EEG-32

THE RUSTLER FORMATION AS A TRANSPORT MEDIUM FOR CONTAMINATED GROUNDWATER

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December 1985
(Reprinted August 1994)

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FOREWORD

The purpose of the Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the potential radiation exposure to people from the proposed Federal radioactive Waste Isolation Pilot Plant (WIPP) near Carlsbad, in order to protect the public health and safety and ensure that there is minimal environmental degradation. The EEG is part of the Environmental Improvement Division, a component of the New Mexico Health and Environment Department -- the agency charged with the primary responsibility for protecting the health of the citizens of New Mexico.

The Group is neither a proponent nor an opponent of WIPP.

Analyses are conducted of available data concerning the proposed site, the design of the repository, its planned operation, and its long-term stability. These analyses include assessments of reports issued by the U. S. Department of Energy (DOE) and its contractors, other Federal agencies and organizations, as they relate to the potential health, safety and environmental impacts from WIPP.

The project is funded entirely by the U. S. Department of Energy through Contract DE-AC04-79AL10752 with the New Mexico Health and Environment Department.

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EXECUTIVE SUMMARY

The WIPP repository is being excavated in the lower part of the 2000 ft thick Salado Formation, 2150 ft below the ground surface. The water-bearing zones in the Rustler Formation, which overlies the Salado, are considered to be the main pathway for the transport of radionuclides to the biosphere after a potential breach of the WIPP repository.

Geological and hydrological characterization of the Rustler Formation has not yet been completed to a desired level of detail for a realistic modeling of breach and transport scenarios through this Formation. The published models and scenarios (Barr, 1983; U.S. DOE, 1980; Wofsy, 1980; Spiegler, 1981) are based on insufficient information about the Rustler and may therefore not be "bounding" or "worst-case". The lack of data which makes it difficult to assume the "bounding" conditions mainly relates to the dissolution history, present recharge (amount and location) and the hydrologic characteristics (transmissivity, storativity, hydraulic gradient) of the Rustler Formation. Currently, the Department of Energy is conducting studies which will significantly enhance our knowledge about the suitability of the Rustler Formation to act as a barrier against the movement of radionuclide contaminated water. A sedimentological study of the cores from several boreholes will help establish the causes for the absence of salt from the Rustler Formation. Several multi-well flow tests over the WIPP site will yield more reliable values for the hydrologic parameters. Rustler water-chemistry data will help in more accurately establishing the flow directions and the pattern of interconnections. Investigations of suspected "dolines" (sinkholes) will aid in resolving the question of direct recharge at the WIPP site. Sorbing tracer tests will provide data for transport modeling of the radionuclides.

In addition to analyzing the geological conditions which affect the hydrological characteristics of the Rustler Formation, this report contains an analysis of radionuclide transport through a Rustler water-bearing zone which is assumed to contain karst conduits. Two scenarios are analyzed; one involves drinking treated Pecos River water at Malaga Bend and the other assumes drinking treated water from a hypothetical well located two miles from the site. The estimated annual dose to an individual from drinking contaminated Pecos River water would exceed the EPA standard (40 CFR 191) if continuously ingested for more than 20 years. The corresponding annual dose from drinking contaminated well water would be greater and would exceed the annual dose permitted for occupational workers after one year.

The validity of the karst-conduit assumption can be checked by carrying out some additional studies outlined in the report. These include a reevaluation of the gravity anomalies over the WIPP site, using electro-magnetic methods to check the lateral variations in the Rustler Formation, and implementation of the recommendations resulting from the water-balance study by Hunter (1985).

It is also recommended that, for extra measure of safety, the WIPP design include engineered barriers such as mixing of a retardant clay with salt backfill, a very careful plugging and sealing of the shafts and boreholes, and isolation of individual "panels" through carefully designed plugs.

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1. INTRODUCTION

1.1 Purpose and Scope

The Waste Isolation Pilot Plant (WIPP), located about 25 miles east of Carlsbad in Southeastern New Mexico is slated to be the first deep geologic repository for permanent disposal of radioactive wastes in the United States. The repository will be located in the lower part of the Salado Formation of Permian age, at a depth of 2,150 feet below the ground surface. The Rustler Formation overlies the Salado (the Rustler/Salado contact is about 1300 feet above the repository horizon) and contains water-bearing beds through which a limited quantity of groundwater under confined pressures flows at a slow rate. The most credible scenarios for the transport of radioactivity to the biosphere after a breach of the WIPP repository involve transportation of radionuclides to the Rustler and through the Rustler aquifers to the biosphere. All the published transport calculations based on such scenarios (e.g. U. S. DOE, 1980: Wofsy, 1980; Spiegler, 1981) used the hydrologic parameters for the Rustler Formation obtained from a very limited number of single-well flow and tracer tests at the WIPP site. Using these values, the scenario analyses indicated minimal or trivial radiation doses to individuals.

The WIPP site is situated in close proximity to Nash Draw (Figure 1), which is a 6 to 12 miles wide subsidence feature,

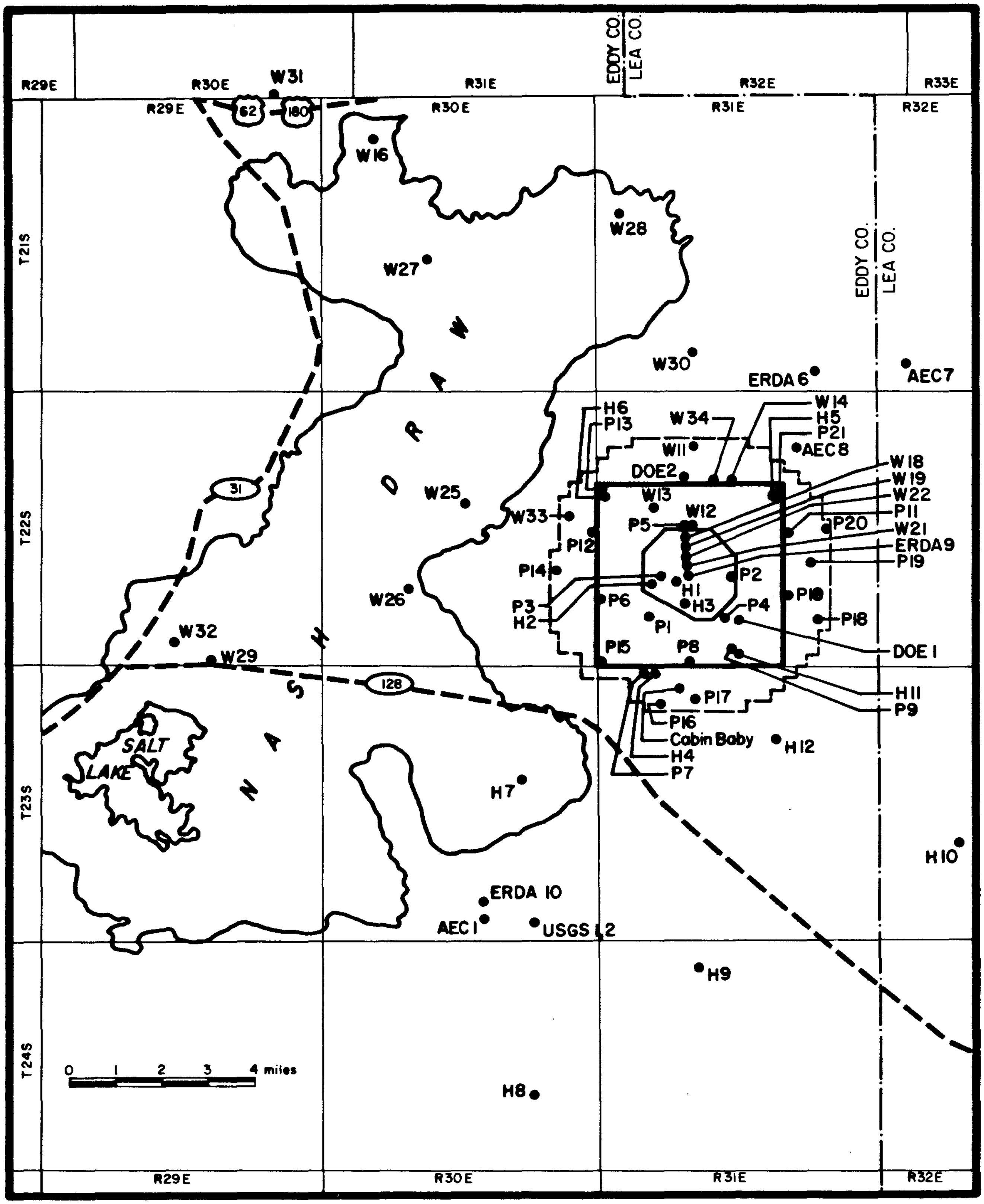

Fig. 1 The location of boreholes drilled in connection with the WIPP project.

where the Rustler Formation has collapsed due to the removal of salt by dissolution from it and from the top part of the underlying Salado Formation. Moving east from Nash Draw to the WIPP site, one encounters a progressively thicker Rustler Formation with increasing thickness and number of halite (salt) layers contained within it. At the center of the WIPP site, halite in the Rustler Formation is found only in its lower part. The Rustler water-bearing zones have a higher transmissivity value and greater well-yield in the western part of the WIPP site, indicating a connection between the absence of salt layers and the ease of groundwater flow. There are only three "hydropads"* in Zone II**, all located in the Southwest corner (H-1, H-2 and H-3, Fig. 1). There are wide variations in the hydrologic properties and in the water chemistry of the Rustler aquifers tested at these wells in Zone II, situated within a mile of each other. The characterization of the hydrology of the Rustler Formation at the WIPP site thus remains incomplete.

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*A "hydropad" is a cluster of 3 wells within about 100 feet of each other, each perforated and developed in a different water-bearing zone within the Rustler. Most "H" wells are groups of 3 wells.

**The "WIPP Site" is a 4 mile x 4 mile square shown by heavy lines in Figure 1. Zone II, located inside, is the octagonal shaped area that marks the boundary of the underground repository. Zone I (now shown on Fig. 1) is a fenced area within Zone II, that will house the surface facilities. The outer octagon shown by broken lines in Figure 1 is the boundary of "Zone IV" which has been relinquished by DOE. It is shown here for the sake of comparison with older (pre 1983) maps of the site. The boundary of old "Zone III" is not shown here, but it was the same as the present 4 x 4 mile "WIPP site" with corners cut to be essentially parallel to the "Zone IV" and "Zone II" boundaries.

The concern which prompted the preparation of this report is not limited to the inadequacy of the Rustler hydrology data. There remain a number of observations which cast doubt on the model of the Rustler hydrology as developed by the U. S. Department of Energy and the U. S. Geological Survey investigators. Thus while the WIPP hydrology studies (Mercer and Orr, 1979; Mercer, 1983; Gonzalez, 1983) characterize three discrete water-bearing zones in the Rustler, there are some indications (see Sec. 3.5) that water flows through several other zones within the Rustler Formation and some moves through the overlying beds. Results from geophysical surveys, regional water balance considerations, data from some wells and a study of the Rustler rock cores, point to the possibility of "karst" type hydrologic conditions in the rocks overlying the Salado in this area (Barrows, 1982, Barrows et al, 1983; Barrows and Fett, 1985). Neill et al (1983) and Chaturvedi and Rehfeldt (1984) briefly discussed the inadequacy of characterization of the Rustler Formation hydrology and recommended additional work to be done. This report analyzes the available information to ascertain whether the Rustler Formation can be considered a reliable barrier to the migration of radionuclides to the biosphere following a breach of the WIPP repository. The analysis includes a calculation of the population and individual doses following a breach and transport through an assumed karst channel through the Rustler Formation.

British Units have been used throughout this report since all the reported hydrologic measurements as well as the distances and dimensions of the WIPP facility are in British units. Converting these numbers to the Metric system (e.g., 4 mile x mile to 6.45 km. x 6.45 km) would make them look artificial and meaningless. Of course, conversions can be made when desired by using the standard conversion factors.

Much of the work reported here is compiled from published literature. Where no reference is cited for descriptions, calculations, measurements or on figures, these represent the work of the authors. Thus, for example, the descriptions of the rock cores from holes H-3-b-3, H-11 and DOE-2 are by Chaturvedi and the calculations in section 4.3 were made by Channell.

The report was reviewd in draft form by Robert H. Neill, Marshall S. Little, Jenny Chapman, Jack Mobley, Harry LeGrand, Larry J. Barrows, Steven J. Lambert, Jerry Mercer, Richard P. Snyder and Mel Merritt. The reviewers were requested to review the draft in their personal capacity and their institutional affiliations are irrelevant. The report benefited greatly from these scientific reviews and the authors are grateful to the individuals named above.

1.2 Summary of WIPP Site Geologic Setting

The WIPP site is situated in the northern part of the Delaware Basin, which is a sub-basin of the well-known Permian Basin of the southwestern United States. The Delaware Basin is bounded by a Permian reef, known as the Capitan Limestone (Figure 2). The basin contains about 15,000 feet of Paleozoic sedimentary rocks overlying the Pre-Cambrian basement. The upper 4,000 feet consist of a sedimentary sequence belonging to the Ochoan Series (Upper Permian), the lower 3500 feet of which consist of the three evaporite formations of interest to the WIPP. These three formations, from oldest to youngest, are the Castile, Salado, and Rustler (Figure 3). Underlying the Ochoan series formations is the Delaware Mountain Group (DMG) which forms the floor of the Delaware Basin evaporite sequence. The total thickness of the DMG is about 4,000 feet but its upper formation, the Bell Canyon, is the most important for site evaluation because it is water-bearing.

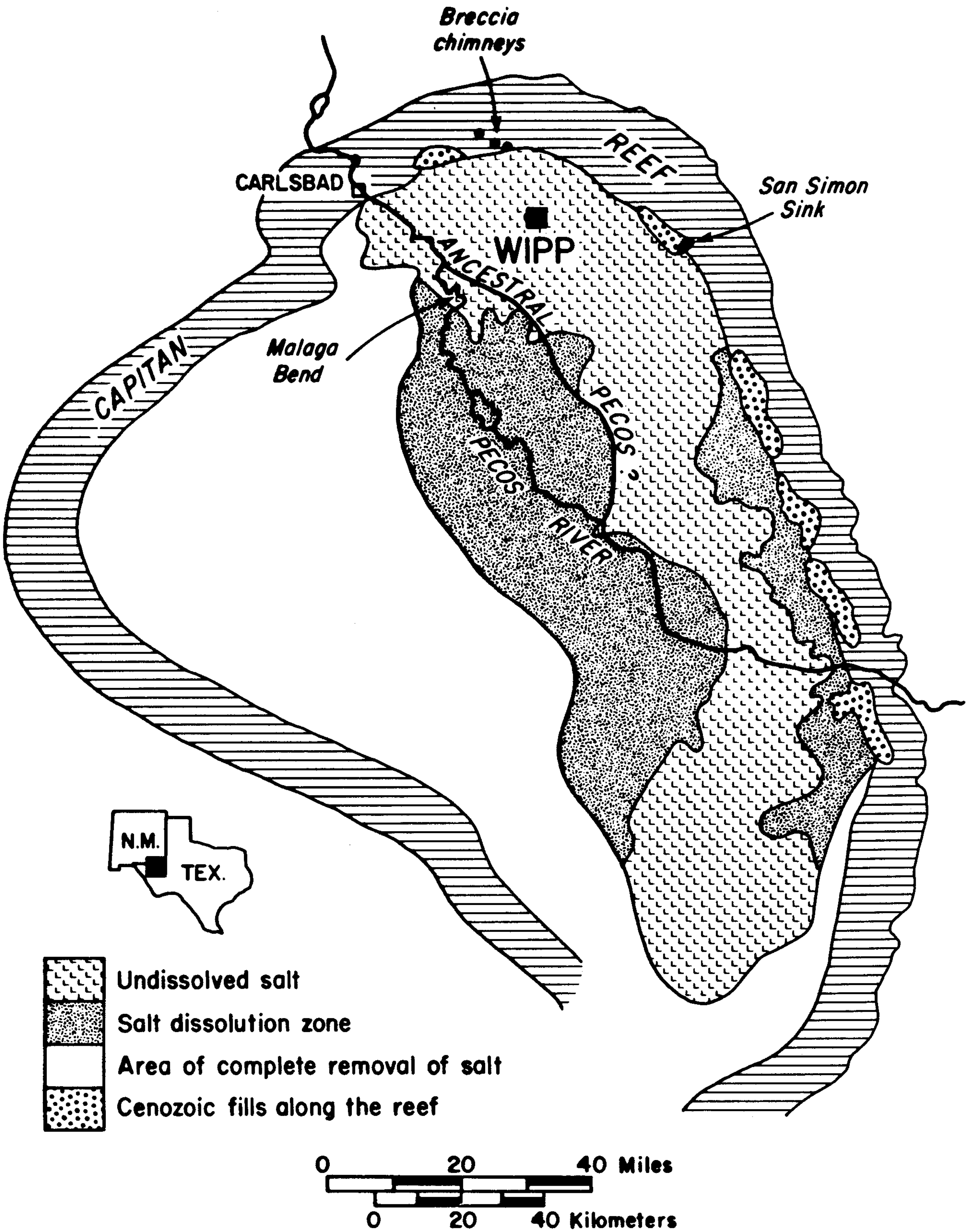

Fig. 2 Regional extent of removal of salt from the Salado Formation. (Adapted from Anderson, 1981, and Bachman, 1984.)

