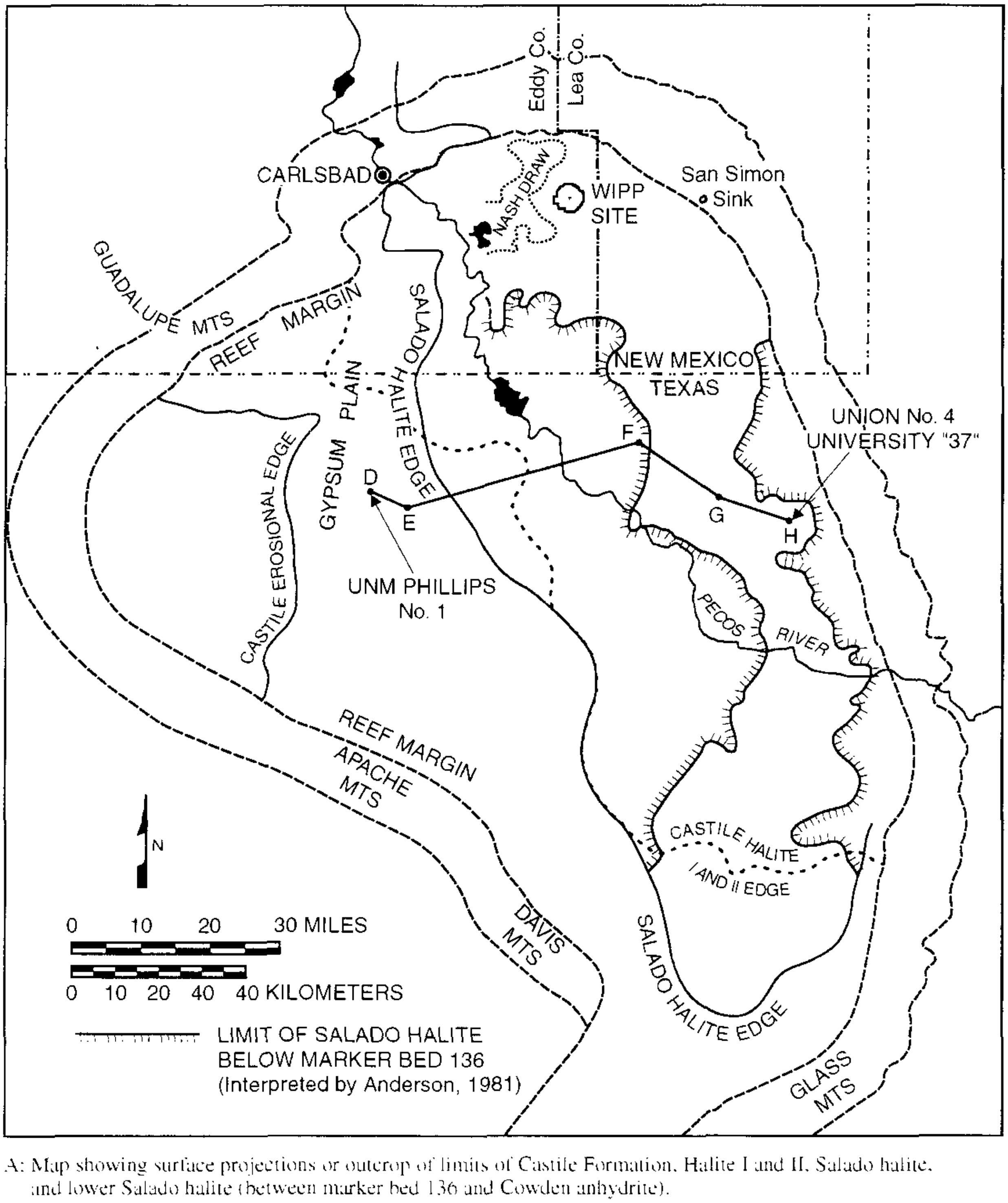
In parallel to the field studies investigating anomalies, studies of known breccia pipes were undertaken to help develop an understanding of the mechanisms leading to their formation. This work included the drilling of WIPP-31 at Hill A in 1978, and drilling WIPP-16 at Hill C and deepening WIPP-31 in 1980. As expected, these two boreholes encountered brecciated and displaced rocks in the Rustler and Salado.

As a contribution to the Geological Characterization Report (Powers et al. 1978), Anderson summarized the then available information on dissolution in the Delaware Basin (Anderson 1978), and described a generalized theory for deep dissolution developed from work in Texas and other areas of New Mexico as well as the Delaware Basin. This hypothesis included the concept of brine density flow which allows upward flow of water through an overlying fractured unit, dissolution of evaporites, and subsequent downward flow of the ensuing, more dense brine. Overlying rocks may then collapse into the resulting solution cavity. Anderson postulated that this type of localized deep dissolution had resulted not only in the features at Hills A-D but also other domes, mounds and depressions in the area. He considered that dissolution at depth on a regional scale had removed significant volumes of halite from the Salado and Castile during the Cenozoic in areas along the western and eastern boundaries of these formations (Figure DEF-5).

Surface mapping of features in the region of the WIPP, and the subsequent drilling of WIPP-16, WIPP-31, WIPP-32, and WIPP-33 led Bachman (1980) and Snyder and Gard (1982) to differentiate between surficial features formed by deep collapse and those formed by shallow dissolution (karst). Bachman supported Anderson's theory of brine density flow, and Snyder and Gard showed that the breccia pipes were related to deep-seated collapse within the Capitan Reef limestones around the northern boundary of the Delaware Basin (Figure DEF-4). There are no known breccia pipes which are not underlain by the Capitan Limestone. The breccia pipes have a positive relief because the cemented breccia is resistant to erosion, and lateral dissolution in Nash Draw has resulted in a lowering of the surrounding beds. San Simon Swale and the enclosed San Simon Sink are features with a negative relief that are also related to collapse within the Capitan Reef limestones, with subsidence occurring as recently as 1927.

Breccia pipes can form above the Capitan Limestone because the hydraulic conductivity of this unit is sufficient to allow significant groundwater flow and transport of dissolved material, thereby allowing the formation of solution cavities. Away from the reef, hydraulic conductivities in other units, such as the Castile anhydrites and the Bell Canyon, have been interpreted by some as too low to allow transport of any brines formed by dissolution (Lambert, 1983; Mercer 1983). However, in a review of the hydrogeology of the Bell Canyon, Davies (1983) calculated that hydraulic conductivities in sandstone channels are sufficient to allow regional groundwater flow and transport of brines from this unit into the Capitan Limestone. Brine density flow through fractures above the Bell Canyon could therefore lead to localized deep dissolution in areas of the Delaware Basin not underlain by the Capitan Reef. If such dissolution took place rapidly then brittle failure of overlying units would be expected, but if dissolution were slow then ductile behavior rather than collapse and brecciation could occur. Davies (1984) identified an area about 2 miles north of WIPP where structural depressions in the Salado suggested slow removal of salt at depth. Borehole DOE-2 was drilled in 1984 to study this feature. Beds in the lower Salado and Castile were found to differ in thickness from the equivalent beds in nearby boreholes: these variations were interpreted to result from deformation rather than dissolution (Borns 1987). Thus there is no unequivocal information that supports the possibility of localized deep dissolution occurring anywhere other than at the edges of the Capitan Reef.

Lambert (1983) examined Anderson's hypothesis that deep dissolution during the Cenozoic has removed as much as 50 percent of the original volume of halite in the western part of the Delaware Basin (Anderson 1978). This hypothesis is based on a correlation between widely spaced boreholes and between cores and wireline logs, and also on the assumption that all the halite units were of uniform thickness across the Delaware Basin at the time of deposition. Lambert called into question the correlations used by Anderson to infer dissolution, and also noted that the present-day, nonuniform thickness of halite beds could well arise from nonuniform deposition of halite, or from removal of halite by subaerial dissolution or erosion soon after deposition. Either of these mechanisms would result in missing halite interbeds among the anhydrite interbeds of the lower Salado.



A: Map showing surface projections or outcrop of limits of Castile Formation, Halite I and II, Salado halite, and lower Salado halite (between marker bed 136 and Cowden anhydrite).

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Figure DEF-5. Distribution of Regional Deep Dissolution in Ochoan Evaporites Interpreted by Anderson (1978)

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Bachman (1980) described the Castile as a series of interfingering, discontinuous beds of halite and anhydrite that were deposited in individual pans within the Castile basin. Furthermore, geochemical evidence suggests (Adams 1969) that the halite beds may have formed during periodic influxes of brines derived from preexisting evaporites, rather than simply from evaporation of seawater. In such a basin, the distribution and thickness of the halite interbeds would be independent of the anhydrite formed from seawater, and there would be a tendency for halite beds to thin towards the margins. Anderson (1978) cited the presence of anhydrite breccias near the basin margin as evidence of later dissolution. Lambert (1983) noted that this type of breccia could also arise from syndepositional slumping along basin margins, leading to anhydrite mounds and consequent thinning of any overlying halites. ERDA-10 was drilled south of the WIPP in an area where Anderson's hypothesis would indicate that significant amounts of halite have been dissolved in the Cenozoic, with consequent collapse and brecciation of the anhydrite units. The absence of an intraformational breccia in ERDA-10 suggests, however, that any dissolution must have taken place relatively soon after deposition.

In summary, Anderson based his conclusions on the significance of regional deep dissolution on the existence of dissolution wedges along the margins of the Salado and Castile. More recent interpretations have questioned the basis for the identification of these wedges and therefore the significance to the WIPP of regional deep dissolution. Localized deep dissolution and collapse features are only known to be present along the margin of the Delaware Basin above the Capitan Reef. Theoretical considerations indicate that localized deep dissolution could occur away from the margin, but extensive geophysical surveys, field mapping, and drilling in the vicinity of the WIPP have failed to confirm that breccia pipes or slow dissolution pose a threat to the WIPP.

DEF.3.2 Lateral Dissolution

Dissolution of the upper Salado and Rustler has been recognized since the earliest studies in the Delaware Basin, and the extent of this dissolution in the region of the WIPP has been a focus for mapping and drilling programs since 1970 because of the influence that dissolution can have on hydrogeological properties. Near-surface dissolution processes, particularly the development of karst, are discussed in the following section. This section describes dissolution resulting from groundwater flow within the affected units. This is termed lateral dissolution because it can lead to lateral variations in porosity and permeability. It is equivalent in large part to the stratabound dissolution described by Lambert (1983).

Eastward tilting of the Delaware Basin during the Tertiary has exposed the Salado and Rustler in the western part of the basin, and infiltration of groundwaters during the Cenozoic has led to dissolution at various horizons in these formations. Nash Draw, some 5 miles (8 kilometers) to the west of the WIPP site, is the most prominent result of such lateral dissolution in the region, formed by collapse of the overlying Rustler where halite has been dissolved at the top of the Salado. Shallow dissolution within the disrupted units of the

Rustler has led to further development of this feature. Lateral dissolution of the Salado has also taken place to the west of Nash Draw.

The extent of dissolution at the top of the Salado was established by a series of boreholes drilled in 1978 (WIPP-25 to WIPP-30). Each borehole was drilled to a recognizable stratigraphic horizon within the upper Salado; in the eastern part of Nash Draw a complete Salado succession below MB103 is present, whereas to the west the succession is complete below the Vaca Triste bed (near MB116). The dissolved units are now represented by an unstructured solution residue comprising gypsum, clay, and sand up to 100 feet (33 meters) thick at WIPP-29. This residue has yielded brine in a number of boreholes and has been termed the brine aquifer. The eastern limit of lateral dissolution in the Salado is to the east of Livingston Ridge, with boreholes drilled close to the WIPP showing a complete stratigraphic section without a solution residue.