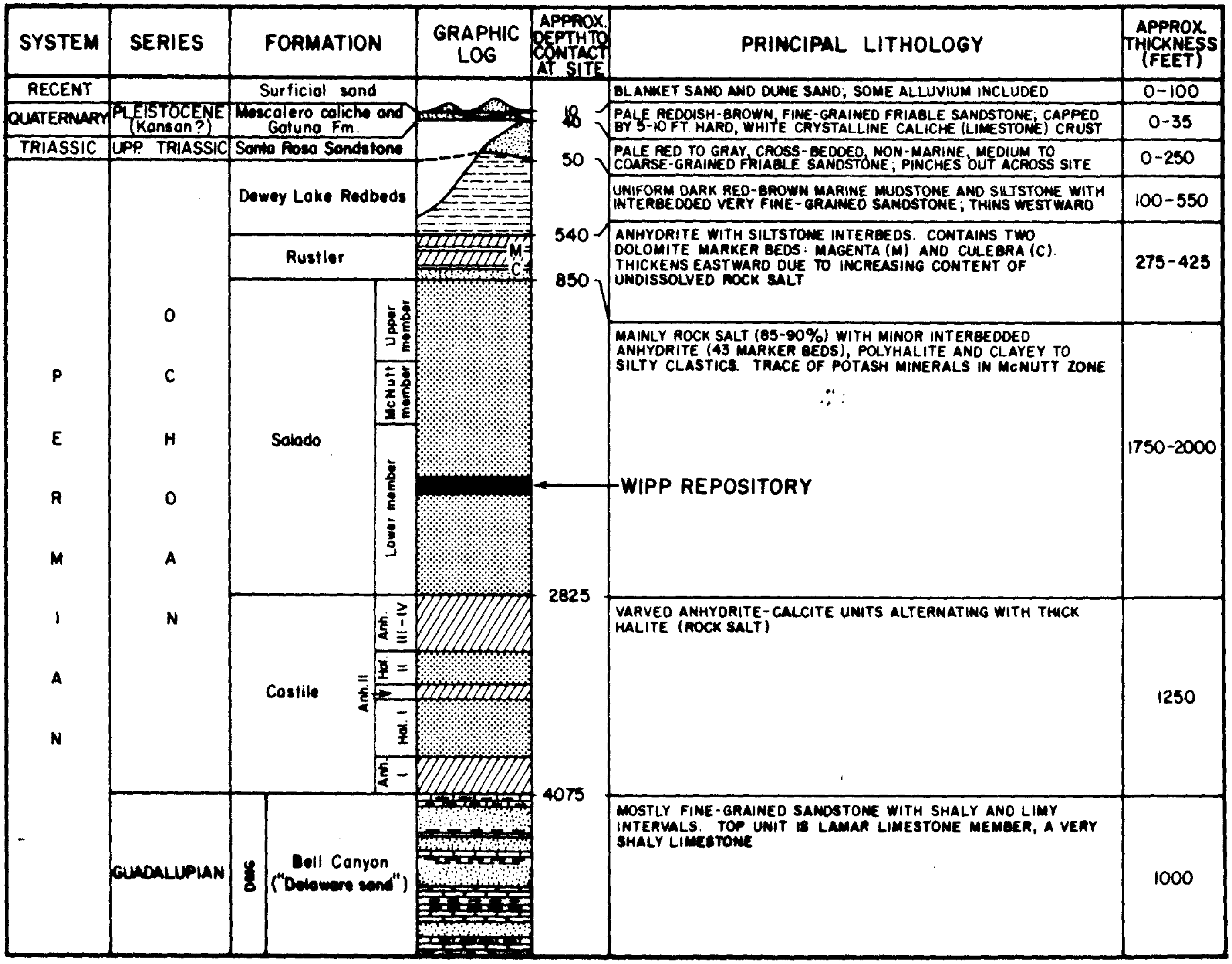

Fig. 3 Generalized stratigraphy at the WIPP site.
(Adapted from Powers, et al., 1978.)

The horizon selected for WIPP is in the lower part of the Salado Formation, 2,150 feet below ground level.

Figure 2 shows the extent of removal of salt from the Salado Formation in the Delaware Basin, according to Anderson (1981). On the basis of interpretation of acoustic logs from a large number of wells in the Delaware Basin, Anderson (1982) concluded that about 50% of the salt in the Salado and Castile formations has been removed by dissolution. According to Bachman (1983), however, major dissolution has been restricted to areas where the Pecos river and its tributaries have initiated karst systems, or to limited areas which overlie the Capitan Reef aquifer. Bachman (1983) has postulated the existence of an ancestral Pecos river (Figure 2), east of the present day Pecos, on the basis of ancient river gravel deposits. According to him, this ancient river system was responsible for the development of the extensive karst terrain seen east of the present day river.

2. LITHOLOGY OF THE RUSTLER AND THE OVERLYING FORMATIONS

2.1 Lithologic Subdivisions of the Rustler

The Rustler Formation was named by Richardson (1904) for exposures on the Rustler Hills in eastern Culberson County, Texas. The now commonly accepted five-fold subdivision of the Rustler was first proposed by Vine (1963) based on field mapping in the Nash Draw quadrangle and a study of the core from the test hole AEC-1 (Figure 1) which was drilled to a depth of 1,500 feet by the U. S. Atomic Energy Commission in connection with the Gnome Project. The core was studied and described by Moore (1958).

The Rustler Formation represents depositional activity during the final stages of the formation of Permian Basin evaporites. It consists of halite, anhydrite (partially or completely hydrated to gypsum), interlaminated dolomite and siltstone. Figure 4 shows the subdivisions of the Rustler Formation.

2.1.1 The Unnamed Lower Member

The Rustler/Salado interface was identified by Vine (1963) as a "leached zone (about 60 ft. thick in drill hole AEC-1) that represents the insoluble residue left after removal of halite in the Salado by groundwater". This zone has since been noticed in the cores of several WIPP related boreholes (e.g., WIPP-19, described in Ferrall and Gibbons, 1980, p.10) and in the WIPP shafts (e.g., the waste shaft, previously called the SPDV ventilation shaft, described in WIPP-SPDV, 1983, Figure 1, sheet 11). The lower part of the Rustler Formation consists of about 120 feet of siltstone and very fine grained sandstone with several interbeds of gypsum or anhydrite. The thickness of this unit remains remarkably uniform (114 to 121 ft) as encountered in a number of WIPP boreholes as far south

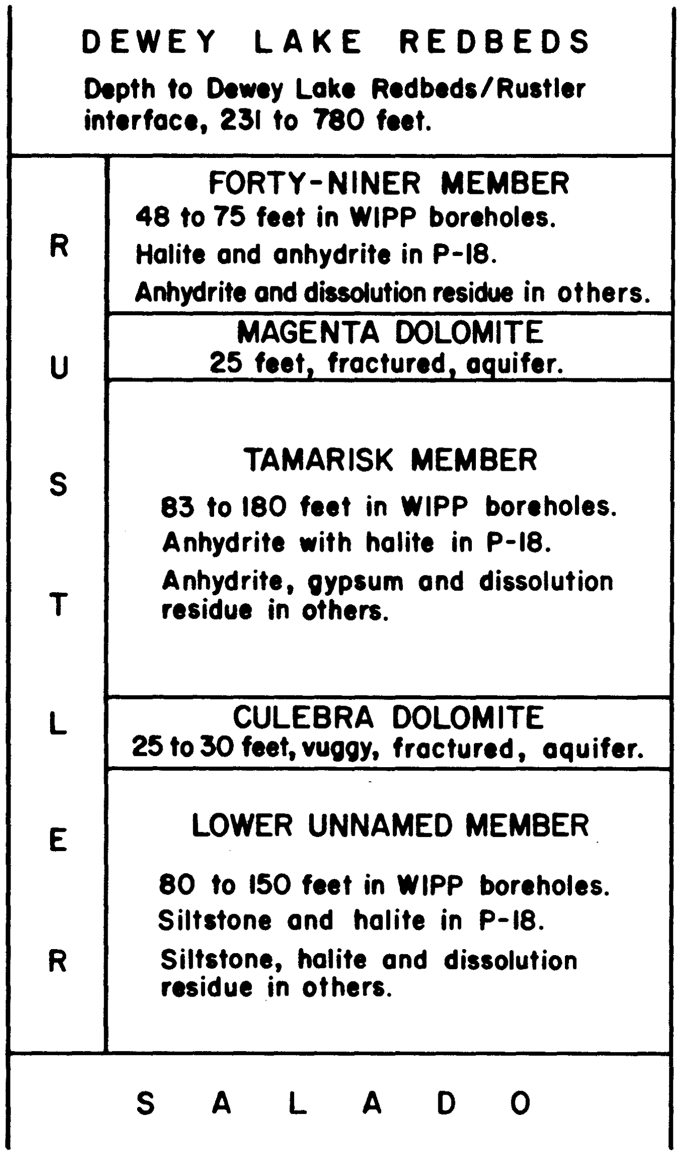

Fig. 4 Subdivisions of the Rustler Formation at the WIPP site.

as AEC-1, located about 2 miles south of ERDA-10 (Figure 1). The thickness increases to 150 feet in P-18 to the east and decreases to 80 feet in WIPP-28 in the northern part of Nash Draw. A layer of argillaceous halite, 20 feet thick, is seen in the cores of some of the wells in the upper part of this member. The halite is seen starting at about 80 ft above the Rustler/Salado interface. Overlying this salt-rich zone, one encounters a layer of anhydrite which is partially gypsified. Overlying the anhydrite and immediately below the Culebra dolomite, there is a layer of black shale which varies in thickness from 2 ft in WIPP-19 to 5 ft in H-3-b-3. This layer required an 8 ft high liner-plate in the SPDV ventilation shaft because of the instability of the shaft wall at this location. This zone is identified as a "washout zone" in the mapping of the SPDV ventilation shaft (WIPP-SPDV, 1983, Table 3).

Ferrall and Gibbons (1980) identified four zones of "solution residue" in the Lower Member from a study of the core from WIPP-19. According to them, these occur at 60 ft, 85 ft, 97 to 99 ft and 106 to 113 ft above the top of the Salado. Fractures are fairly common in the Lower Member. Most of these are vertical or very high angled, but horizontal fractures and vugs are also seen. Many of these have halite or gypsum fillings. Plate 1 shows a photograph of a large open fracture in the mudstone, about 45 feet above the Rustler/Salado contact in the WIPP-SPDV ventilation shaft.* Plate 2 shows a close-up of the "washout zone" just below the Culebra dolomite in the same shaft. The "washout zones" are the zones where "liner plates" had to be installed in the shaft due to caving. Stratigraphically, these zones correspond roughly with the "solution residue" zones of Ferrall and Gibbons (1980).

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*Now known as Construction and Salt Handling Shaft (C&SH Shaft)

2.1.2 The Culebra Dolomite Member

Adams (1944) was the first geologist to use the name Culebra for the predominantly dolomitic member overlying the lower member. He credits Walter B. Lang with "favoring" the name Culebra from Culebra Bluff on the east side of the Pecos river, where the member is well exposed. This unit, about 25 to 30 feet thick, consists of a uniformly fine textured microcrystalline grayish or light brownish dolomite with numerous small (< 1cm) vugs. These vugs are seen in the surface exposures, in cores and in the exposed walls of the WIPP shafts. Because of their presence in the core of AEC-1, Vine (1963) ruled out the possibility of these originating from some kind of surface weathering and ascribed either a primary depositional or a diagenetic phenomenon for their origin. Some of these vugs are filled with gypsum, but most of them are open.

Ferrall and Gibbons (1980) found numerous bedding plane fractures in the Culebra in the core from WIPP-19, as many as 3 to 8 per vertical foot in the lower two third and 1 to 3 per vertical foot in the upper part. They recorded numerous irregular gypsum filled, near-vertical fractures as well as high-angle planar fractures. They also described the lower 15 feet as partially leached, "so that some of the carbonate has been removed and the remaining rock appears relatively clayey and only partially cemented." Large vugs (1 to 2" diameter) were noticed in a zone about 7 feet below the top of Culebra in the SPDV ventilation shaft. A fairly prominent 1" wide clay seam is exposed near the top of Culebra. Several vertical fractures, generally 1 to 2 feet long were mapped in the lower part. One long, clay-filled fracture, about 9 feet long, was mapped in the middle part. Several clay laminae were also recorded (WIPP-SPDV, 1983, Figure 3).

The Culebra Dolomite is the major water-bearing unit above the WIPP repository.

2.1.3 The Tamarisk Member

The Tamarisk Member is that part of the Rustler Formation sandwiched between the two dolomite members, the Culebra and the Magenta. Vine (1963) gave this member its name based on its outcrop in the Tamarisk Flat area in the southern part of Nash Draw. The Tamarisk mainly consists of anhydrite and occasionally gypsum in the subsurface. In surface exposures in Nash Draw, it is highly altered to loosely packed gypsum grains and shows a high degree of deformation due to collapse following the dissolution of underlying salt. In the WIPP boreholes, the member appears as mainly anhydrite with local gypsification. The thickness varies from 83 feet in WIPP-19 to 180 feet in WIPP-13. In the SPDV-ventilation shaft, the unit was measured to be 85 feet thick and is described as mainly a gray, crystalline anhydrite with some gypsum stringers. Three clay seams, varying in thickness between 1" and 6" were mapped in the lower 25 feet of the Tamarisk. One of these forms the interface between the Culebra dolomite below and the anhydrite above. A 12 feet thick silty claystone layer was mapped, with its base 15 feet above the top of Culebra. This is identified as a "washout zone" (WIPP-SPDV, 1983, Table 3) and a liner plate had to be installed in the shaft to keep this layer stable.

In the core of borehole H-3-b-3, an 8 ft thick zone, with its base 17 ft above the top of Culebra, consists of brownish clay with breccia clasts of anhydrite and some gypsum stringers. This is clearly a dissolution residue. Ferrall and Gibbons (1980) identified a "gray clayey residue with a mottled texture" at approximately the same stratigraphic location in WIPP-19. The core of borehole H-11 also consists of brecciated anhydrite pieces in a brown clay matrix between the depths 714 to 721 ft (Plate 3). The top of Culebra in this borehole is at 739 ft depth.

2.1.4 The Magenta Dolomite Member

The Magenta Dolomite is the upper one of the two dolomite beds within the Rustler Formation. According to Adams (1944), W. B. Lang named this member after Magenta Point, a bluff north of the Salt Lake. In the outcrop, the Magenta is characterized by alternating layers of dolomite and anhydrite (or gypsum) arranged in wavy or lenticular laminae 0.2 to 5 cm thick (Vine, 1963).

In the WIPP waste shaft, 24 ft thick Magenta was mapped as dolomite with anhydrite and many gypsum stringers (WIPP-SPDV, 1983). A prominent clay seam was mapped near the upper boundary. Several open vertical fractures, up to 9 ft long, were also recorded (WIPP SPDV, 1983, Figure 2). The Magenta Dolomite shows clear horizontal bedding or layering and often the high-angled fractures show small amounts of a normal-fault like displacement across them. One such "fault" in the Magenta can be seen in Plate 4.

The Magenta Dolomite is the upper water-bearing unit of the Rustler Formation.

2.1.5 The Forty-Niner Member

Vine (1963) gave the name to the uppermost member of the Rustler from Forty-Niner ridge on the east side of Nash Draw where the member is exposed. According to Vine (1963), in outcrop the Forty-Niner member consists of about 40 to 65 ft of broken and slumped gypsum and a bed of massive siltstone near the base. In the wells, the thickness of this unit varies from 48 ft in WIPP-13 to 75 ft in P-18 with ERDA-9, WIPP-19 and the WIPP shafts recording 58 ft. The bed of siltstone seen in the outcrop also appears in the well cores and the WIPP shafts, separated from the Magenta by 15 to 20 ft of hard anhydrite. In the WIPP-SPDV shaft, this siltstone was described as a silty mudstone (12 ft) with traces of gypsum and anhydrite and a 7 ft zone of soft brown mudstone with 2.5 ft deep "washout" (WIPP-SPDV, 1983). The mudstone had to be covered by a liner plate in the shaft. Ferrall and Gibbons (1980) identified an eleven feet thick zone at the same stratigraphic horizon as this mudstone as "solution residue" in their study of the WIPP-19 core. Jones, et al (1960) also interpreted this siltstone/mudstone to represent the insoluble residue from the dissolution of a bed of halite present in the subsurface to the east.

Overlying the mudstone in the shaft there is a 30 ft layer of anhydrite with randomly oriented gypsum-filled fractures. Ferrall and Gibbons (1980) indentified four zones of leaching in this upper anhydrite in WIPP-19. From the top of Rustler, these were between 5 and 6 ft, at 10 ft, between 15 and 16.5 ft, and between 18 and 22 ft. The total thickness of the upper anhydrite in the Forty-Niner in WIPP-19 is 29 ft. Ferrall and Gibbons (1980) noted that these leached zones do not display a high degree of gypsification and concluded that, "this may be an instance of water dissolving anhydrite but removing it from the site before the calcium sulfate can be redeposited as gypsum."

2.2 Lithology of the Overlying Formations

2.2.1 The Dewey Lake Redbeds

Overlying the Rustler is a formation of clastic sedimentary beds named "Pierce Canyon Redbeds" by Lang (1935) after its outcrop in the Pierce Canyon south of the Malaga Bend. The name Dewey Lake Redbeds (DLR) was later adopted for this formation (e.g. Nicholson and Clebsch, 1961) as defined from outcrops in West Texas (Page and Adams, 1940). At the WIPP site, the formation varies in thickness from 200 ft in the SW corner to 550 ft in the SE corner (Snyder, 1983, Fig. 2-27). Lang (1935) described this formation as, "fine sandy to earthy redbeds, polka-dotted with green reduction spots and usually irregularly veined with thin secondary selenite fillings". This clear and precise description applies very well to the lithology of DLR as seen in the WIPP shafts and the drill-cores. The Dewey Lake Redbeds lie apparently conformably over the Rustler anhydrite and therefore should be assigned Permian age. There is some lingering doubt on this point, however, since at some locations it appears to grade into the overlying Santa Rosa sandstone of late Triassic age (Lang, 1947). Plate 5 shows the gypsum-filled veins in the Dewey Lake Redbeds.