A tributary of the Pecos River flowed across the area of Nash Draw in Gatuña times (Figure DEF-6), depositing beds of gravel, which are now exposed on both sides of Nash Draw up to 200 feet (67 meters) above the floor. These gravels are dated at about 0.6 million years from included volcanic glass. The Mescalero caliche, dated at 420,000 to 570,000 years old from included ash layers, is present in collapse blocks along the eastern edge of Nash Draw, indicating some growth of Nash Draw in the late Pleistocene. Bachman (1974) provided initial estimates of dissolution rates at the top of the Salado based on the assumption that all dissolution occurred during the Quaternary. However, it is now recognized that some dissolution was pre-Cenozoic, and thus lateral dissolution has taken place at a slower rate (Bachman 1980; Szabo et al. 1980; Lambert 1983). In any event, the calculated rates are too slow for lateral dissolution to reach the controlled area during the period of regulatory concern.

In the vicinity of Nash Draw, halite is absent from all the units of the Rustler. Further east, towards the WIPP site, halite progressively appears in younger units. This has led many investigators to conclude that halite has been dissolved from the Rustler by groundwater in a process akin to lateral dissolution at the top of the Salado (see, for example, Lambert 1983, Bachman 1984, and Lowenstein 1987). However, a detailed hydrogeological model to explain the cross-stratal distribution has not been formulated.

An alternative interpretation of the distribution of halite within the Rustler was presented by Holt and Powers (1988) following detailed mapping of the Rustler exposed in the WIPP ventilation and exhaust shafts in 1984. Fossils, sedimentological features, and bedding relationships were identified in units that had previously been interpreted from boreholes as dissolution residues. Cores from existing boreholes, outcrops, geophysical logs and petrographic data were also reexamined to establish facies variability across the area. As a result of these studies, the Rustler was interpreted to have formed in variable depositional environments, including lagoon and saline playas, with two major episodes of marine flooding to produce the carbonate units. Sedimentary structures were interpreted to indicate synsedimentary dissolution of halite from halitic mudstones around a saline playa and fluvial

System	Series	Group	Formation	Member
Recent	Recent		Surficial Deposits	
Quaternary	Pleistocene		Mescalero Caliche	
			Gatuña	
Tertiary	Mid-Pliocene		Ogallala	
Triassic		Dockum	Santa Rosa	
Permian	Ochoan		Dewey Lake	
			Rustler	Forty-niner
				Magenta Dolomite
				Tamarisk
				Culebra Dolomite
				lower
			Salado	upper
				McNutt Potash
				lower
			Castile	
	Guadalupian	Delaware Mountain	Bell Canyon	
			Cherry Canyon	
			Brushy Canyon	

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Figure DEF-6. Site Geologic Column

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transport of more distal clastic sediments. The halite in the Rustler, by this interpretation, has a distribution similar to that at the time the unit was deposited; some localized, marginal solution of halite may have occurred, but not over large areas.

The reanalysis of the Rustler by Holt and Powers (1988) has not led to significant changes in the interpreted distribution of halite in the Rustler in the region of the WIPP. This reinterpretation does not therefore influence the conceptual model for the hydrogeology of the present-day system, and neither interpretation of the Rustler would appear to predict threats to the integrity of the disposal system over the regulatory period.

DEF.3.3 Shallow Dissolution

The term shallow dissolution has been used in a variety of ways by different authors. It is used here in the sense of solution-and-fill as discussed by Lambert (1983), and excludes lateral or stratabound dissolution which is discussed in the previous section.

Much of the early work on the effects of dissolution in the region of the WIPP focused on deep dissolution and the potential for this to disrupt the integrity of the repository. When it was established that localized deep dissolution was restricted to units above the Capitan Reef, and that regional deep dissolution had not taken place to the extent envisaged by Anderson, the focus changed to shallow dissolution. In particular, the possibility that karst features had developed at or near the WIPP site was of interest because of the significant effects that such karst could have on the hydrogeology of units overlying the Salado. In some release scenarios, these overlying formations could provide a potential pathway for radionuclide transport to the accessible environment.

The geomorphology of the region around the WIPP, and particularly around Nash Draw, is clearly influenced by shallow dissolution, and this has been recognized in all geological studies of the region. The first specific studies were those conducted in relation to Project Gnome, in which Vine (1960) mapped a variety of geomorphological features. Bachman continued the mapping of the region in the early 1970s, and a number of boreholes were drilled to investigate features of uncertain origin. A synthesis of this work (Bachman 1980) differentiated between those surficial features formed by deep collapse (for example, Hills A-D) and those formed by shallow dissolution. Anderson (1978) compiled information on dissolution in the region as a contribution to the Geological Characterization Report, but did not focus on shallow dissolution.

A gravity survey was conducted in the northern part of the WIPP site in 1980 and showed anomalies consistent with shallow density changes (Barrows et al. 1983). Some of these anomalies corresponded to known surficial features such as dolines, or to other karst features known from borehole data or other geophysical data. Barrows et al. (1983) extended the interpretation of karst to encompass all of the gravity anomalies, inferring that the site is located in karst terrain and neglecting other mechanisms to explain apparent mass loss.

The concerns raised by the interpretation of the WIPP region as a karst terrain led the EEG to commission a study by LeGrand (reported in Chaturvedi and Channel, 1985). LeGrand concluded that – in the region of the WIPP – there were similarities and important differences to classical karst terrain. In particular, he distinguished between Nash Draw, where karst features are developed, and a more easterly region, including the WIPP site, where there is no significant shallow dissolution of halite, anhydrite or dolomite. These two regions are separated by a transition zone which includes a prong of dissolution extending from Nash Draw towards the site of WIPP-14.

Bachman (1985) also reexamined the evidence for karst features in the vicinity of the WIPP. He provided a useful summary of the main surficial and underground karst features. The former include dolines, collapse sinks, karst valleys, swallow holes, solution-subsidence troughs, blind valleys, karst plains, and a variety of minor surface features. All of these features have been identified in Nash Draw, along the Pecos drainage north of Carlsbad or on the Gypsum Plain to the southwest of the Pecos River. Only a few small clusters of shallow dolines on the Mescalero caliche have been identified on the Los Medaños plateau east of Livingstone Ridge (Figure DEF-7).

Karstic features, such as collapse sinks and swallow holes, are common within Nash Draw, and the depression itself is an example of a karst valley. Some of these karstic features might have developed if the Rustler had remained unfractured, but collapse of the Rustler beds through dissolution at the top of the underlying Salado has caused extensive fracturing and brecciation and allowed more extensive percolation of groundwater. East of Livingstone Ridge there is a decrease in the extent of Salado dissolution and a consequent decrease in the extent of fracturing of the Rustler. The extent of dissolution of primary minerals and fracture infills also decreases eastward from Livingstone Ridge.

Dissolution and fracturing are important controls on the hydraulic conductivity of the Rustler, and an understanding of these processes is important to understanding the future evolution of this unit. The discussion of lateral dissolution above concludes that the edge of halite dissolution at the top of the Salado will not reach the controlled area until well after the period of regulatory concern. The present-day pattern of secondary gypsum in fractures is the result of changes in rainfall and percolation over many climate cycles during the past 500,000 years or more. There is no evidence for a progressive change in this pattern across the area and, although some dissolution and precipitation of gypsum as fracture infills will inevitably occur in the next 10,000 years. Significant lateral changes in hydraulic conductivity are not expected to occur over the next few climate cycles.

DEF.3.4 Importance to the WIPP

In summary, early investigations in the region of the WIPP identified several styles of dissolution as of potential importance to the performance of the disposal system. Each of these dissolution styles was methodically and intensively examined by the DOE and other investigators as part of site characterization. Although there is not complete agreement on all

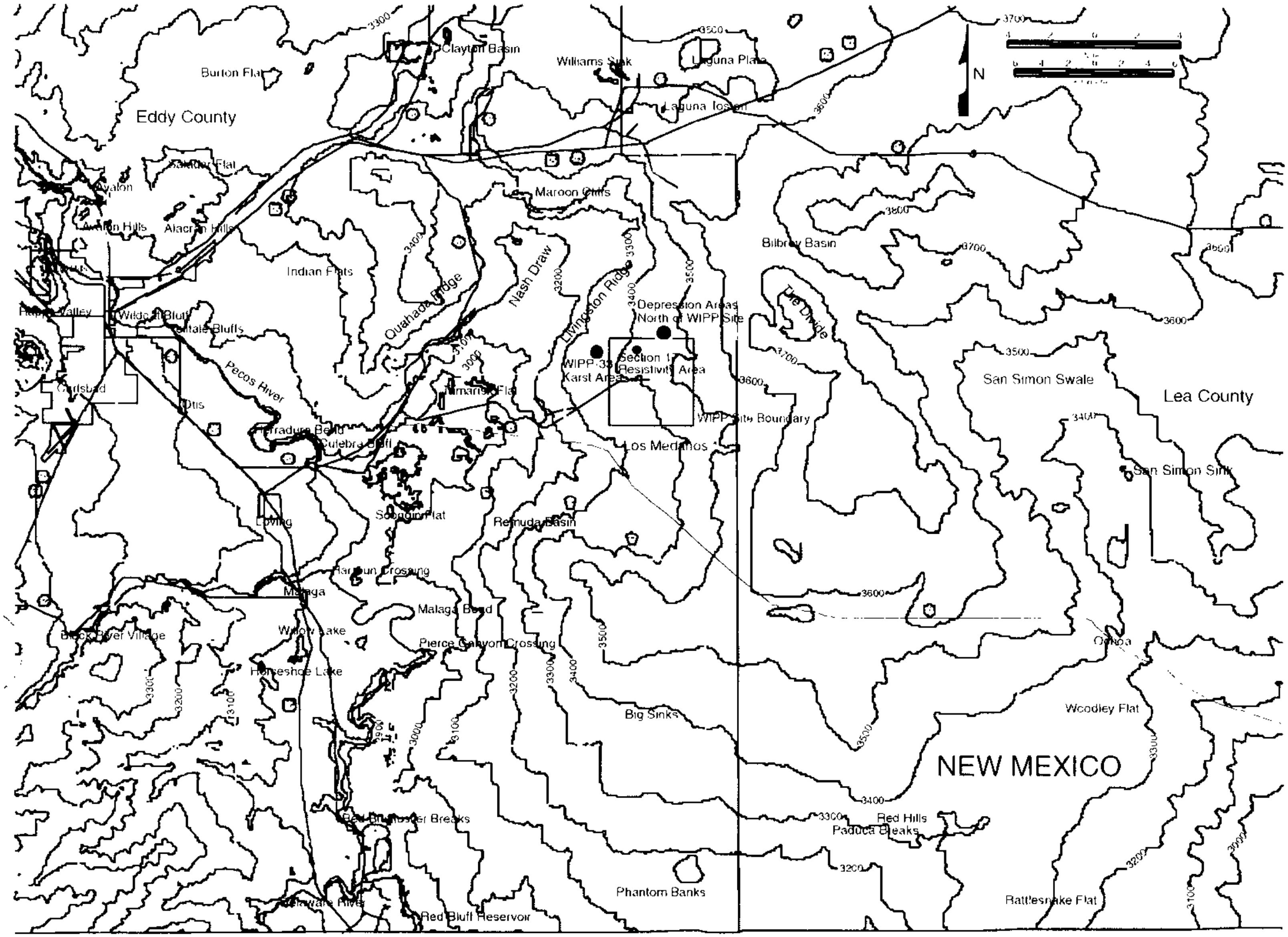

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Figure DEF-7. Topographic Map of the Area Around the WIPP Site

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aspects of the possible extent and timing of the different types of dissolution, there is a high level of confidence that dissolution sufficient to affect the performance of the disposal system is physically unreasonable and will not occur over the regulatory timeframe.