In the Palo Duro Basin in the Texas Panhandle, a lithologically and stratigraphically similar formation is known as the "Quartermaster Formation". In several outcrops in Palo Duro Canyon and in Caprock Canyon State Park, as well as in cores, the red Permian mudstone belonging to the Quartermaster Formation is seen to be complexly fractured and the fractures are filled with gypsum. The appearance is identical to that shown on Plate 5. Gustavson et al (1980) hypothesized that "The complex fracturing probably occurred as a result of collapse of strata over areas of salt dissolution. As salts were removed, roof collapse spread upward, and fractures that developed in the collapsing overburden were filled with gypsum (satinspar). As dissolution and collapse occurred at depth, precipitation of gypsum in the fractures helped to hold the fractures open. Close examination of fracture fillings in outcrops indicates that several episodes of fracturing occurred." (Gustavson, et al, 1980, p.22)

2.2.2 <u>The Undivided Dockum Group (Triassic)</u>

The Dockum Group (sometimes erroneously correlated with the Santa Rosa Sandstone) unconformably overlies the Dewey Lake Redbeds and consists of cross-stratified, medium to coarse-grained, gray to yellow-brown sandstone. At the WIPP site it "...occurs as an erosional wedge pinching out westward just beyond the center of the site.' (Powers, et al, 1978). At the center of the site, in ERDA-9 and the WIPP shafts, only 9 ft of Triassic were recorded. In the eastern part of the site, as much as 200 ft of this formation has been encountered in the boreholes (Snyder, 1983, Figure 2-29).

3. DISSOLUTION OF SALT FROM THE RUSTLER FORMATION

3.1 The Nash Draw

The WIPP site is situated in close proximity to a major topographic depression feature called Nash Draw (Figure 5). This depression is formed by land-subsidence resulting from dissolution and erosion of the evaporite rocks present near the surface. According to Bachman (1981), who has studied these processes in Nash Draw in detail, the draw exhibits a complex karst topography with caves, sinks and tunnels formed in the Rustler Formation. Salt from the underlying Salado Formation has also been dissolved so that the thickness of the upper part of Salado (Rustler/Salado interface to Marker Bed 101) ranges between 24 to 78 feet in Nash Draw as compared to 117 feet in WIPP-12.

Collapse sinks are common throughout Nash Draw and have coalesced to form large basins at many locations. The salt lake, Laguna Grande de la Sal, in the southern part of the draw (Figure 5) most likely originated in this manner. The drainage in Nash Draw is typical of karst regions. There are no perennial streams but several arroyos drain in collapse sinks. Nash Draw represents about 200 feet of collapse.

Although the nearest edge of the Nash Draw (as defined by the Livingston Ridge escarpment) from the WIPP site is about a mile from the northwestern corner of WIPP, the processes of dissolution and collapse which characterize the Nash Draw have affected the subsurface to the east of the Nash Draw boundary. The borehole WIPP-33 (Figure 1) is located just outside the northwestern corner of WIPP, about 1.5 miles east of the eastern edge of Nash Draw. This hole was drilled in a closed depression (shown in Figure 5) to determine if the depression was the result of dissolution and collapse and to determine if

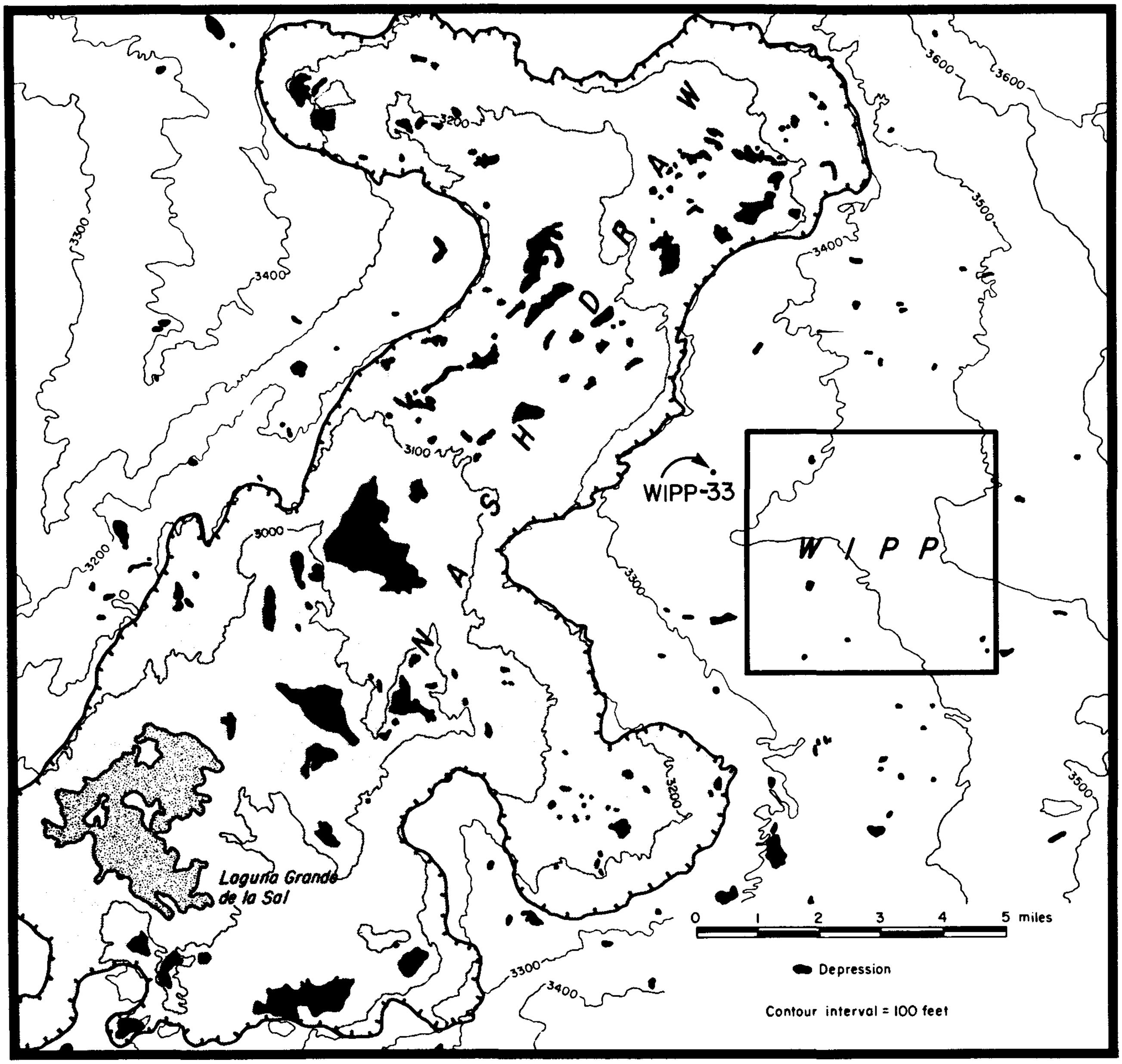

Fig. 5 Closed depressions at and near the WIPP site, based on USGS Nash Draw Quadrangle, 15 minute series.

dissolution has been active in beds underlying the Rustler Formation. According to Bachman (1981), "The Rustler Formation in WIPP-33 was found to be cavernous throughout much of its interval where dissolution has been active". Bachman (1981) further believes that the spring deposits composed of gypsite found in Nash Draw, about 2 miles west of WIPP-33 "...resulted from evaporation of groundwater which drained from the surface into fractures and circulated through and dissolved the Rustler Formation". It is thus clear that the processes which created Nash Draw, primarily dissolution of the Rustler Formation, have had an advanced effect in the subsurface to the east, at least to WIPP-33.

Bachman (1985) has concluded, "...true karst features should not be predicted on the Livingston Ridge surface east of the indicated dissolution front in the Rustler." Bachman's "dissolution front" is the line dividing Zones 1 and 2 in Fig. 9 of this report which is about 1 mile east of WIPP-33. Since salt from the Rustler above the Culebra is missing for a further 2 miles to the east (see Fig. 9), the prediction of karst features on this basis alone would encompass practically the entire WIPP site. Other aspects of the karst proposition are discussed in Chapter 4.

3.2 The Rustler Isopachs

The thickness of the Rustler Formation varies between 300 to 320 feet in all the wells drilled west of the eastern boundary of Zone II of the WIPP site, but changes dramatically as one proceeds east. Figure 6 is an isopach map of the Rustler Formation as prepared by Griswold (1977). There is a more recent map by Snyder (1983) based on a few additional boreholes, drawn with a contour interval of 25 feet, but the basic picture remains the same. Figure 7 shows the isopach lines for the upper Salado Formation, between the top of

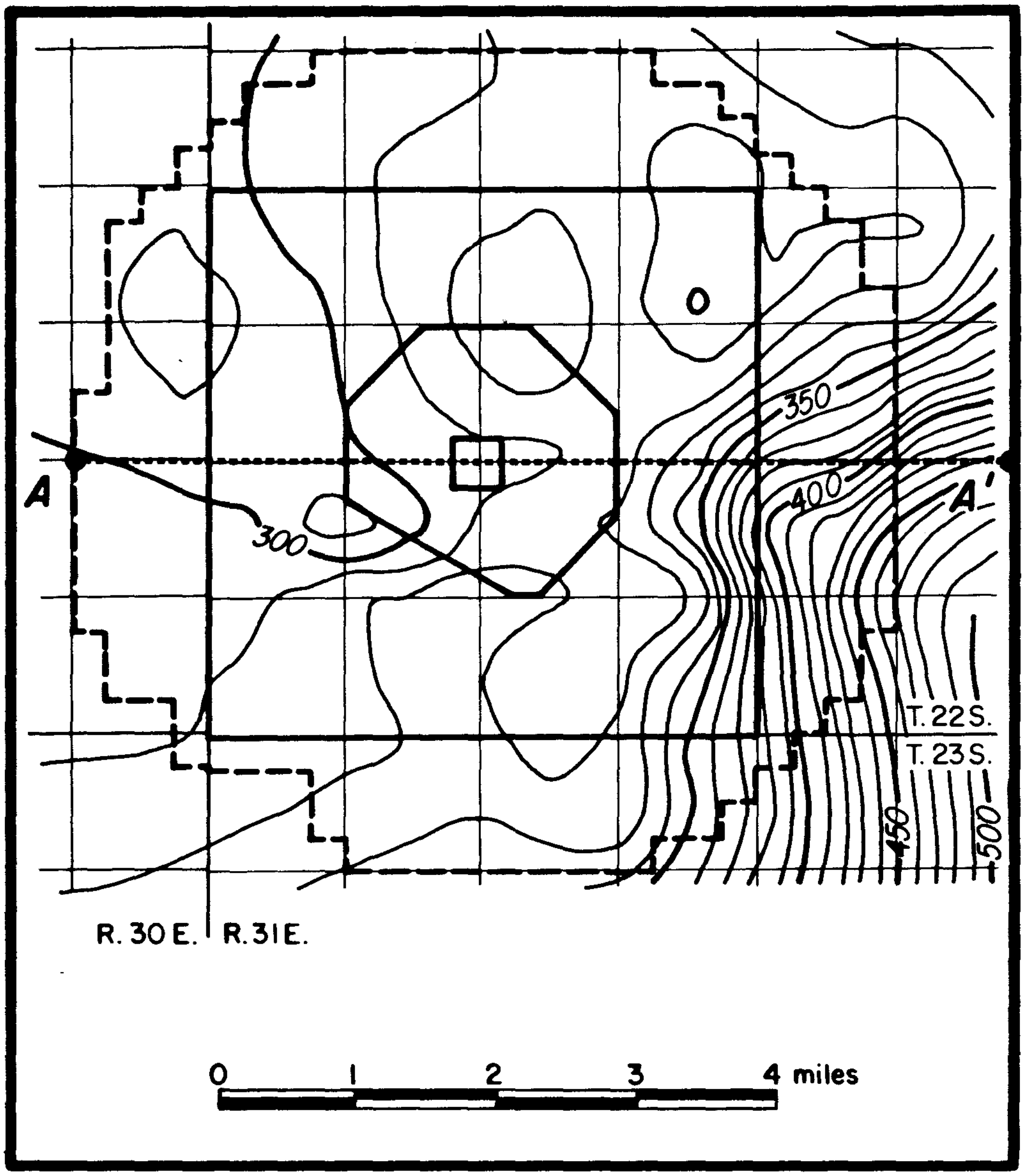

Fig. 6 Isopach map of the Rustler Formation (after Griswold, 1977).

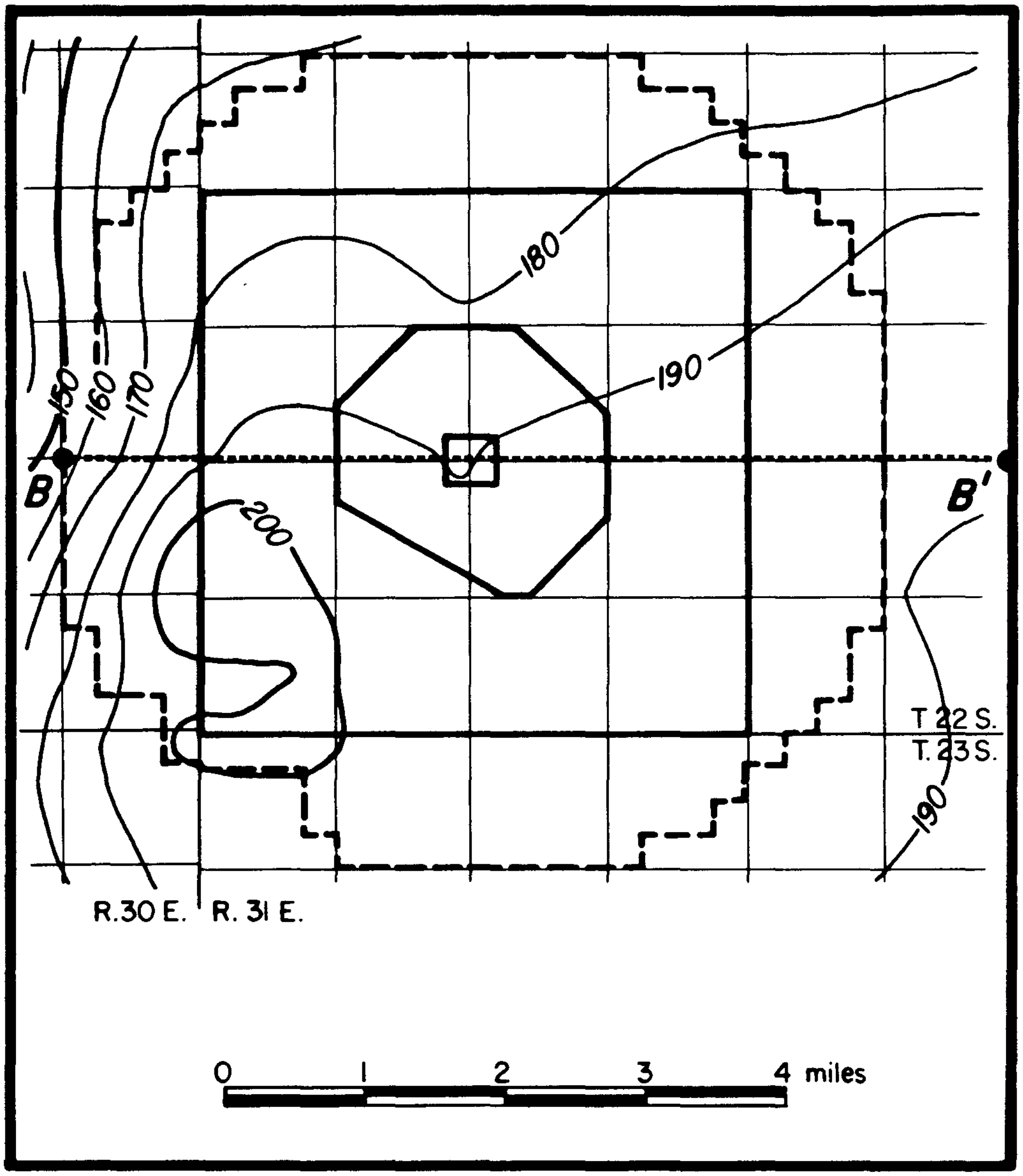

Fig. 7 Isopach map of the Upper Salado Formation (top of Salado to M.B. 103). (After Griswold, 1977.)