DEF.4 Salado Penetrations

Within the 16-square miles (41-square kilometers) WIPP site boundary, 36 boreholes have been identified as penetrating into the Salado (Figure DEF-8; Table DEF-1). Thirty of these boreholes terminate near the top of the Salado; the remaining six boreholes were completed through the Salado to deeper formations. These boreholes have either been plugged and abandoned, or recompleted for use as hydrologic monitoring wells.

The six wells that penetrate through the Salado are two exploration wells and four drilled in support of the WIPP. Two hydrocarbon exploration wells, Clayton Williams #1 Badger Unit and Michael Grace #1 Cotton Baby, were drilled within the WIPP site boundary. The location of these wells is shown on Figure DEF-8, and the construction information is provided in Table DEF-1. These wells did not produce economical quantities of hydrocarbons and were plugged and abandoned in accordance with the state of New Mexico plugging criteria. The four additional deep boreholes, WIPP-12, WIPP-13, DOE-1, and ERDA-9, were drilled as stratigraphic holes for geologic site characterization (Figure DEF-8; Table DEF-1). These four boreholes have been recompleted and are currently used for hydrologic testing and sampling.

Most of the 30 boreholes completed near the top of the Salado were drilled in support of the WIPP. Seven of the boreholes (designated with an "H" prefix on Figure DEF-8) were drilled to just below the Rustler/Salado contact and were completed as hydrologic exploration wells. These wells were completed with the section in the Salado either left as an open hole or, in some cases, a cement plug was installed to prevent mixing of groundwater between the Rustler and Salado. Five boreholes were drilled within the boundary to characterize the site stratigraphy. Four of these boreholes (WIPP-18, WIPP-19, WIPP-21, and WIPP-22) were subsequently recompleted for hydrological testing and sampling purposes and are currently in use. The remaining stratigraphic borehole, B-25, was drilled as part of the geotechnical foundation analysis program. This borehole was plugged, as described in Table DEF-1. Industry potash and WIPP potash assessment boreholes (designated as D, I, or P, respectively, in Figure DEF-8) were drilled within the site boundary. These boreholes were plugged with cement and abandoned, except for borehole P-15. This borehole was plugged as described in Table DEF-1 and recompleted as a hydrologic test well.

Table DEF-1. Information for Boreholes Within the 16-Square Mile (41-Square Kilometer) WIPP Boundary

Borehole No.	Location T/R/SEC.	Completion Date	Total Depth (ft)	Purpose	Comments
B-25	22S/31E/20	2/13/79	902	Stratigraphy	Plugged and abandoned; cement plug from 902 feet to 461 feet, sand from 461 feet to 5 feet, cement plug from 5 feet to surface
CW#1	22S/31E/15	9/13/93	15,225	Hydrocarbon Explor.	Plugged and abandoned, 9/17/93
Cotton Baby	22S/31E/34	6/16/75	6,700	Hydrocarbon Explor.	Plugged and abandoned, 12/22/75
DOE-1	22S/31E/28	7/28/82	4,057	Stratigraphy	Converted to hydrologic monitoring
D-123	22S/31E/34	--	1,880	Potash Exploration	Plugged and abandoned
D-207	22S/31E/19	--	1,613	Potash Exploration	Plugged and abandoned
ERDA-9	22S/31E/20	6/26/76	2,875	Geo. Exploration	Converted to hydrologic monitoring
H-1	22S/31E/29	6/10/76	856	Hydro. Exploration	7 inches OD casing to 848 feet, cement plug to 831 feet
H-2c	22S/31E/29	2/5/77	795	Hydro. Exploration	6-5/8 inches OD casing to 742 feet, open hole to TD
H-3B1	22S/31E/29	8/12/76	902	Hydro. Exploration	6-5/8 inches OD casing to 891 feet, cement plug to 864 feet
H-5c	22S/31E/15	6/3/78	1,076	Hydro. Exploration	5-1/2 inches OD casing to 1,024, open hole to TD
H-6c	22S/31E/18	6/26/78	741	Hydro. Exploration	5-1/2 inches OD casing to 699 feet, open hole to TD
H-16	22S/31E/20	8/-/87	851	Hydro. Exploration	7 inches OD casing to 469 feet, open hole to TD
H-18	22S/31E/20	10/-/87	831	Hydro. Exploration	7 inches OD casing to 673 feet, cement plug to 766 feet
I-374	22S/31E/30	--	1,538	Potash Exploration	Plugged and abandoned

OD - Outer Diameter
TD - Total Depth

Table DEF-1. Information for Boreholes Within the 16-Square Mile (41-Square Kilometer) WIPP Boundary (Continued)

Borehole No.	Location T/R/SEC.	Completion Date	Total Depth (ft)	Purpose	Comments
I-375	22S/31E/33	--	1,746	Potash Exploration	Plugged and abandoned
I-376	22S/31E/20	--	1,702	Potash Exploration	Plugged and abandoned
I-377	22S/31E/22	--	1,876	Potash Exploration	Plugged and abandoned
I-456	22S/31E/27	--	1,975	Potash Exploration	Plugged and abandoned
I-457	22S/31E/27	--	1,885	Potash Exploration	Plugged and abandoned
P-1	22S/31E/29	9/2/76	1,591	Potash Exploration	Plugged and abandoned; 4-1/2 inches OD casing from 591 feet to 974 feet, plugged with cement
P-3	22S/31E/20	9/7/76	1,676	Potash Exploration	Plugged and abandoned; 4-1/2 inches OD casing from 490 feet to 826 feet, plugged with cement
P-4	22S/31E/28	9/4/76	1,857	Potash Exploration	Plugged and abandoned; recovered all casing, plugged with cement
P-5	22S/31E/17	9/21/76	1,830	Potash Exploration	Plugged and abandoned; 4-1/2 inches OD casing from 435 feet to 1,003 feet, plugged with cement
P-6	22S/31E/30	9/16/76	1,573	Potash Exploration	Plugged and abandoned; recovered all casing, plugged with cement
P-9	22S/31E/33	9/25/76	1,796	Potash Exploration	Plugged and abandoned; recovered all casing, plugged with cement
P-13	22S/31E/18	9/23/76	1,576	Potash Exploration	Plugged and abandoned; recovered all casing, plugged with cement