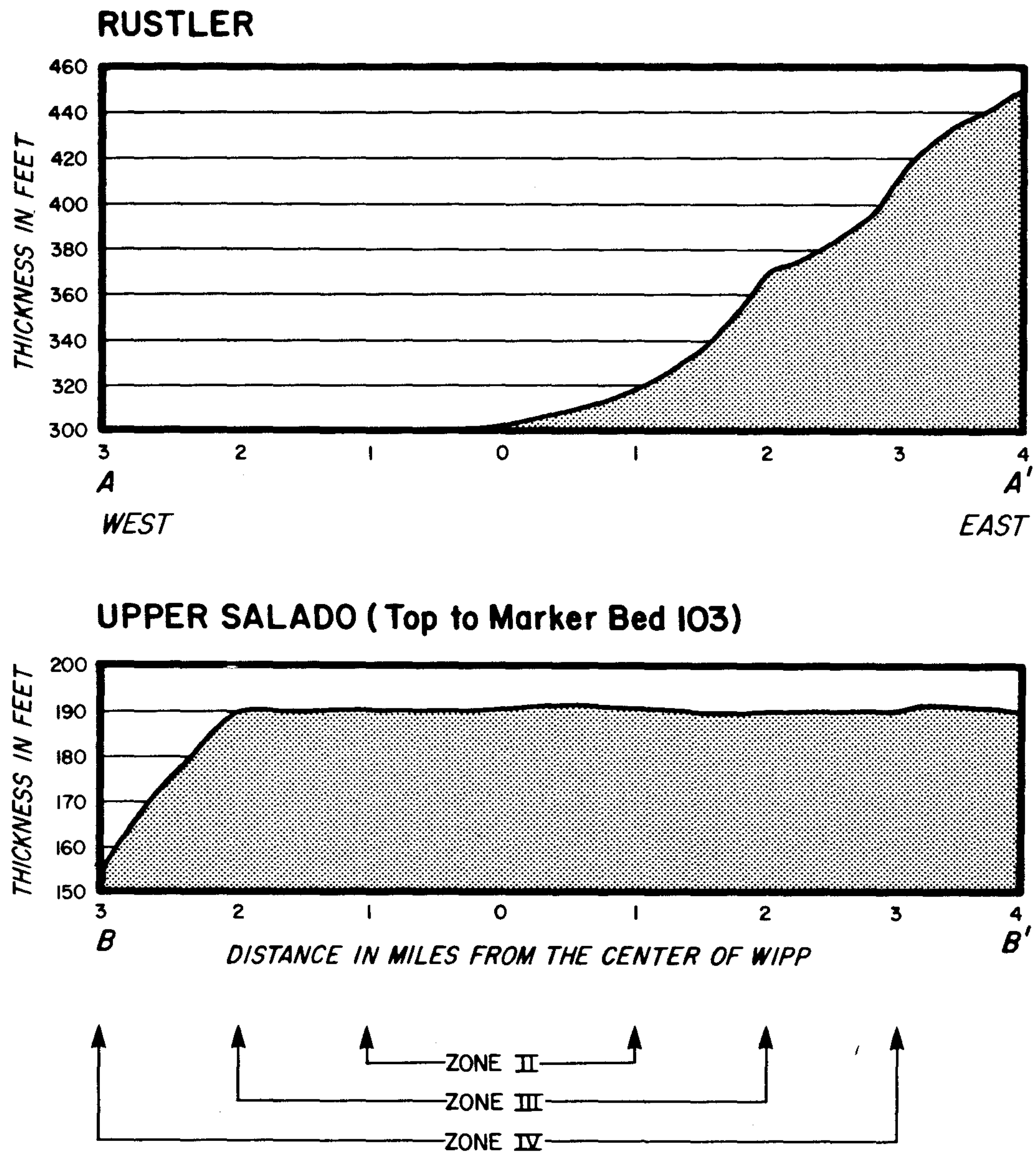

Fig. 8 Change in thickness of the Rustler and the Upper Salado Formations across the WIPP site. (See Figures 6 and 7 for A-A' and B-B'.)

Salado to Marker Bed 103. This approximately 190 feet thick unit remains remarkably uniform in thickness throughout the WIPP site except to the west of the 4 x 4 mile "WIPP site" boundary where it begins to narrow rather severely so that its thickness is reduced by 20% in one mile. Figure 8 is a graphic presentation of the change in thickness of the Rustler and the Upper Salado across the WIPP site from west to east.

If one assumes that there were only minor variations in the depositional thickness of the Rustler and the Upper Salado within the small area constituting the WIPP site, then the changes in thickness must have been caused by post-depositional phenomena. The abrupt thinning of the Rustler Formation directly above the WIPP site very likely reflects the effect of salt removal from this Formation.

The thickness of the Rustler encountered in the boreholes drilled in Nash Draw (WIPP-25,26,27,28,29 and 32) is approximately the same as at the center of the site (e.g. ERDA-9, WIPP-12, 13, 19 and H-3), even though the salt is completely dissolved from the Rustler in Nash Draw. Snyder (1985) attributes this to the volume increase associated with extensive gypsification of the Rustler anhydrites in the Nash Draw region.

3.3 Halite Beds in the Rustler

About 50% of the Rustler consists of halite in areas where the Rustler shows maximum thickness. Thus borehole P-18 was found to contain three thick beds of halite (with minor amounts of polyhalite, gypsum and clay) totalling 54% of the thickness of Rustler (interpreted from the lithologic log, pp. 351-365, Jones, 1978). These were found above the Magenta (upper halite, 32 feet thick), between Magenta and Culebra (middle halite, 105 feet thick) and below Culebra (lower halite, 120

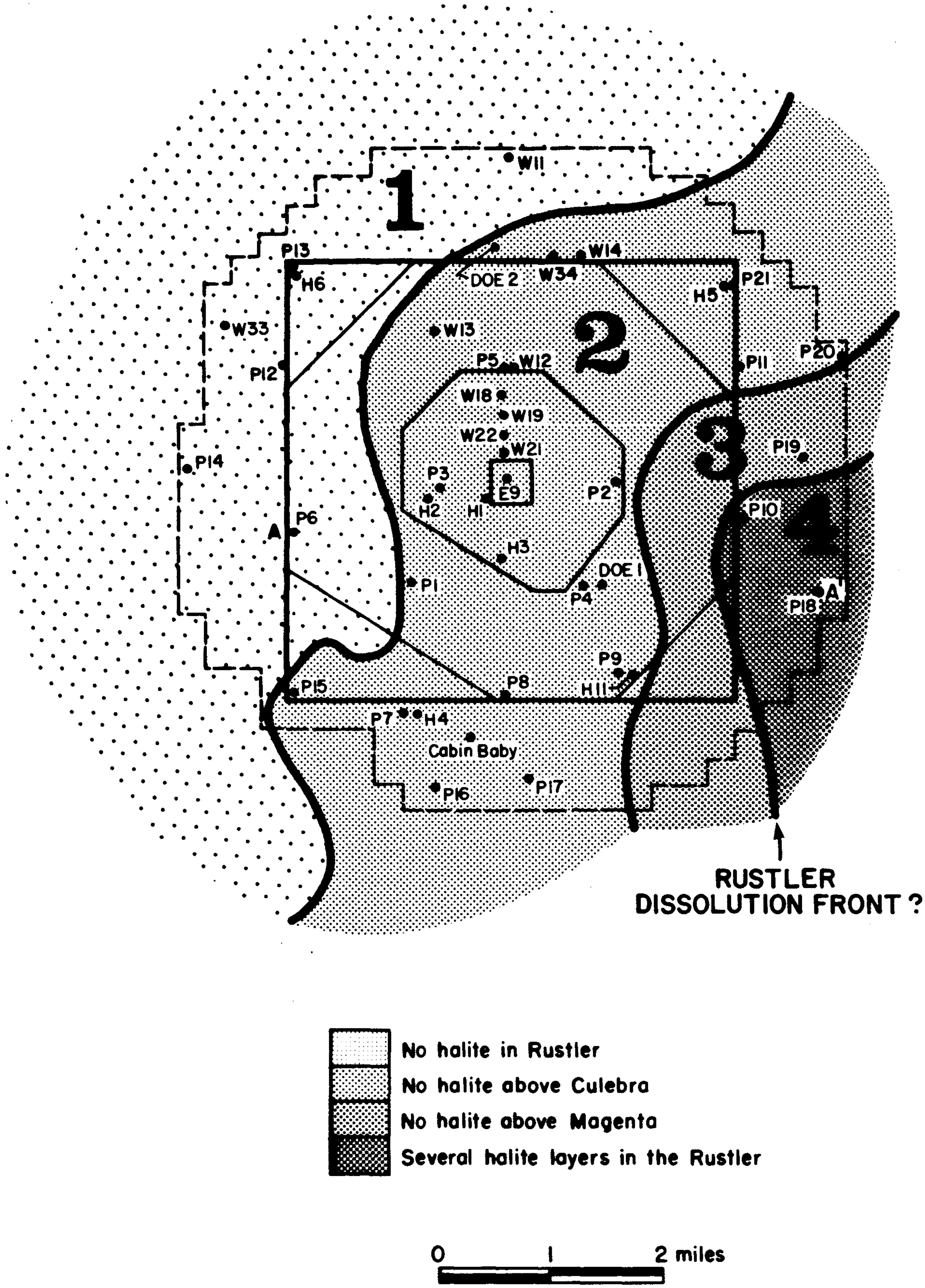

Fig. 9 Pattern of absence of halite in the Rustler Formation across the WIPP site (modified from Snyder, 1985).

feet). The description of intact, undissolved Rustler, therefore should characterize it as mainly a salt formation with anhydrite, dolomite and clastics.

The Rustler salt beds are absent to the west of P-18 in a pattern as depicted in Figure 9. Salt is found above Magenta, between Magenta and Culebra and below Culebra in region 4 (in P-10 and P-18). The salt layer above Magenta is absent in region 3; P-19 is the only WIPP related well that falls in this region. Region 2 wells found halite below Culebra but none above it. WIPP Zone II falls completely within this region. As shown in Figures 17, 18 and 19 of Gonzalez (1983), there was some doubt about the presence of halite below Culebra in H-3, H-11 and DOE-1. Recent examination of cores from boreholes H-3-b-3 and H-11-b-3 clearly shows that halite is present below Culebra in both of these. In the recently drilled core of DOE-2, halite is seen mixed with brown clay, at a depth of 864 feet below the surface, 18 feet below the bottom of Culebra. Information from DOE-1 is unreliable because, "The fresh water mud used for the first 1,130 feet of drilling probably dissolved any halite occurring in the Rustler so none was observed directly." (WIPP-TME 3159, p.3-7). Finally, the wells located in Region 1 found no halite in Rustler. Figure 10 shows a comparison between the geophysical logs taken from the wells P-6 and P-18. Snyder (Personal Communication) has correlated the polyhalite bed seen as a sharp kick on Gamma Ray log of P-18 at 200 ft, with the clay kick at about 160 ft on P-6 Gamma Ray log (Fig. 10). The polyhalite bed is also found in holes P-10, H-10 and H-12 (east and southeast of WIPP site) and can be correlated with the "clay kicks" in geophysical logs and dissolution residue in cores of wells to the west.

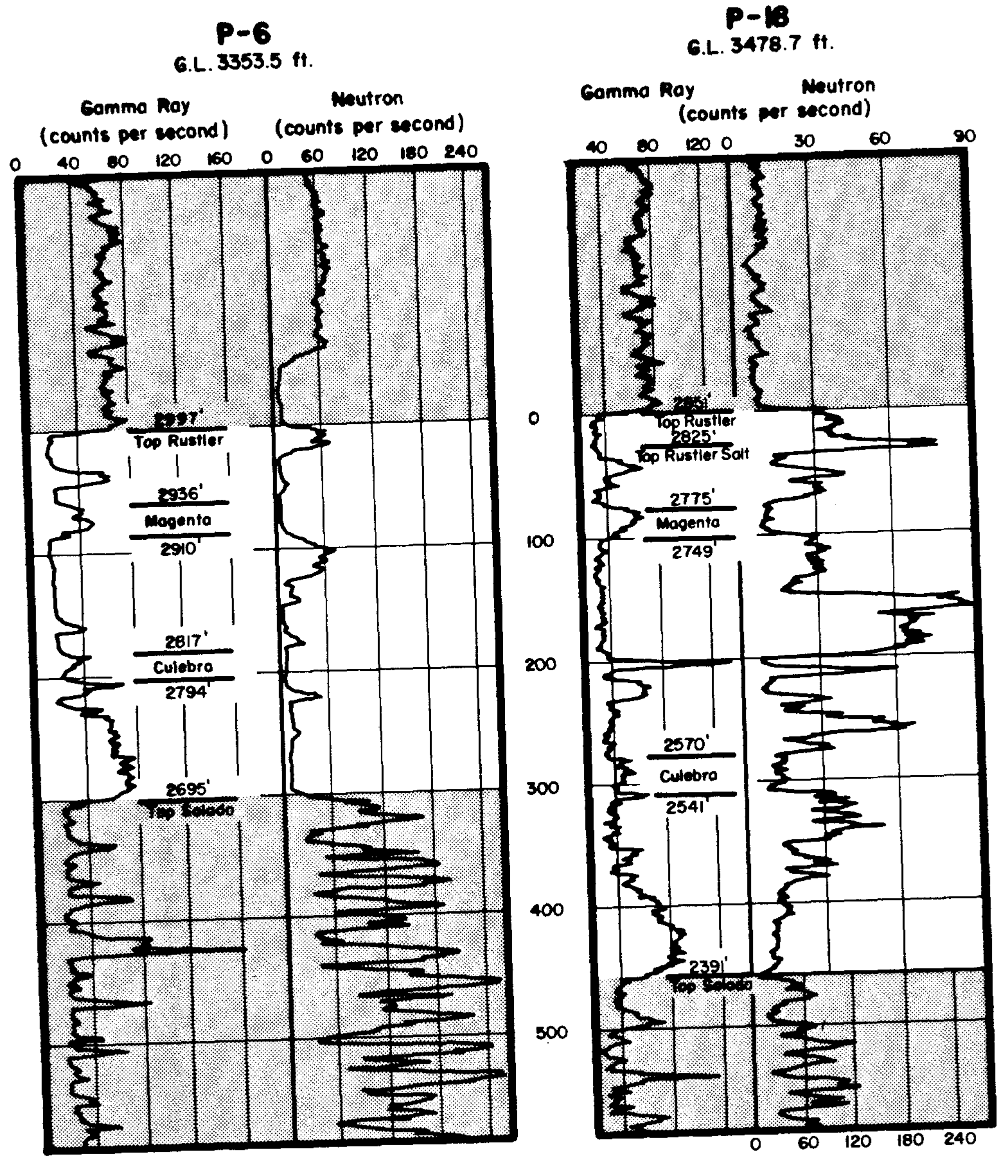

Fig. 10 A comparison between the geophysical logs of wells P-6 and P-18.

3.4 Dissolution Residues

The only layer of clastic sedimentary rock seen in the cuttings and geophysical logs of the Rustler Formation in well P-18, here taken as representing a complete Rustler section, is in the bottom 30 feet of the formation (Jones, 1978). The rest of the formation at this location consists of layers of halite, anhydrite and dolomite. Compared to this, the wells in Regions 1 and 2 (Figure 9) where halite is completely missing from the Rustler or is found only below the Culebra, encounter several layers of clastics (mudstone, siltstone and breccia in clay matrix) at different horizons in the formation. These layers are at the same stratigraphic locations as the halite layers of the wells in Region 4, and may have therefore resulted from the dissolution of salt.

Figure 11 is a stratigraphic cross-section along the line A-A′ of Figure 9. It shows three zones of "Breccia and Mudstone" corresponding to the halite layers in P-18. These are here called the upper, middle and lower dissolution residues.

3.4.1 The Upper Residue

In DOE-1, Magenta was found between 722 to 745 feet below the surface. Directly above the Magenta, there is an approximately 10 ft thick layer with low gamma-ray and high bulk density on the geophysical logs and identified as anhydrite in the cuttings. Overlying the anhydrite, there is an approximately 10 ft thick layer with high gamma-ray readings and distinctly low bulk density. In the cuttings this material is identified as "dark - reddish - brown sandy siltstone and yellow-green claystone" (DOE-WIPP,1982). In the core from borehole H-3-b-3 between 533 and 543 ft below surface, stratigraphically equivalent material is seen as reddish brown mudstone containing anhydrite clasts and gypsum

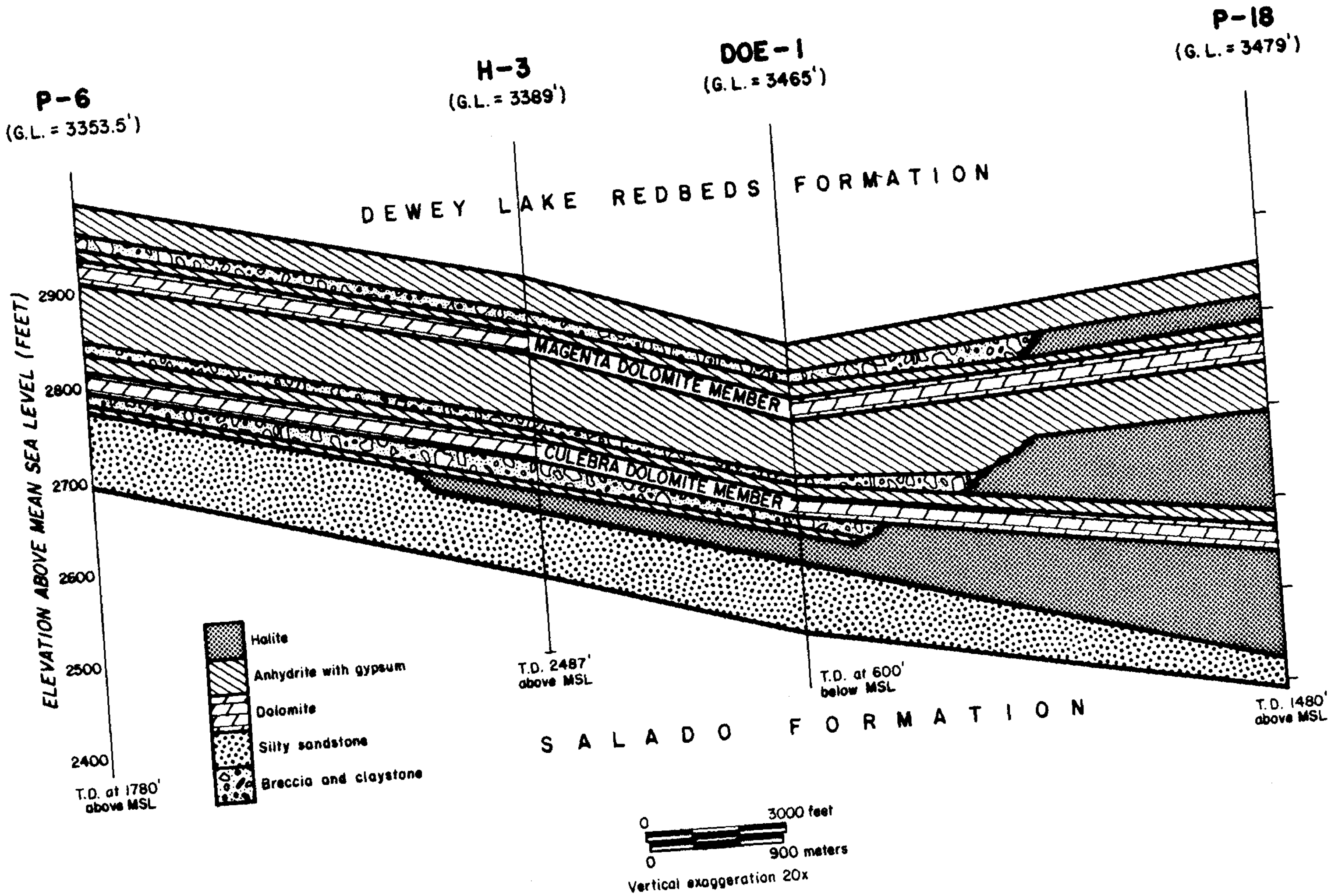

Fig. 11 Geologic cross section of the Rustler Formation scross the WIPP site. (See Fig. 9 for the line of section A-A'.)

veins grading into a greenish claystone at the bottom and separated from the Magenta by about 10 ft of anhydrite. In P-6, a high gamma-ray layer in the Forty-niner is separated from the Magenta by 13 feet of anhydrite. This layer of breccia and claystone in the Forty-niner is seen in the cores or cuttings of other wells also at the same stratigraphic position. Among the wells for which Basic Data Reports are not yet available, H-11-b-3 core shows a 6 ft layer of clay with breccia separated from the Magenta by 20 ft of anhydrite. DOE-2 core shows an 8 feet thick zone of dark-brown-sandy siltstone separated from the Magenta by 20 feet of anhydrite. Ferrall and Gibbons (1980) found this layer in WIPP-19 to include, "some gypsum stringers and occasional breccia clasts and gypsum-filled voids" and called it the "49'r (sic) member solution residue" (p.34).