OD - Outer Diameter
TD - Total Depth

Table DEF-1. Information for Boreholes Within the 16-Square Mile (41-Square Kilometer) WIPP Boundary (Continued)

Borehole No.	Location T/R/SEC.	Completion Date	Total Depth (ft)	Purpose	Comments
P-15	22S/31E/18	10/15/76	1,465	Potash Exploration	Converted to hydrologic monitoring, cement plug from 1465 to 620 ft
P-21	22S/31E/15	10/26/76	1,915	Potash Exploration	Plugged and abandoned; recovered all casing, plugged with cement
WIPP-12	22S/31E/17	12/7/78	3,928	Geo. Exploration	9-5/8 inches OD casing to 1,001 feet; cement plug to 2,784 feet; converted to hydrologic monitoring
WIPP-13	22S/31E/17	8/6/78	3,856	Geo. Exploration	9-5/8 inches OD casing to 1,023 feet; open hole to TD, converted to hydrologic monitoring
WIPP-18	22S/31E/20	4/3/78	1,060	Stratigraphy	5-1/2 inches OD casing to 1,050 feet; cement plug to 1,050 feet; converted to hydrologic monitoring
WIPP-19	22S/31E/20	5/8/78	1,040	Stratigraphy	5-1/2 inches OD casing to 1,035 feet; cement plug to 1,035 feet; converted to hydrologic monitoring
WIPP-21	22S/31E/20	5/27/78	1,045	Stratigraphy	5-1/2 inches OD casing to 1,014 feet; cement plug to 1,014 feet; converted to hydrologic monitoring
WIPP-22	22S/31E/20	5/24/78	1,452	Stratigraphy	5-1/2 inches OD casing to 950 feet; cement plug to 941 feet; converted to hydrologic monitoring

OD - Outer Diameter
TD - Total Depth

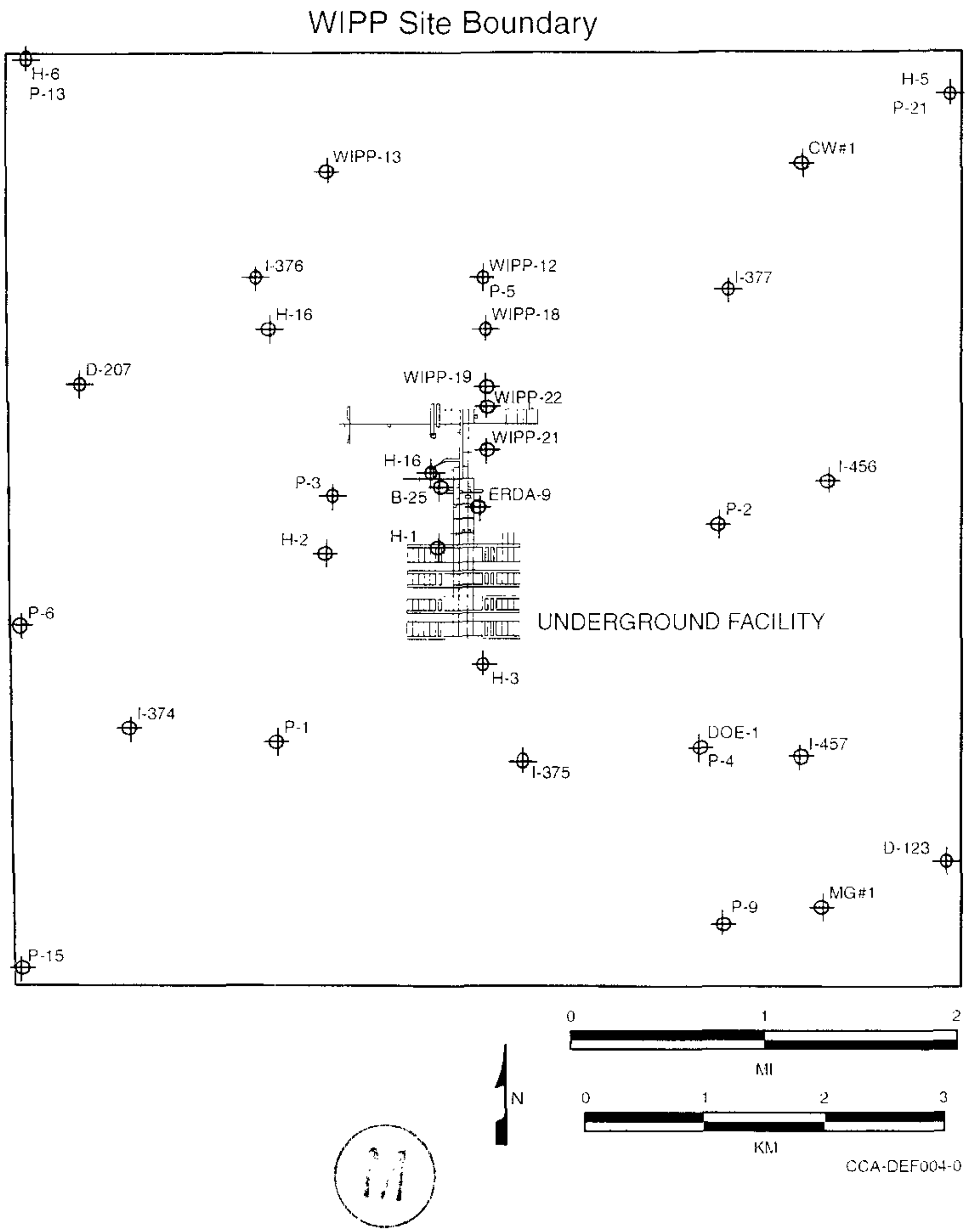

Figure DEF-8. Salado Drillhole Locations Within WIPP Site Boundary

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REFERENCES

Adams, S.S., 1969. "Bromine in the Salado Formation, Carlsbad Potash District, New Mexico," *NM Bureau of Mines and Mineral Resources Bulletin,* 93.