3.4.2 The Middle Residue

The Tamarisk Member consists mostly of a very uniform gray anhydrite with white gypsum rims. This very typical and easily identifiable rock is described from the cuttings from P-6, P-18 and DOE-1 and in the core from H-3-b-3. The anhydrite cuttings from P-6 and DOE-1 from this zone are mixed with about 5% of dark-reddish-brown siltstone, whereas the P-18 cuttings show no trace of any clastic material in the Tamarisk. The lower 2/3rd of the Tamarisk in P-18, except the lowest 10 ft, consists of clear halite with small amounts of red-orange polyhalite and fine-grained anhydrite. In the cuttings of DOE-1 and P-6 there is increasing amount of dark-reddish-brown-siltstone in the lower Tamarisk with a thin layer of anhydrite just above the Culebra. The core of H-3-b-3 clearly shows the nature of this zone. From about 640 ft to 654 ft depth in this borehole, angular pieces of anhydrite in a clay/silt matrix are seen. This 14 ft thick zone appears to represent a residue produced from the dissolution of halite from the halite-rich zone found at the same stratigraphic horizon to the east, e.g. in P-18. This zone is separated from the underlying Culebra Dolomite by an approximately 10 ft thick zone of anhydrite, which is also seen in P-18.

Ferrall and Gibbons (1980) have studied this dissolution residue in the cores of several WIPP boreholes. A particularly good example illustrated by them from WIPP-13 core is of breccia clasts of anhydrite up to 1 foot thick which are infilled with the residue, implying collapse.

3.4.3 The Lower Residue

The "breccia and claystone" just below the Culebra Dolomite shown in Figure 11 is classified here as the lower residue. Immediately underlying the Culebra Dolomite, there is an approximately 2 ft thick layer of black shale which appears to have been deposited preceding the deposition of the dolomite. Immediately underlying this shale layer, there is approximately 7 to 8 ft of cemented red-brown siltstone with brecciated anhydrite clasts and gypsum stringers. Most boreholes show poor core recovery from this interval. No core was recovered in DOE-2 from 847.6 to 849 ft depth, just below the black shale zone. In H-3-b-3, only 20% of the core was recovered from a 5.5 feet zone directly below the Culebra dolomite from 691.5 feet to 697 ft depth. In H-11-b-3, there was no recovery from 764 to 766 ft depth, just below the black shale layer. The poor core recovery attests to the poorly consolidated nature of this dissolution zone.

Ferrall and Gibbons (1980) have identified two more dissolution residues in the lower unnamed member of the Rustler below the one just described. However, since these zones are sandwiched between halite-bearing sediments in H-3 and DOE-1, these are not interpreted here as dissolution residue zones.

In the lithologic log of P-18, the black shale occurring below the Culebra is not identified. There is, however, a distinctive gamma-ray "kick" in the P-18 geophysical log at the base of Culebra at 938 ft depth, (2541 ft above M.S.L., Fig. 10) which most likely indicates the shale layer. The lithologic log of P-18 from 940 ft to 1,005 ft depth shows "clear halite with trace of polyhalite." Minor amounts of brown clay started appearing from 1,005 to 1,020 ft and increased to "large amounts of brown clay" between 1,020 to 1,060 ft. The rest of the Rustler, down to 1,090 ft, consists of red-brown mudstone/siltstone. The core of H-12 (See Fig. 1) also contains 5.5 ft of red-brown siltstone underlying the black clay (Snyder, personal communication). There is thus no indication of dissolution to the east and southeast of WIPP site.

3.5 Movement of Water Through Rustler

The geohydrology of the Rustler Formation in the vicinity of the WIPP site has been described by Robinson and Lang (1938), Theis and Sayre (1942), Cooper and Glanzman (1971), Brokaw et al (1972), Mercer and Orr (1979), Gonzales (1983) and Mercer (1983). The following description summarizes the essential features of the Rustler hydrology.

There are three primary zones within the Rustler Formation which contain water, viz, the Magenta, the Culebra and the Rustler/Salado contact zone (Fig. 4). Brokaw et al (1972) contoured the water levels in wells drilled in the Rustler and overlying formations. Such a generalized water level contour map provides a rough regional picture of groundwater flow directions which is to the southwest in the vicinity of the WIPP site (Fig. 12). Mercer (1983) has drawn the adjusted potentiometric surface maps for the three main water-bearing zones within the Rustler. The potentiometric contours in

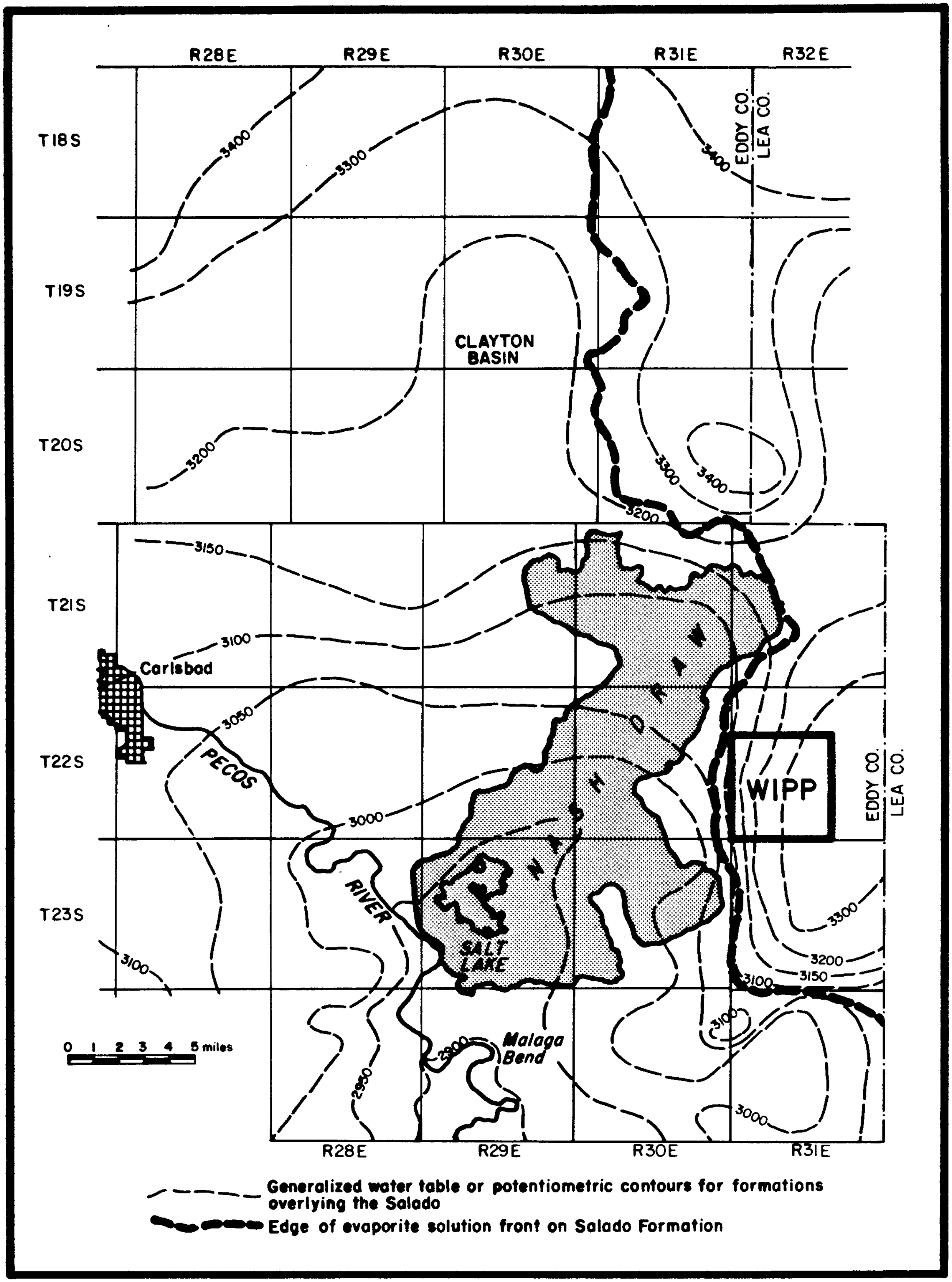

Fig. 12 A generalized water level contour map for formations overlying the Salado. (Data from Brokaw, et al., 1972.)

these maps (Figs. 13, 14 and 15) indicate the altitudes at which water having a density of 1.00 gm per c.c. would stand in a tightly cased well.

Figure 13 shows the potentiometric contours for the Rustler-Salado contact residuum as drawn by Mercer (1983). This zone was called the "brine aquifer" by pre-WIPP investigators and it was assumed to be confined to Nash Draw (Robinson and Lang, 1938) in the absence of data east of Nash Draw. The data from WIPP boreholes shows that the aquifer extends east of the Livingston Ridge on to the WIPP site and is not confined by the physiographic depression of Nash Draw. Most of the WIPP boreholes have found moisture at this zone. In fact, the hole P-18 produced more water from this zone than from the Culebra and the recovery rate was comparatively much faster (Mercer and Orr, 1979, p.120).* Figure 14 of Mercer (1983) -not reproduced here- shows the "brine aquifer" confined to Nash Draw and is therefore not up-to-date. The potentiometric contours show the flow direction to be southwesterly from the WIPP site, towards Laguna Grande de la Sal and the Malaga Bend on the Pecos River.

Figure 14 shows the adjusted potentiometric contours of the Culebra Dolomite Member of the Rustler Formation, as drawn by Mercer (1983). The general direction of flow in the Culebra is to the south and southwest from the WIPP site to the Pecos River at Malaga Bend. The hydraulic gradient at the site and

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*The following is the complete quotation from Mercer (1983): "The long-term Rustler-Salado recovery rate was much faster than the Culebra recovery rate. This might be attributed to several factors. The Rustler-Salado contact may indeed be more permeable, resulting in greater production and faster recovery rates or fractures contributing to the Culebra permeability may have been sealed off during cementing or missed completely during perforation."

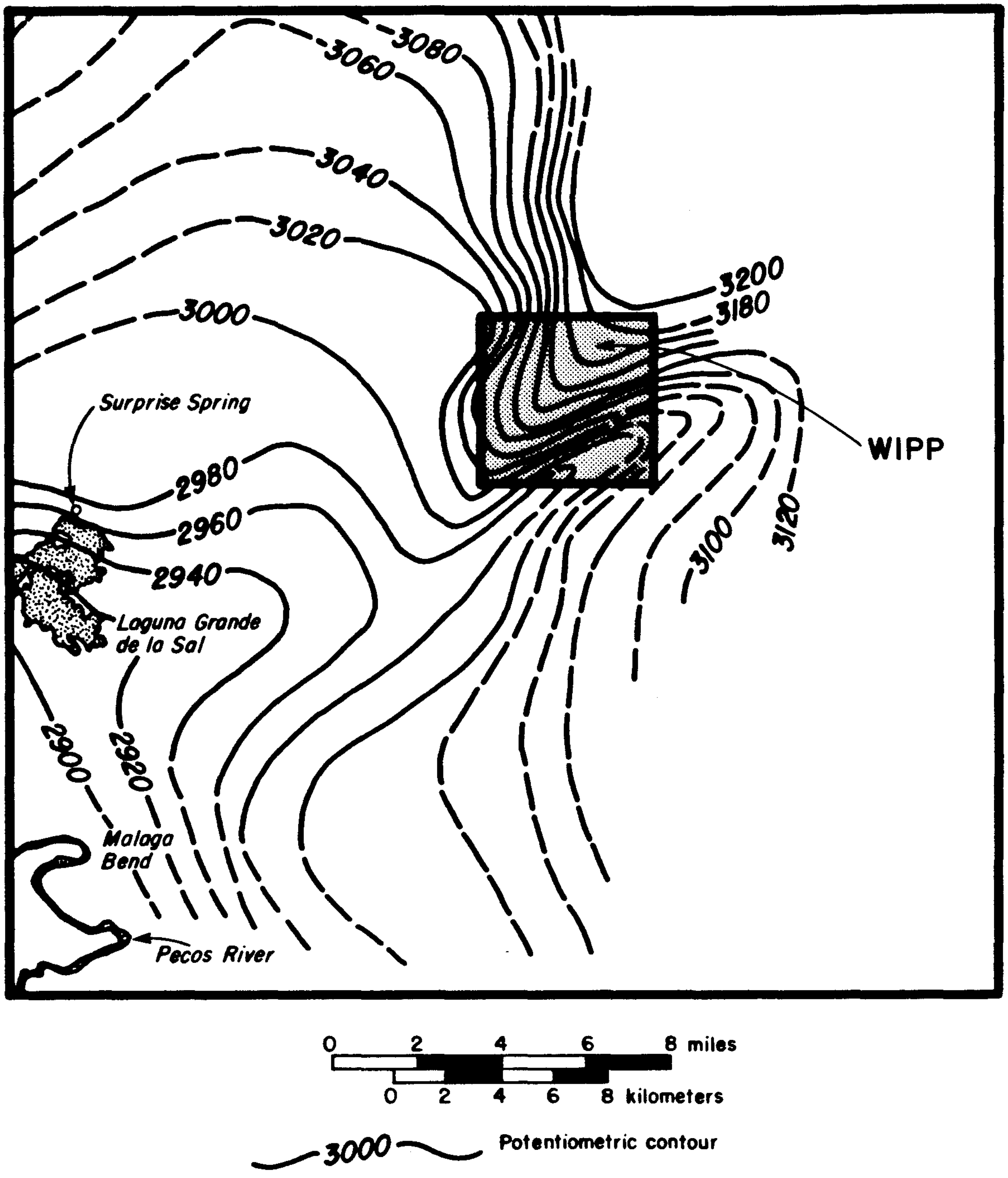

Fig. 13 Adjusted potentiometric contours of the Rustler/Salado contact residuum (from Mercer, 1983).