Anderson, R.Y., W. E. Dean, D.W. Kirkland and H.I. Snider. 1972. "Permian Castile Varied Evaporite Sequence, West Texas and New Mexico," *Bulletin of the Geological Society of America*, Vol. 83, pp. 59-86.

Anderson, R.Y. 1978. "Deep Dissolution of Salt, Northern New Mexico." Report for Sandia National Laboratories, Albuquerque, New Mexico. WPO 29527 - WPO 29530.

Anderson, R.Y. and D.W. Powers. 1978. "Salt Anticlines in the Castile-Salado Evaporite Sequence, Northern Delaware Basin, New Mexico," in *Geology and Mineral Deposits of Ochoan Rocks in Delaware Basin and Adjacent Areas*, Circular 159, New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico.

Bachman, G.O. 1974. "Geological Processes and Cenozoic History Related to Salt Dissolution in Southeastern New Mexico," *Open File Report 74-194*, U.S. Geologic Survey, p. 81.

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

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

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

Barr, G.E., S.J. Lambert and J.A. Carter. 1979. "Uranium Isotope Disequilibrium in Groundwaters of Southeastern New Mexico and Implications Regarding Age-Dating of Waters," in *Proceedings of the International Symposium on Isotope Hydrology*, International Atomic Energy Agency, Vol. 2, pp. 645-660.

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

Barrows, L., and J.D. Fett. 1985. "A High-Precision Gravity Survey in the Delaware Basin of Southeastern New Mexico," *Geophysics,* Vol. 50, pp. 825-833.

Billo, S. M. 1986. *Petroleum Sedimentology of the Ochoan Group, Texas and New Mexico.* Abstracts. *12th International Sedimentological Congress*, Canberra, Australia, pp. 30-31.

Borns, D.J. 1983. *Petrographic Study of Evaporite Deformation Near the Waste Isolation Pilot Plant (WIPP).* SAND83-0166. Sandia National Laboratories, Albuquerque, New Mexico.

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

Borns, D.J. 1985. *Marker Bed 139: A Study of Drillcore from a Systematic Array.* SAND85-0023. Sandia National Laboratories, Albuquerque, New Mexico.

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

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

Chaturvedi, L. and J.K Channell. 1985. "The Rustler Formation as a Transport Medium for Contaminated Groundwater," EEG-32. Environmental Evaluation Group, Santa Fe, NM.

D'Appolonia Consulting Engineers, Inc. 1982. "Data Field Report - ERDA-6 and WIPP-12 Testing," report prepared for Westinghouse Electric Corporation and the U.S. Department of Energy, Albuquerque, New Mexico, 7 volumes.

Davies, P.B. 1983. "Assessing the Potential for Deep-Seated Salt Dissolution and Subsidence at the Waste Isolation Pilot Plant (WIPP)," *State of New Mexico Environmental Evaluation Group Conference: WIPP Site Suitability for Radioactive Waste Disposal, Carlsbad, NM, May 12-13, 1983.*

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

Earth Technology Corporation. 1987. *Final Report for Time Domain Electromagnetic (TDEM) Surveys at the WIPP.* SAND87-7144. Sandia National Laboratories, Albuquerque, New Mexico.

Elliot, C.L. 1976. "An Experimental Detailed Resistivity Survey of Known or Suspected Breccia Pipes and Sinkholes, Eddy County, New Mexico." Tucson, AZ: Elliot Geophysical Company.

Elliot, C.L. 1977a. "Evaluation of the Proposed Los Medaños Nuclear Waste Disposal Site by Means of Electrical Resistivity Surveys, Eddy & Lea Counties, New Mexico." Tucson, AZ: Elliot Geophysical Company.

Elliot, C.L. 1977b. "Maps to Accompany Evaluation of the Proposed Los Medaños Nuclear Waste Disposal Site by Means of Electrical Resistivity Surveys, Eddy & Lea Counties, New Mexico." Tucson, AZ: Elliot Geophysical Company.

Gera, F. 1974. "On the Origin of the Small Hills in Nash Draw and Clayton Basin, Southeastern New Mexico," ORNL 74-2-29, Oak Ridge, TN: Oak Ridge Natioanl Laboratory.

Griswold, G.B. 1977. *Site Selection and Evaluation Studies of the Waste Isolation Pilot Plant (WIPP), Los Medaños, Eddy County, New Mexico.* SAND77 0946. Sandia National Laboratories, Albuquerque, New Mexico.

Holt, R.M. and D.W. Powers. 1988. *Facies Variability and Post-Depositional Alteration Within the Rustler Formation in the Vicinity of the Waste Isolation Pilot Plant, Southeastern New Mexico.* DOE/WIPP-88-004. U.S. Department of Energy, Carlsbad, New Mexico.

Jarolimek, L., M.J. Timmer and D.W. Powers. 1983. *Correlation of Drillhole and Shatt Logs, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico.* TME-3179, U.S. Department of Energy, Albuquerque, New Mexico.

Jones, C.L. 1981. "Geologic Data tor Borehole ERDA-6, Eddy County, New Mexico," *Open File Report 81-468,* U.S. Geological Survey, Denver, Colorado.

Jones, C.L., M.E. Cooley and G.O. Bachman. 1973. "Salt Deposits of Los Medaños Area, Eddy and Lea Counties, New Mexico, *Open File Report 4339-7,* U.S. Geological Survey, p. 67.

King, P.B. 1948. *Geology of the Southern Guadalupe Mountains, Texas.* Professional Paper 215. U.S. Geological Survey, Washington, DC.

Kirkland, D.W. and R.Y. Anderson. 1970. "Microfolding in the Castile and Todilto Evaporites, Texas and New Mexico," *Geological Society of America Bulletin*, Vol. 81, pp. 3259-3282.