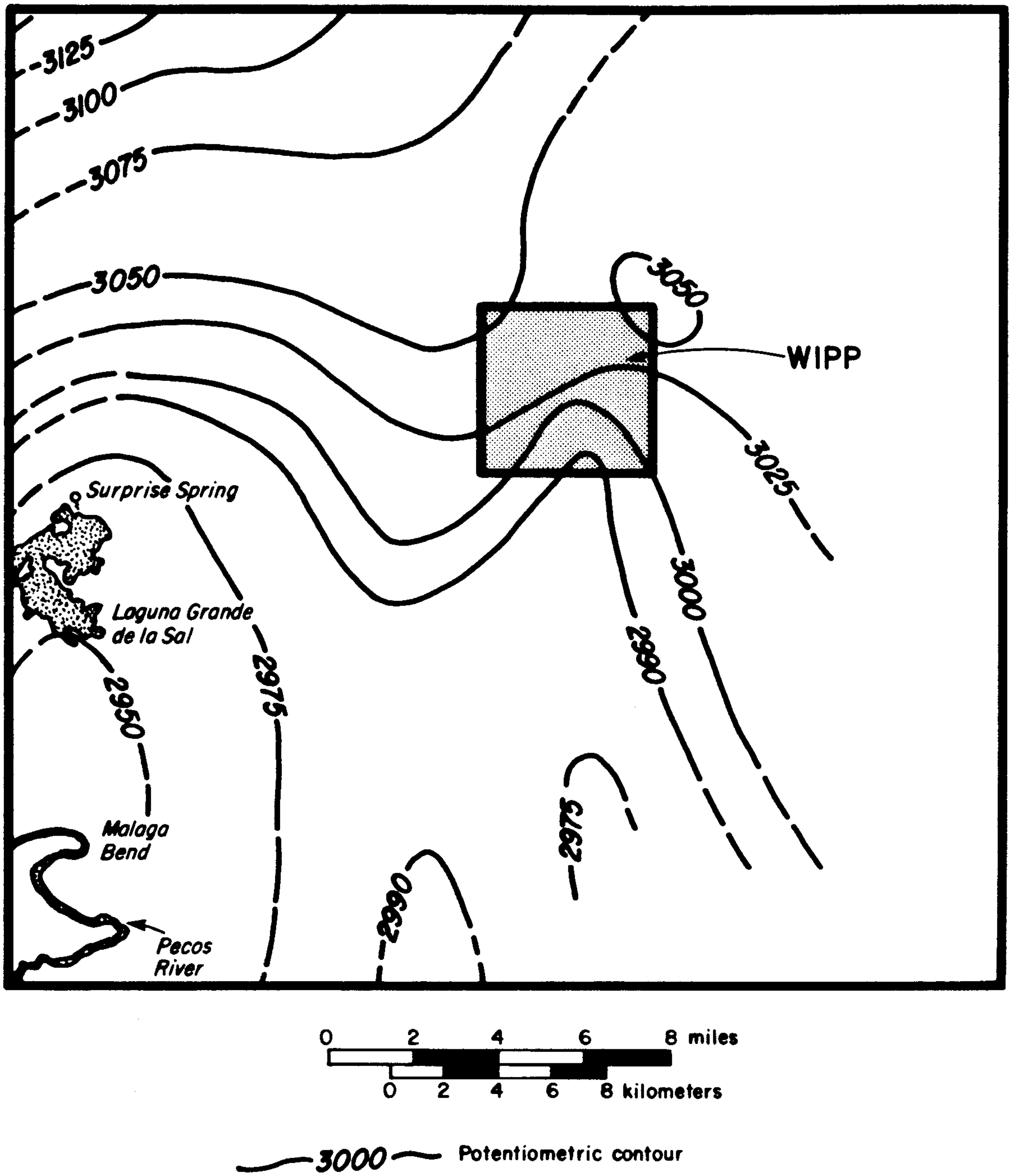

Fig. 14 Adjusted potentiometric contours of the Culebra Dolomite Member of the Rustler Formation (from Mercer, 1983).

in Nash Draw is approximately 20 ft per mile, which flattens to about 7 ft per mile between Laguna Grande de la Sal and the Malaga Bend. Transmissivities measured by single-hole tests at the WIPP site range from 1×10^{-3} ft^2/day at P-18 in the eastern part of the WIPP site to 140 ft^2/day at P-14 (Mercer, 1983). The assumption of Culebra transmissivities at the WIPP site as being "generally less than 1 foot squared per day" (Mercer, 1983, p.58) is not correct since a transmissivity of 19 ft^2/day was measured at H-3, (Mercer, 1983 Table 7), which is located less than 200 ft from the proposed repository. Also, the results of a flow test conducted by pumping DOE-1 for 18 days at an average rate of 10 gpm and using H-3 as one of the observation wells showed the transmissivity at DOE-1 to be between 25 and 36 ft^2/day (Gonzales, et al, 1984). An aquifer test conducted for Culebra in the northern part of the site at DOE-2 with observed drawdowns at H-5 and H-6 also yielded a transmissivity value of approximately 50 ft^2/day (Beauheim, 1984). Some wells near the WIPP repository, e.g. H-1 and H-2, yielded transmissivity values below 1 ft^2/day in single-well tests (Mercer, 1983).

Figure 15 shows the adjusted potentiometric contours for the Magenta Dolomite Member, as drawn by Mercer (1983). The general flow direction from the WIPP site is west-southwest. The hydraulic gradient is about 15 to 20 ft per mile on the eastern side of the WIPP site, steepening to 30 feet per mile to the west. The gradient in Nash Draw, northwest of the WIPP site, is 13 feet per mile which reflects a more uniform permeability compared to the WIPP site (Mercer, 1983). The measured transmissivity for Magenta is less than that for Culebra, 0.3 ft^2/day at H-6 and 0.1 ft^2/day at H-3. The Magenta is much more transmissive in Nash Draw, e.g., T=375 ft^2/day at WIPP-25.

There are some indications that water exists in the Rustler Formation outside the three discrete zones described above.

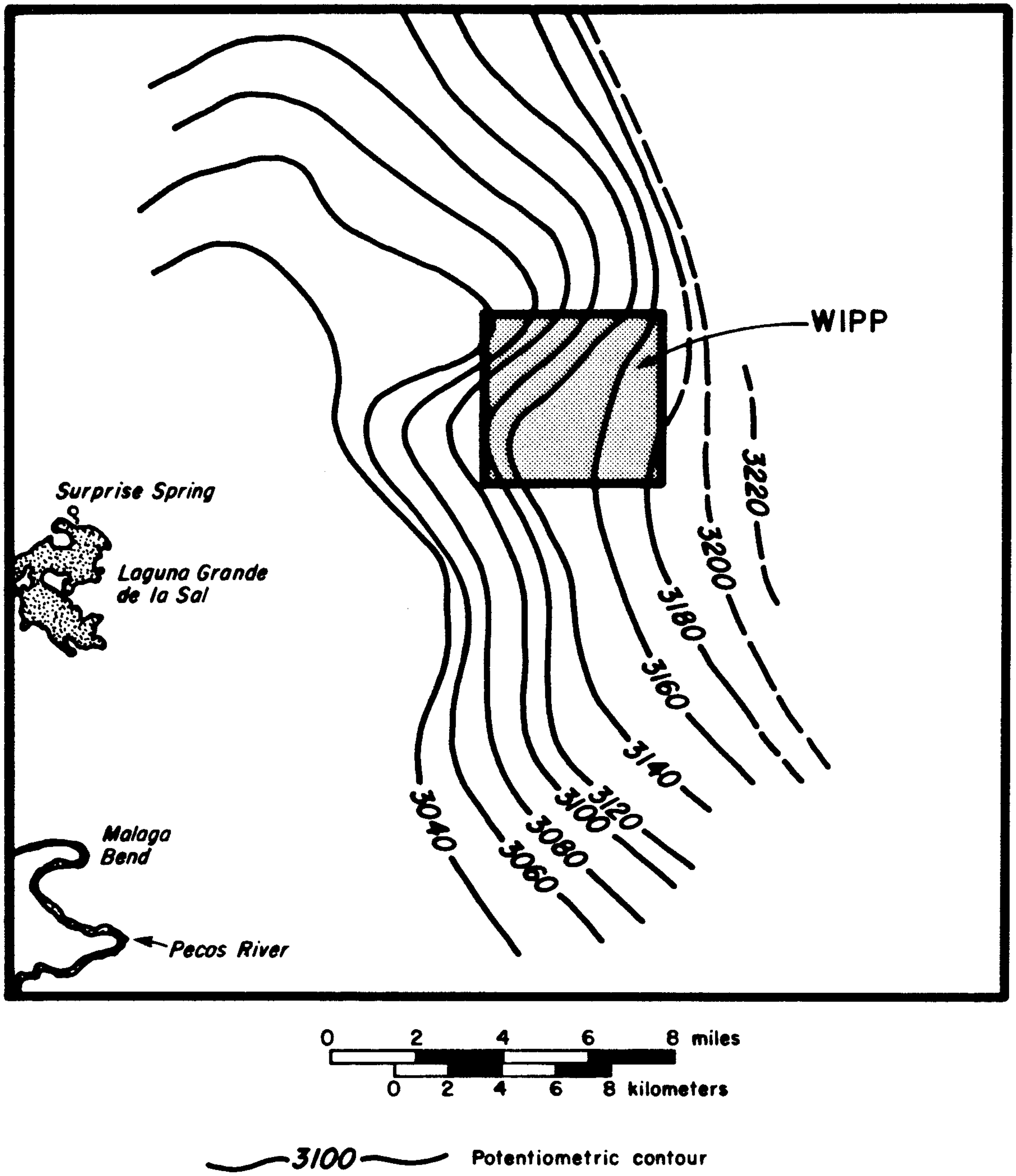

Fig. 15 Adjusted potentiometric contours of the Culebra Dolomite Member of the Rustler Formation (from Mercer, 1983).

Mercer and Orr (1979) described drill-stem tests in "salt-residue zones". Such a zone in the Tamarisk Member of Rustler (in well H-1) yielded water at a rate of 0.933 gallons per hour while the Culebra yielded 0.922 gallons per hour, Magenta yielded 0.962 gallons per hour and the Rustler/Salado contact yielded 0.455 gallons per hour (Mercer and Orr, 1979, p.28). Similarly, a salt residue in the lower unnamed member of the Rustler Formation was tested in the borehole H-3. In a drill-stem test, this zone yielded as much water as the Magenta, Culebra and the Rustler/Salado contact (Mercer and Orr, 1979, p.44). A direct observation of a "salt-residue zone" in the Forty-niner Member of the Rustler Formation yielding water was made in the ventilation shaft (the waste shaft before enlargement). The water was observed seeping into the shaft from a zone 30 feet above the top of Magenta. Another indication of the existence of water in zones outside the three identified water-bearing units in the Rustler is provided by the readings of piezometers in the Construction and Salt Handling shaft. Ten piezometers, two each at five different levels within the Rustler were installed to continuously measure the hydrostatic pressures in the rock. One set each was installed in the Magenta and the Culebra and the remaining three pairs were installed at levels above the Magenta, between the Culebra and the Magenta and below the Culebra. All the piezometers, including those outside the recognized water-bearing zones, showed a reading of between 100 and 125 psi during the 2 years of operation from July 1982 through December 1984 (U.S. DOE, 1985, pp.2-28 to 2-37).

There are indications of the existence of fracture zones outside the Magenta and Culebra Dolomites in the Rustler. Open fractures were observed during the mapping of the WIPP shafts (Plate 1). During the drilling operations, a few wells are reported to have encountered zones of loss of circulation in various parts of the Rustler. Well H-1 encountered a loss of circulation in the Forty-niner Member above the Magenta (Mercer and Orr, 1979, p.23). WIPP-33 encountered several such zones and is described in chapter 4. Table 1 provides information on the measured and corrected water levels in several WIPP boreholes for the three major water-bearing units of the Rustler Formation. The last three columns of this table show the differences in fresh-water hydraulic heads between the Magenta and the Rustler/Salado contact residuum, between the Magenta and the Culebra, and between the Culebra and the Rustler/Salado contact residuum, respectively. It is clear from these values that the Magenta water is at a higher hydraulic head than water in both the Culebra and the Rustler/Salado contact residuum. The comparison of fresh water heads between the Culebra and the R/S contact is, however, confusing. In most cases, the uncorrected Culebra level is higher than the uncorrected Rustler/Salado contact. When corrected to fresh water densities, out of the data for 15 wells, 8 show Rustler/Salado contact head higher than the Culebra and the remaining 7 show the reverse.

There is a clear pattern, however, to the head difference between the Magenta and the Culebra, which is maximum to the east and zero in Nash Draw. Thus, the Magenta/Culebra head difference at the center part of the WIPP site in H-3, H-4, H-1 and H-2 are 155 ft, 151 ft, 138 ft and 115 ft, respectively. Moving from northeast to southwest in the area south of the WIPP site, the difference is 198 ft at H-10, 144 ft at H-9, and 38 ft at H-8. The head difference in the Nash Draw wells W-25 and W-27 are 4 ft and -8 ft respectively.* These last

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*Wells W-26 and W-28 showed Magenta to be "unsaturated" (Mercer, 1983, Table 7). Figure 21 of Mercer (1983), however, provides the water quality of Magenta water from W-26. Details of hydraulic testing in these wells have not been published and therefore the cause and significance of paucity of water in W-26 cannot be ascertained.

TABLE 1

WATER LEVEL ALTITUDES OF THE THREE RUSTLER WATER-BEARING ZONES

Well	Well Altitude	RUSTLER/SALADO WATER LEVEL Depth	Altitude	Corrected Altitude	CULEBRA WATER LEVEL Depth	Altitude	Corrected Altitude	MAGENTA WATER LEVEL Depth	Altitude	Corrected Altitude	Corrected Δh (MAG-R/S)	Corrected Δh (MAG-CUL)	Corrected Δh (CUL-R/S)
H-1	3397.1	-	-	-	382.5	3015	3020	246.5	3151	3158	-	138	-
H-2	3377.8	343.0	3035	3140	348.7	3029	3033	233.1	3145	3148	8	115	-107
H-3	3389.5	-	-	-	397.0	2992	3000	238.3	3151	3155	-	155	-
H-4	3333.5	411.0	2923	2969	340.8	2992	2996	189.3	3144	3147	178	151	27
H-5	3506.4	-	-	-	485.2	3021	3067	344.5	3162	3165	-	98	-
H-6	3347.9	410.5	2937	3003	298.8	3049	3061	289.8	3056	3059	56	-2	58
H-7	3163.5	205.7	2958	2967	170.2	2993	2993	-	-	-	-	-	26
H-8	3433.0	463.0	2970	3012	443.7	2990	2991	405.1	3028	3029	17	38	-121
H-9	3405.9	656.0	2750	2828	425.8	2980	2980	282.0	3123	3124	295	144	152
H-10	3686.9	-	-	-	697.8	2989	3020	586.8	3100	3218	-	198	-
P-14	3359.6	389.0	2971	3009	320.1	3040	3044	-	-	-	-	-	35
P-15	3309.5	313.9	2996	3032	305.4	3004	3014	-	-	-	-	-	-18
P-17	3335.9	365.0	2971	3039	367.3	2969	2988	-	-	-	-	-	-51
W-25	3212.5	238.4	2974	3007	165.0	3048	3051	159.0	3054	3055	48	4	44
W-26	3151.9	191.7	2960	2984	146.0	3006	3007	-	-	-	-	-	13
W-27	3177.2	192.0	2985	3051	105.0	3072	3092	102.0	3075	3084	33	-8	41
W-28	3346.2	303.0	3044	3088	277.0	3070	3077	-	-	-	-	-	-11
W-29	2977.0	17.6	2959	2989	8.2	2969	2975	-	-	-	-	-	-14
W-30	3427.5	307.0	3121	3210	412.0	3016	3033	303.6	3124	-	-	-	-177

0 All altitudes and depths expressed in feet

0 Data from Gonzalez (1983)

two numbers are well within the range of possible errors in measurements and should therefore be considered as zero. Given the several possibilities for inaccuracies (in the measurement of water levels, sampling for determining the specific gravity and the chemical analyses), the pattern displayed by the results is remarkable. Clearly, somewhere between the center part of the WIPP site and the Nash Draw, the drainage from the Magenta to the Culebra obliterates the hydraulic distinction between the two zones. It is interesting to note that this difference is -2 ft at H-6 in the northwest corner of the WIPP site, indicating that the Magenta and the Culebra have hydraulically merged almost 2 miles east of the Livingston Ridge.

Observations at the borehole WIPP-33, 3/4 mile southwest of H-6, provide further indication that the integrity of the Magenta and the Culebra as distinct water-bearing zones has been breached well east of the Nash Draw. According to the Basic Data Report for WIPP-33 (SNL/USGS, 1981), there were three zones where the drill string dropped above the Magenta and several zones of "No core recovery", "No cuttings recovery" and "Lost circulation" throughout the Rustler Formation, including parts of the Magenta and the Culebra. Nearly all the Rustler anhydrite in this hole was found as gypsum and the Magenta Dolomite Member has lost much of its dolomite by dissolution (SNL/USGS, 1981, p. 6). This well lies in the "No halite in Rustler" zone (Fig 9). In addition, the upper part of the Salado contained, "...about 1 foot of dissolution residue which may represent about 10 feet of salt" (SNL/USGS, 1981).

If one draws a north-south line along the western boundary of WIPP zone II and another N-S line through the well H-6, (See Fig. 9) there are no Rustler hydrologic data between these two lines. It is therefore not known where the Magenta and the Culebra Members lose their separate hydrologic identity between these two lines. In the absence of data, the boundary between the "No halite in Rustler" and the "No halite in Culebra" zones of Figure 9 may represent a logical boundary to the west of which the Magenta and the Culebra waters have merged to form a single water-bearing zone.

The recharge and discharge areas of groundwater to and from the Rustler Formation have not yet been identified. On the basis of potentiometric surfaces, Mercer (1983) has suggested Bear Grass Draw (T.18 s, R.30 E.) and the Clayton Basin (see Fig. 12) as possible areas of recharge. Hunter (1985) has concluded, "Existing data are inadequate to determine evaporation from and recharge to the groundwater system in the vicinity of the WIPP site." This point is discussed further in Chapter 4.

Based on the presence of saline seeps along the Malaga Bend of the Pecos river (Fig. 16) a marked increase in salinity of the river south of this bend, and the potentiometric lines (Figs. 12, 13, 14 and 15) of the various water-bearing beds in the Rustler, most workers have identified the Malaga Bend as the primary area of Rustler discharge. Theis and Sayre (1942) estimated that the Rustler "Brine aquifer" was contributing about 200 gallons per minute of brine to the Pecos river at Malaga Bend. Another area of potential discharge from the Rustler is the Salt lake - Laguna Grande de la Sal. Robinson and Lang (1938) identified several springs on the margins of this lake (Fig. 17), and estimated that the most prominent of these, the Surprise Spring, discharged between 115 to 125 gallons per minute of brine into the lake. The lake is underlain by the Tamarisk Member of the Rustler Formation, and according to Mercer (1983), the Tamarisk is the most likely source of the brine of the Surprise Spring. Lambert (1983)

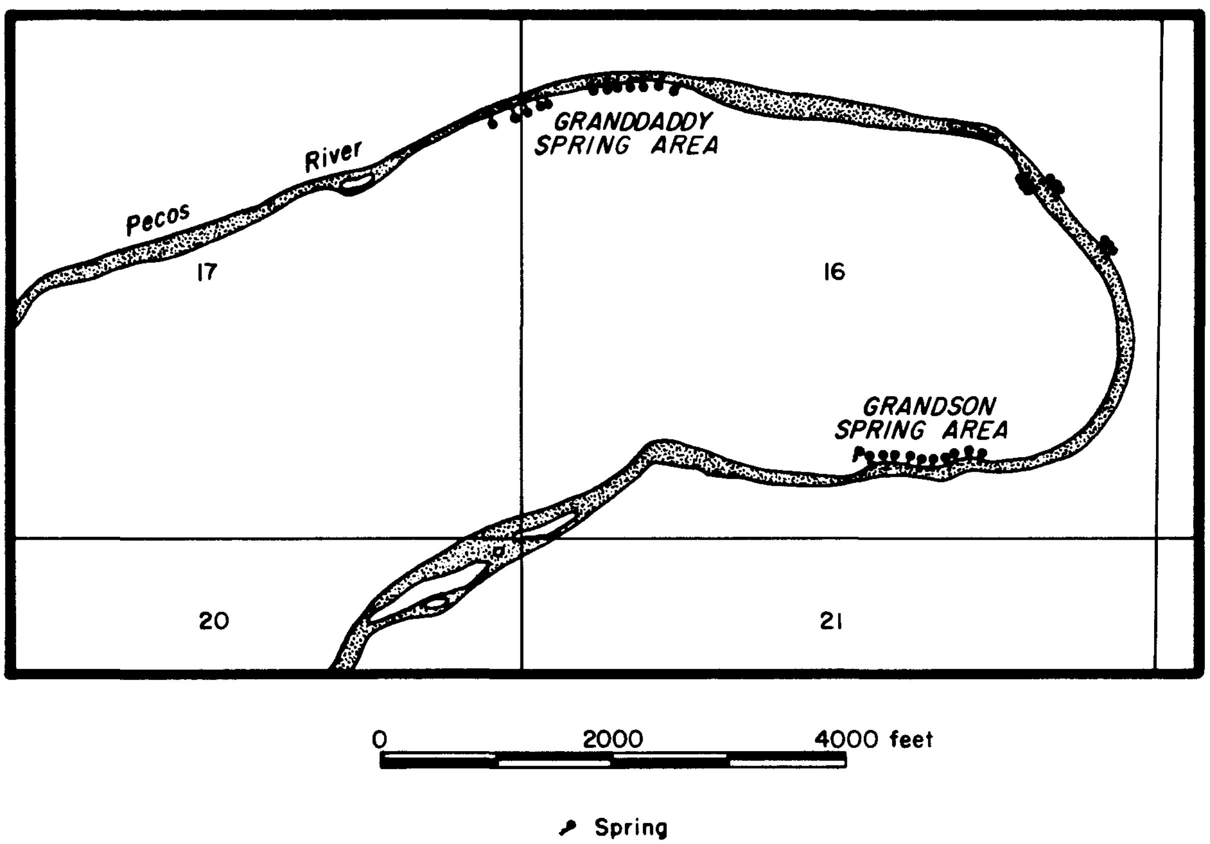

Fig. 16 Map of the Malaga Bend of the Pecos River showing the location of natural saline springs (seeps). (After Robinson and Lang, 1938.)

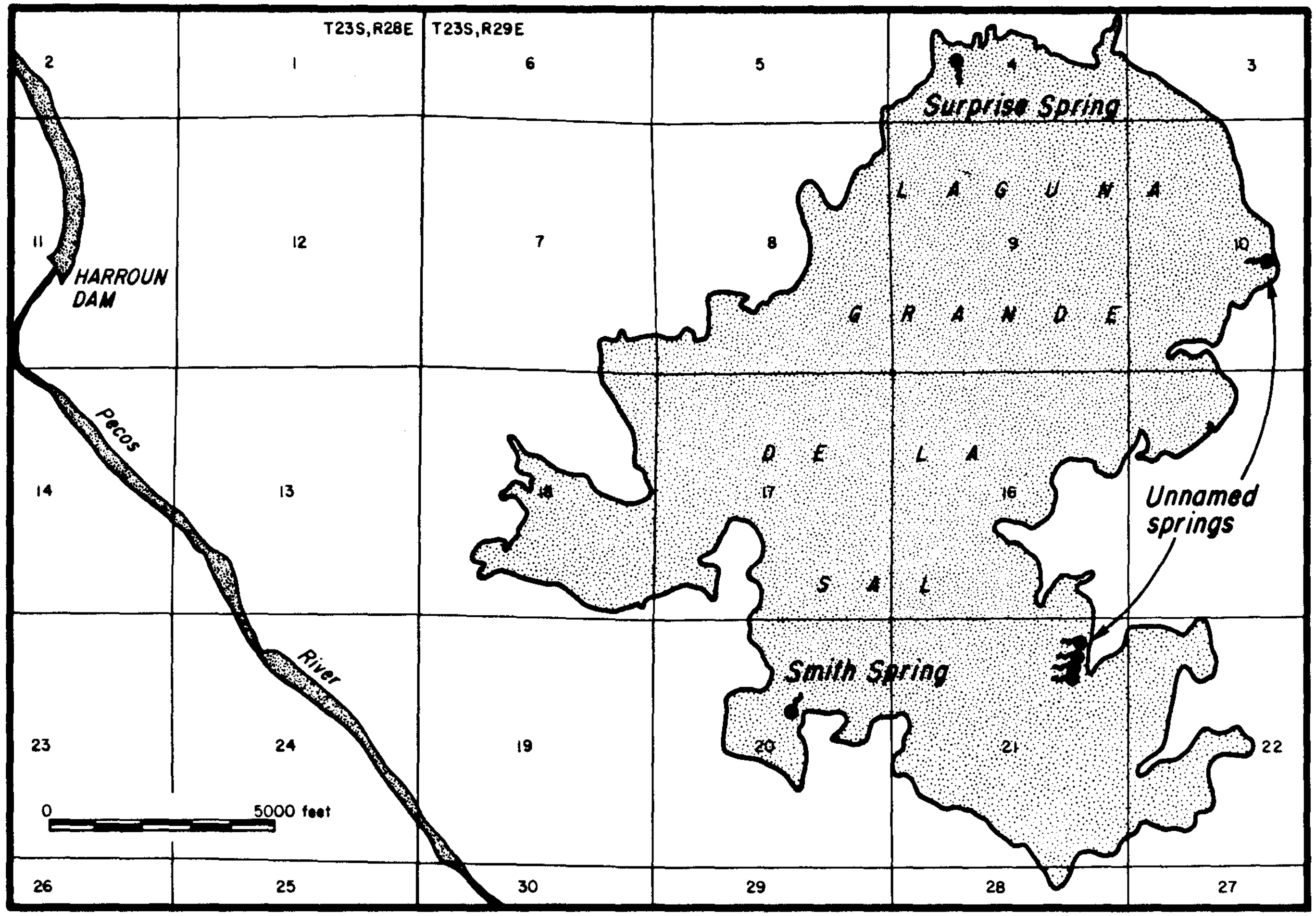

Fig. 17 Map of the Salt Lake, Laguna Grande de la Sal, showing the locations of springs. (After Robinson and Lang, 1938.)

dismissed the possibility of Laguna Grande de la Sal deriving water either from the Culebra or the "brine aquifer" because both of these aquifers have chloride contents of at least 60,000 mg/L and the Surprise Spring contains 57,000 mg/L total dissolved solids, 30,000 mg/L of which are chloride. It is, however, possible that the chloride-rich water from the Culebra rises upward and mixes with the local precipitation seeping down into the Tamarisk before emerging at the Surprise Spring. The potentiometric contours for various zones within the Rustler (Figs. 12, 13, 14 and 15) point to the Laguna Grande de la Sal as a discharge point for the Rustler waters where at least some water from the underlying semi-confined Culebra leaks out and mixes with locally derived unsaturated water. The major discharge point is probably along the Pecos river. The Culebra water may be under water-table conditions in the area between the Salt lake and the Pecos river (Mercer, 1983, p.56).

3.6 Mechanics of Dissolution

There is a relationship between the pattern of absence of halite in the Rustler Formation across the WIPP site (Fig. 9) and the transmissivity values measured in various holes located within the WIPP site (Mercer, 1983, Table 7, p.105). This general relationship is relevent even though one may question particular values used for representing a particular zone in modeling. Thus the transmissivity of Culebra measured at the well P-18 situated in the area with maximum salt preserved is reported to be 0.001 ft^2/day. For wells H-1, H-2,H-4, H-5, P-15 and P-17, all situated in an area with "No halite above Culebra," the value ranges between 0.07 and 1.0 ft^2/day. Well H-3 however, also located in this zone, had a transmissivity of 19 ft^2/day. Wells H-6, P-14 and the ones in Nash Draw show a transmissivity value of 73 ft^2/day and above. It is therefore important to understand the extent and mechanics of salt dissolution and its effect on the hydrologic properties of the Rustler Formation.

Several workers (Cooper and Glazman, 1971; Powers et al, 1978; Lambert, 1983; Mercer, 1983; Snyder, 1983 and Bachman, 1984) have endorsed the concept of salt dissolution from the Rustler near the WIPP site. More recently, however, Powers and Holt (1984) and Holt and Powers (1984) have expressed doubts about this concept on the basis of detailed mapping in the WIPP Waste Handling Shaft and have categorically stated, "Post-depositional dissolution features were not observed in any stratigraphic horizons in the Waste Shaft. In fact, several zones previously identified as dissolution residues in nearby boreholes (e.g. ERDA-9) contain pronounced primary sedimentary features. This is of great significance since dissolution has, historically, been considered as an important process that has greatly modified the Rustler Formation in this area." (Holt and Powers, 1984). In as much as this statement is based only on the mapping of one shaft, it requires no further discussion unless the results of detailed sedimentological studies of the rock cores from several wells, now under way, point to the depositional mode for the absence of salt in Rustler as a more logical explanation. The following discussion is based on the assumption that there has been post-depositional dissolution in the Rustler.

In hypothesizing about the mechanics of dissolution, an important issue to be resolved is (1) whether the salt was removed because higher permeability zones allowed groundwater to move more freely in certain areas, or (2) the higher permeability zones have resulted from the removal of salt followed by collapse. Bachman(1985, p.36) states, "Increased permeability in the Culebra allows unsaturated groundwater to come in contact with, and dissolve the halite," and thus appears to favor (1). In order to accept this concept, there must be a logical explanation for the creation of high permeability zones in the first place and the clear coincidence of the high permeability with the pattern of absence of salt from the east to west across the WIPP site. In the absence of an independent explanation for the creation of high permeability, it seems more logical to assume that the removal of halite from between the anhydrite and dolomite beds resulted in the collapse and increased permeability of the dolomite beds with some water moving through the dissolution residue zones, i.e. concept no. 2. There are problems, however, in working this out in detail in terms of the recharge, discharge and the direction of movement of water through the Rustler.

The proximity of Nash Draw to the WIPP site is the most important factor in assessing the mechanics of removal of salt at the WIPP site. Other related factors are that the Rustler beds dip east, but the water flows to the west and southwest. Updip is down-gradient in the confined water-bearing zones of Rustler until the water reaches well into Nash Draw where, due to extreme collapse resulting from dissolution and alteration, the water exists in water-table conditions in southern Nash Draw. The recharge area has been variously estimated to be northwest of the WIPP site (Mercer, 1983) to northeast of the WIPP site (Hunter, 1984). Some recharge is probably taking place at the WIPP site itself (Barrows, 1982). Bachman (1985) has mapped stream gravels in the Gatuna Formation on both sides of the Nash Draw and concludes from it that, "Streams flowed across the area now encompassed by Nash Draw before it became a topographic depression." This provides a clue to a possible mechanism for the removal of salt from the Rustler Formation.

The Gatuna stream gravel deposits mapped by Bachman (1985) show the existence and movement of streams during the Gatuna

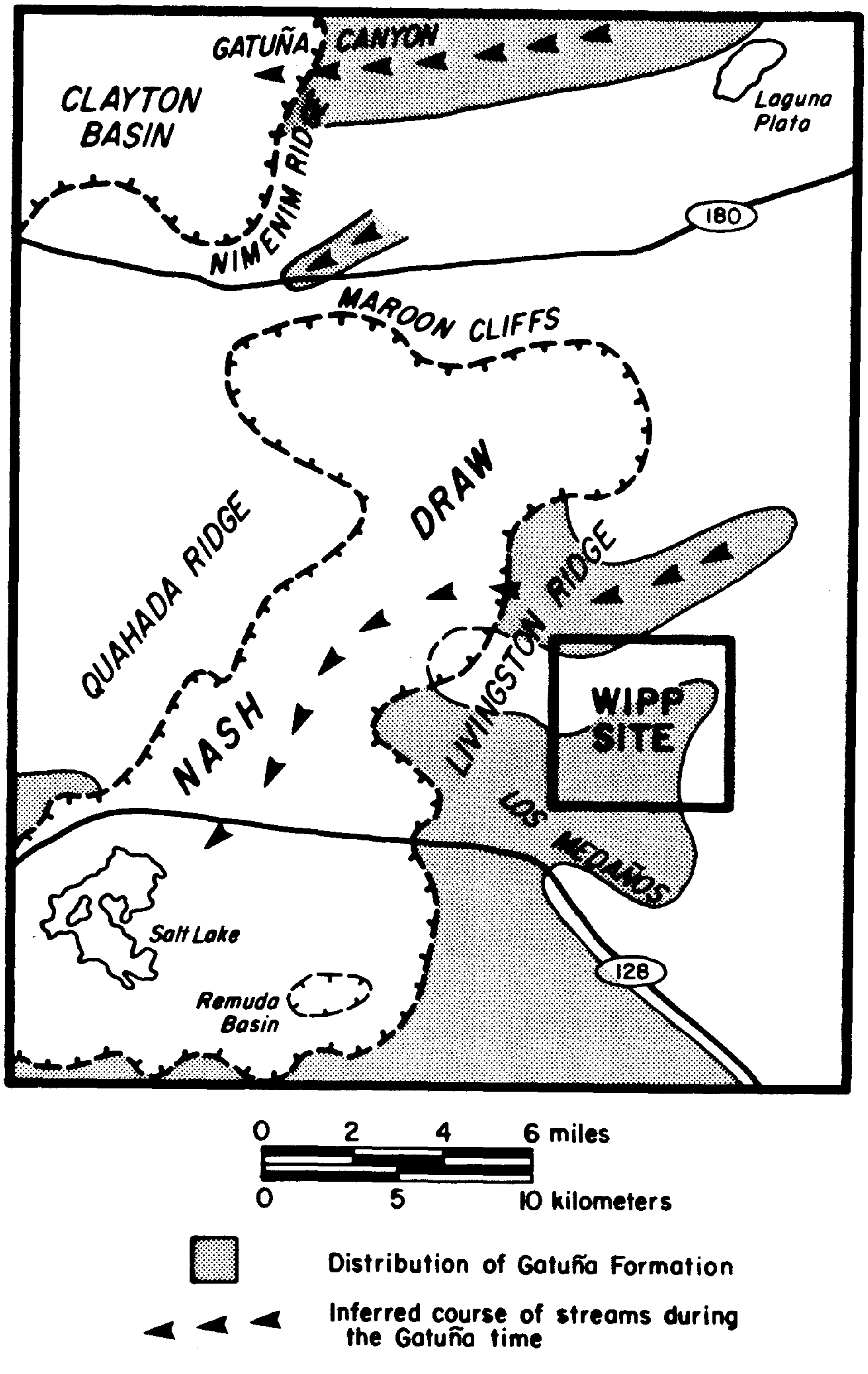

Fig. 18 Occurrence of the Gatuna Formation near the WIPP site and inferred course of streams during the Gatuna time. (After Bachman, 1985.)

time from the WIPP site to the Nash Draw area (Fig. 18). The gravels represent a high energy stream system and large quantities of water must have flowed over and near the area that is now the WIPP site. These streams must have flowed over the Dewey Lake Redbeds and cut channels in that formation. Some of this surface water may have infiltrated through the Dewey Lake Redbeds siltstone into the underlying Rustler Formation. The infiltration may have occurred through the primary porosity of the siltstone as well as through fractures in it. In the Nash Draw, which appears to have been the location of a major stream of the Gatuna time, the water seeped to the base of the Rustler, dissolved all the salt from it, converted anhydrite into gypsum and started dissolving the top of the Salado salt. East of Nash Draw toward the WIPP site, the depth of infiltration and salt dissolution must have become progressively more shallow, which is reflected in the pattern of the absence of salt shown in Figure 9. Note that the Gatuna deposits do not exist (Fig. 18) in the eastern part of the WIPP site where most of the salt in the Rustler is preserved (Fig. 9). As the salt was dissolved, more permeable insoluble residue was left in its place and the overlying competent rocks were fractured. The total thickness of the Rustler was progressively reduced to the west. Further west of the WIPP and in Nash Draw, a counter factor of anhydrite hydration worked to increase the thickness. It is not known at present whether the frequency of the fractures in the overlying Dewey Lake Redbeds filled with selenite veins has any relationship with the removal of salt in the Rustler. If these gypsum-filled fractures were formed as proposed by Gustavson et al (1980) for the Quartermaster Formation in Texas (see Sec. 2.2.1), such a relationship could exist.

While there is good evidence to suggest that the bulk of salt removal may have occurred during the Gatuna time, there are

indications that the process has not ceased. Indications and implications of the continuation of this process through the present are discussed in the next chapter.

4. RADIONUCLIDE MIGRATION THROUGH RUSTLER

4.1 Travel Times to the Biosphere

The calculation of the rates of water flow through the Rustler aquifers from the WIPP site to the most plausible discharge points along the Malaga Bend of the Pecos river, is a complicated process. Such calculations require an assumption of darcian flow and field determinations of transmissivities, porosities and hydraulic gradients along the postulated pathways. The water travel time to Malaga Bend used in most Rustler scenarios has been 4,000 years (WIPP Safety Analysis Report, U. S. DOE, Table 8.3-1). This travel time was obtained by assuming a porosity of 10% and dividing the flow path into 3 segments with hydraulic conductivity values of 1 ft/day (for 6 miles), 4 ft/day (for 9 miles), and 32 ft/day (for 0.5 miles). The 1 ft/day value around the site is consistent with the values of 1.0-1.4 ft/day obtained from pumping well H-3 (Gonzales, et al, 1984). However, existing data would support other assumptions of path length and hydraulic conductivity in the segments. For example, D'Appolonia (1981, Table 2-12) concluded that a flow time of 1850 years was plausible.