Lambert, S.J. 1983. *Dissolution of Evaporites In and Around the Delaware Basin, Southeastern New Mexico and West Texas.* SAND82-0461. Sandia National Laboratories, Albuquerque, New Mexico.

Lambert, S.J. 1978. "Geochemistry of Delaware Basin Ground Water," Circular 159, New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico, pp. 33-38.

Lambert, S.J. and J.A. Carter. 1984. *Uranium-Isotope Disequilibrium in Brine Reservoirs of the Castile Formation, Northern Delaware Basin, Southeastern New Mexico, l: Principles and Methods.* SAND-830144. Sandia National Laboratories, Albuquerque, New Mexico.

Long, G.J. and Associates, Inc. 1977. "Final Report, Waste Isolation Pilot Plant (WIPP), Los Medaños Area, Eddy and Lea Counties, New Mexico," report submitted to Sandia National Laboratories, Albuquerque, New Mexico.

Lowenstein, T.K. 1987. "Post Burial Alteration of the Permian Rustler Formation Evaporites, WIPP Site, New Mexico." EEG-36, New Mexico Health and Environment Department, Santa Fe, New Mexico.

Madsen, B.M. and O.B. Raup. 1988. "Characteristics of the Boundary Between the Castile and Salado Formations Near the Western Edge of the Delaware Basin, Southeastern New Mexico," *New Mexico Geology*, Vol.10, No.1, pp.1-6, 9.

Mercer, J.W. 1983. "Geohydrology of the Proposed Waste Isolation Pilot Plant Site, Los Medaños Area, Southeastern New Mexico." Water Resources Investigation Report 83-4016. U.S. Geological Survey, Albuquerque, NM.

Mercer, J.W., R.L. Beauheim, R.P. Snyder and G.M. Fairer. 1987. *Basic Data Report for Drilling and Hydrologic Testing of Drillhole DOE-2 at the Waste Isolation Pilot Plant (WIPP) Site.* SAND86-0611. Sandia National Laboratories, Albuquerque, New Mexico.

Neill, R.H., J.K. Channell, L., Chaturvedi, M.S. Little, K. Rehfeldt, and P. Speigler. 1983. "Evaluation of the Suitability of the WIPP Site," EEG-23, Environmental Evaluation Group, Santa Fe, New Mexico.

Popielak, R.S., R.L. Beauheim, S.R. Black, W.E. Coons, C.T. Ellingson and R.L. Olsen. 1983. *Brine Reservoirs in the Castile Formation, Southeastern New Mexico.* TME-3153, Department of Energy, Albuquerque, New Mexico.

Powers, D.W., S.J. Lambert, S-E. Shaffer, L.R. Hill, and W.D. Weart, eds. 1978. *Geological Characterization Report for the Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico.* SAND78-1596, Volumes I and II, Sandia National Laboratories, Albuquerque, New Mexico.

Robinson, J.Q. and D.W. Powers. 1987. "A Clastic Deposit Within the Lower Castile Formation, Western Delaware Basin, New Mexico," *Guidebook 18,* El Paso Geological Society, pp. 69-79.

Sandia National Laboratories and D'Appolonia Consulting Engineers, 1982. *Basic Data Report for Drillhole AEC-7 (Waste Isolation Pilot Plant - WIPP).* SAND82-0268. Sandia National Laboratories, Albuquerque, New Mexico.

Sandia National Laboratories and U.S. Geological Survey. 1979. *Basic Data Report for Drillhole WIPP-11 (Waste Isolation Pilot Plant - WIPP).* SAND79-0272. Sandia National Laboratories, Albuquerque, New Mexico.

Sandia National Laboratories and U.S. Geological Survey. 1981. *Basic Data Report for Drillhole WIPP-34 (Waste Isolation Pilot Plant - WIPP).* SAND81-2643. Sandia National Laboratories, Albuquerque, New Mexico.

Snider, H.I. 1966. "Stratigraphy and Associated Tectonics of the Upper Permian Castile-Salado-Rustler Evaporite Complex, Delaware Basin, West Texas and Southeast New Mexico," Ph.D. Dissertation, University of New Mexico, Albuquerque, New Mexico.

Snyder, R.P., and Gard, Jr., L.M. 1982. "Evaluation of Breccia Pipes in Southeastern New Mexico and Their Relation to the Waste Isolation Pilot Plant (WIPP) Site, with Section on Drill-Stem Tests." *Open-File Report 82-968.* U.S. Geological Survey, Denver, CO.

Szabo, B.J., W.C. Gottschall, J.N. Rosholt, and C.R. McKinney. 1980. "Uranium Series Disequilibrium Investigation Related to the WIPP Site, New Mexico. Part I: A Preliminary Study of Uranium-Thorium Systematics in Dissolution Residues at the Top of Evaporites of the Salado Formation, Implications to Process and Time. Part II: Uranium Trend Dating of Surficial Deposits and Gypsum Spring Deposits Near WIPP Site, New Mexico." *Open-File Report 80-879.* Denver, CO: U.S. Geological Survey.

Vine, J.D. 1960. "Recent Domal Structures in Southeastern New Mexico," *Am. Assoc. Petroleum Geologists Bull.*, v. 44, no. 12, p. 1903-1911, 7 figs.

BIBLIOGRAPHY

Sandia National Laboratories and University of New Mexico. 1979. *Basic Data Report for Drillhole WIPP15 (Waste Isolation Pilot Plant - WIPP).* SAND79-0274. Sandia National Laboratories, Albuquerque, New Mexico.

Sandia National Laboratories and D'Appolonia Consulting Engineers. 1982. *Basic Data Report for Drillhole WIPP-12 (Waste Isolation Pilot Plant - WIPP).* SAND82-2336. Sandia National Laboratories, Albuquerque, New Mexico.

Vine, J.D. 1963. "Recent Domal Structures in Southeastern New Mexico." *American Association of Petroleum Geologists Bulletin.* Vol. 44, no. 12, 1903-1911.