All of the above data and analyses assume that water flow can be modeled by darcian flow assumptions. Pathways of faster flow, if present near the WIPP site, may have been undetected by prior studies and could lead to drastically reduced travel times to the Pecos River.

4.2 The Karst Proposition

In May 1982, Larry Barrows, who was then a geophysicist working on the WIPP project with the Sandia National

Laboratories (SNL), prepared a manuscript titled, "WIPP Geohydrology-The Implications of Karst." In this manuscript, Barrows argued that the gravity surveys conducted over the WIPP site display a complex pattern of high-amplitude and short-wavelength gravity anomalies which were interpreted by him as "...resulting from density (and acoustic velocity) alterations in the vicinity of karst channels." He made other arguments, viz. the thinning of the Rustler Formation from east to west over the WIPP site, existence of closed topographic depressions over the WIPP site, cavities found in the borehole WIPP-33, and a lack of surface runoff at the WIPP site, to support his contention that karst-type conditions may exist in the Rustler Formation in the immediate vicinity of the WIPP site and therefore this formation is not a reliable barrier to the migration of contaminated water. Barrows has since published the essential parts of his thesis in Barrows (1983), Borns et al (1983) and Barrows and Fett (1985). Since the original manuscript has aroused considerable interest and speculation, it is published here as Appendix I, with Dr. Barrows' permission.

The Environmental Evaluation Group (EEG) requested Harry LeGrand, a well-known authority on karst, whose work was cited by Barrows in support of his thesis, to examine this issue. The entire correspondence between EEG, LeGrand and Barrows on this subject is reproduced here in Appendix II. EEG also organized a field trip on May 11, 1983 to afford Larry Barrows an opportunity to point out the field evidence for the presence of karst at the WIPP site to an invited group of 20 geologists and hydrologists. The field trip notes, prepared by Barrows, are included here in Appendix III. A discussion of the question of karst was included in the EEG report, "Evaluation of the Suitability of the WIPP site" (Neill, et al, 1983, pp. 81-85).

4.3 Radiological Significance of Karst

4.3.1 Previous Evaluations

Several investigators (Wofsy, 1980; Spiegler, 1981; U.S. DOE, 1980) have evaluated breach and leach scenarios involving injection of radionuclide contaminated water into the Rustler aquifer. These evaluations included calculations of the assumed transport of those radionuclides to either a natural outlet (presumed to be the Pecos River at Malaga Bend) or to a water supply well located several miles from the repository. These scenarios have generally concluded that radiation doses to individuals would be minimal or trivial. The assumptions used in these scenarios are re-examined in this report to consider the implications of karst conditions.

Wofsy (1980) estimated concentrations of ^{239}Pu that might occur in the Pecos River as a result of a breach of the repository and calculated the radiation doses to individuals. This report also included a parametric analysis where the effects of increasing the hydraulic conductivity and decreasing the distribution coefficient were evaluated. The highest concentration of ^{239}Pu in the Pecos River considered to be plausible was 1.7 pCi/l which would lead to an annual 50-year dose commitment (from one year's intake) of 0.024 millirem to the bone. Under the various assumptions, the ^{239}Pu was assumed to begin entering the Pecos River from 1,600 to 30,000 years after repository closure.

Spiegler (1981) estimated the doses from drinking treated water from a well withdrawing from the Rustler Formation 3 miles downstream from the repository. The evaluation included all uranium and plutonium radioisotopes and assumed that the plutonium and uranium arrived at the well 2,000 years and 21,000 years respectively after repository closure. Highest estimated individual 50-year dose commitments (from one year intake) were 2.9 millirem whole body and 120 millirem to the bone from plutonium and 6.6 millirem to the whole body and 97 millirem to the bone from uranium.

4.3.2 New Factors Related to the Karst Assumption

Wofsy (1980) and Spiegler (1981) concluded that the doses following a low probability breach and leach scenario would be minimal and not occur for several thousand years. This may not be the conclusion, however, if karst conduits are assumed to exist in the Rustler aquifers. If such conditions exist, the following factors need to be considered. The following calculations do not consider the mechanics and travel times for the radionuclides to travel from the repository to the Rustler aquifers, a vertical distance of approximately 1500 feet.

4.3.2.1 Radionuclide Travel Time: In order to simplify the calculations for the effect of the release of radionuclides to the bioshpere, following a breach of the repository, it is necessary to estimate the travel time for water from the repository to the Pecos river at Malaga Bend, a distance of 15 miles. The hydraulic conductivity (K) is the most important parameter for calculation of travel time. The following table lists some of the observed values for K between the WIPP site and the Pecos river. The Culebra is 24 feet thick at the WIPP site and this thickness is used to convert transmissivity (T) to hydraulic conductivity (K). See Figure 1 for the location of wells.

Location	T(Ft^2/d)	K(Ft/d)	Ref.
H-3	25-36	1	Gonzalez et al (1984)
P-14	140	6	Mercer and Orr (1979)
USGS-1	535	22	Cooper (1962)
Between the Salt Lake and the Malaga Bend	8000	333	Hale, et al (1954)

Since the hydraulic conductivity of a karst channel will be much higher than the average conductivities measured by assuming 24 ft thickness of the aquifer, it appears reasonable to assume K=50 ft/day for a karst channel connecting the site to the river. Further justification for assuming this value of K is provided by a range of values for K for different kinds of rocks given by Freeze and Cherry (1979, p. 29). The higher range for measured K values in fractured crystalline rocks is more than 100 ft/day and for karst limestone, it is greater than 1000 ft/day.

Using the values of K=50 ft/day, hydraulic gradient = 20 ft/mile, porosity = 0.1, and a distance of 15 miles, one gets a water travel time from the WIPP site to the Pecos river, of 114 years. Travel time to a well located 2 miles from the point of injection would be 15 years.

The distribution coefficient (K_d) measures the extent that the velocity of a given radionuclide is retarded relative to the rate that water moves in an aquifer. This mechanism can be very important in normal aquifers where intergranular flow occurs. However, in an aquifer where karst flow predominates and water can be presumed to move in conduits with lesser contact with the formation, it is reasonable to assume that the K_d value will decrease drastically. In the calculations below it is assumed that 10 percent of the radionuclides travel without retardation (i.e., their $K_d=0$). Although the bounding assumption for this parameter would be to assume all the flow had a K_d of zero, this assumption is believed to be sufficiently conservative.

4.3.2.2 Other Radionuclides: Several radionuclides other than ^{239}Pu could significantly influence the doses received by individuals in breach and leach scenarios if the radionuclides reached the accessible environment within a few hundred years after the repository closed. Such short travel times (e.g.

114 years to Malaga Bend) would occur if karst conditions existed.

Other alpha-emitting plutonium radionuclides, principally ^{238}Pu and ^{240}Pu, are dissolved along with ^{239}Pu and become a part of the solubility limit for plutonium. Since both ^{238}Pu and ^{240}Pu have shorter half-lives than ^{239}Pu their inclusion in the brine will increase the total plutonium curies injected into the aquifer in a plutonium saturated solution.

The Uranium-233 inventory in the repository at the time of closing is expected to be about 4,000 Ci, approximately 0.1% of the total radionuclide inventory. However, since it has a solubility (about 50 mg/l) that is 50 times that of plutonium, it needs to be considered in this scenario. If it is assumed that a liter of brine intruding into the repository would absorb only the amount of ^{233}U included in the average waste volume associated with a liter of void space (i.e. the space that would be filled with the liter of brine), then the concentration of ^{233}U would be about 1.3 mg/l and the rate of entry into the aquifer would be 37,000 pCi/s for a brine injection of 3 cm^3/s.

Americium-241 contributes only about 1 percent of the total TRU waste alpha curies in the FEIS inventory but in the updated inventory it is 3 percent. Americium also has a low solubility limit (about 1.9×10^{-7} g/l at pH 5.0) which controls the amount injected. In either inventory the quality of ^{241}Am injected would be 1,800 pCi/s.

Strontium is very soluble in chloride saturated brines and there is a projected ^{90}Sr inventory of 2.5 million curies at time of repository closing. Even though ^{90}Sr has a half-life of only 29 years there will still be considerable quantities present for several hundred years. For example, the injection rate would be 270,000 pCi/s at 200 years after closing and 23,000 pCi/s at 400 years after closing.

4.3.2.3 Rate of Injection: The rate of injection of ^{239}Pu into the Rustler aquifer was calculated to be 21,000 pCi/s by Wofsy (1980) and Spiegler (1981). The injection rate of other plutonium and uranium radionuclides into the Rustler aquifer was assumed by Spiegler (1981) to be in the same ratio as their abundance in the repository inventory. This injection rate was adopted from that used in the FEIS and SAR and was based on the assumption that plutonium would dissolve as rapidly as salt in the repository. While this assumption appears to be conservative, it turns out that for the assumptions used in the FEIS (U. S. DOE, 1980) scenarios the concentration of plutonium in the contaminated brine leaving the repository is about 90 percent of the maximum solubility limit. A more important effect of this assumption is that it restricts the rate that brine can leave the repository to the rate that salt can be dissolved (1.25 ft^3/day).

Somewhat higher injection rates are possible. For example, consider a scenario where an unlined borehole connects the Bell Canyon aquifer, the repository, and the Rustler aquifer. Since ongoing tests at the Cabin Baby borehole suggest that the hydraulic head in the Bell Canyon aquifer is higher than in the Rustler aquifer the flow in this borehole would be upward to the Rustler aquifer. If some mechanism existed for limited circulation of the Bell Canyon water in the repository en route to the Rustler aquifer the water could pick up radionuclides and inject them into the Rustler aquifer. A variation of this scenario is the two-borehole case used by Channell (1982) to connect a pressurized brine reservoir, the repository, and the Rustler aquifer. In either case, providing there were sufficient pressure differential, the injection rate would be determined by the ability of the

Rustler aquifer to accept water and the solubility limit of the various radioactive elements in brine. The duration of the injection would depend on the reservoir volume and pressure.

The hydraulic conductivity (K) chosen for this scenario was 50 ft/day for a 2 feet wide section of the 24 feet thick Culebra aquifer. A 2 feet wide section was assumed to approximate the width that would be influenced by a borehole penetrating the aquifer. A K value of 50 ft/day is about 40 times the average value observed when pumping DOE-1 but a localized value could be somewhat larger than the average value and probably not be apparent from a pumping test where drawdowns are observed over a several square mile area. Even with this large a K value the amount of water flow is small, about .05 gallons per minute (3 cm^3/s).

Solubility limits of plutonium are low and influenced by a number of water quality and waste chemical form parameters. EEG has previously concluded (Channell, 1982) that maximum feasible plutonium solubility limits in brine would fall in the range of 0.1-1.0 mg/l. Using a value of 1.0 mg/l and the 3 cm^3/s injection rate gives a plutonium injection rate of 220,000 pCi/s, over 10 times that used by Wofsy (1980) and Spiegler (1981).

4.3.3 <u>New Factors Unrelated to the Karst Assumption</u>

There are some other factors which have a potential impact on the calculated doses following a hypothetical breach of the WIPP repository. These factors, based on new information, should also be taken into account in a re-evaluation of breach scenarios.

4.3.3.1 <u>Updated Inventory</u>: Current estimates of the TRU waste inventory are considerably different from those used in the FEIS, both in total curies and in the distribution between various radionuclides. The most important change is in the greatly increased amount of ^{238}Pu (plutonium activity percentages at time of closing are assumed to be 94.2% ^{238}Pu, 4.8% ^{239}Pu, and 1.0% $240_{Pu)}$. Since ^{238}Pu has a specific activity (Ci/g) about 280 times that of ^{239}Pu a saturated solution would contain almost 7.5 times the total plutonium radioactivity concentration as assumed by Wofsy (1980) and Spiegler (1981). These modifications result in a plutonium injection rate at 100 years after repository closing of 1.7 million pCi/s, about 80 times that used in previous DOE and EEG scenarios.

4.3.3.2 <u>100 Year Breaching Time</u>: Previous scenarios had assumed the earliest time of breaching would be 1,000 years after repository closure. There are no fundamental reasons why a breach could not occur at a somewhat earlier time although it is obvious that the probability of a breach occurring from either natural or man-made causes increase with time. Calculations presented below assume the earliest time of occurrence is 100 years. This time was chosen because the EPA standards do not allow credit to be taken for an active institutional control period of longer than 100 years.

4.3.3.3 <u>Dose Conversion Factors</u>: Dose conversion factors are used to convert the amount of a radionuclide taken into the body of an individual to the dose that will be received in either one year or 50 years by specific organs or the whole body. There are significant differences among the various dose conversion tables being used for some radionuclides. The dose conversion factors used here are from WIPP-DOE-176, Revised.

4.3.3.4 <u>Comparison with EPA Standards</u>: The EPA High Level Waste Standard (40 CFR 191) contains limits on the total curies of certain radionuclides that can reach the accessible environment over a 10,000 year period. No attempt will be made in this report to estimate the effect of karst conditions on the ability of the site to meet 40 CFR 191.

4.3.4 Calculated Doses at the Pecos River

The doses that would occur from ingesting treated Pecos River water (treatment is assumed to reduce radionuclide concentration to 0.1 of that in the river) are presented in the table below. All nuclides are assumed to be at their saturation limits upon injection into the aquifer at 100 years after repository closing. Travel time to the Pecos River for 10 percent of the radionuclides is assumed to be an additional 100 years. The inflow is diluted by 510 l/s of Pecos River water. Annual drinking water intake for an individual is presumed to be 730 l/y.

4.3.5 Calculated Doses From A Water Supply Well

The doses at a water supply well located 2 miles away from the point of injection into the Rustler are calculated exactly as was done for Pecos River water doses. The concentrations will be higher for ^{90}Sr, ^{239}Pu, and ^{241}Am since for a breach beginning at 100 years after closure the first arrival time will be 115 years after repository closing. Dilution and treatment factors used are the same as in Spiegler (1981) i.e. a 5×10^{-3} dilution of the contaminated brine in aquifer water and an effective 10 fold dilution from treating the water. With the further assumption that only 10 percent of the radionuclides move with the water, the total dilution factor become 5×10^{-5}. With an injection volume of 3 cm^3/s, the final concentration in pCi/l will be equal to 0.0167 x injection rate in pCi/s x decay factor for 15 years.

TABLE 2

RADIATION DOSES FROM PECOS RIVER WATER

(50-Year Dose Commitment From One Year's Intake, Millirem)

Nu-clide	Inject Rate pCi/s	Dschrg Rate pCi/s	Final Conc. pCi/s	Annual Intake pCi	Effec. Dose Conv.F. mrem/pCi	Effec. Dose Dose	Bone Dose Conv.F. mrem/pCi	Bone Dose Dose
^{90}Sr	3.0+6*	2.7+4	5.3	3.9+3	1.3-4+	0.5	1.4-3	5.5
^{233}U	5.3+4	5.3+3	1.0	7.6+2	1.1-3	0.83	1.7-2	13
^{238}Pu	1.5+6	6.9+4	14.0	1.0+4	4.0-4	4.0	6.8-3	68
^{239}Pu	1.7+5	1.7+4	3.3	2.4+3	4.4-4	1.1	7.6-3	18
^{240}Pu	0.36+5	0.36+4	0.71	5.2+2	4.4-4	0.23	7.6-3	4.0
^{241}Am	1.8+3	1.6+2	0.031	2.3+1	2.2-3	0.05	3.9-2	0.9
TOTAL	4.7+6	1.1+5		1.8+4		6.7		110

*3.0+6 = 3.0×10^{6}

+1.3-4 = 1.3×10^{-4}

TABLE 3

RADIATION DOSES FROM WATER SUPPLY WELL

(50-Year Dose Commitment From One Year's Intake, Rem)

Nu- clide clide	Discharge Rate pCi/s	Final Conc pCi/l	Annual In-take pCi	Effective Dose	Bone Dose
^{90}Sr	2.1+6	3.5+4	2.6+7	3.3	36.0
^{233}U	5.3+3	8.9+2	6.5+5	0.71	11
^{238}Pu	1.3+6	2.2+4	1.6+7	6.4	110
^{239}Pu	1.7+5	2.8+3	2.0+6	0.88	15
^{240}Pu	3.6+4	6.0+2	4.4+5	0.19	3.3
^{241}Am	1.8+3	3.0+1	2.2+4	0.048	0.85
TOTAL	3.6+6		4.5+7	12	180

4.3.6 Dose Significance

The water supply well doses calculated above for assumed karst conditions are not trivial. The annual effective dose equivalent is double that which would be permitted for an occupational worker and could continue for many years unless detected. The doses to an individual from an outlet at the Pecos River are somewhat less; they would remain below the 25 millirem annual dose equivalent to the whole body or 75 millirem to any critical organ that the EPA standard (40CFR191) will permit during the first 1,000 year period after disposal until an individual had ingested the water for about 20 years. However, the total quantity of radionuclides reaching the accessible environment at the Pecos River is more significant because this water will be used for a variety of purposes prior to its discharge to the Gulf of Mexico and could generate a sizeable population dose. Population doses are actually more important than individual doses at these low levels and this is the reason that the EPA standard contains a total curie discharge limit rather than an individual dose limit.

4.3.7 Sensitivity Considerations

When scenarios such as these are postulated it is appropriate to ask how reasonable the calculated values are and whether they should be labled as bounding, conservative, likely, or non conservative. All of the variables chosen will have a range of variation which can be large. In some cases the appropriate range in parameter values has a rational basis, although the most likely value may not be apparent. For other parameters, the appropriate range is more subjective. Table 4 attempts to quantify the possible range of values for the pertinent parameters. This analysis assumes that a breach will occur and inject radionuclide contaminated water into the

Rustler aquifer during the first 9,900 years after closing and no attempt is made to estimate the probability that contaminated water will be injected into a Karst channel in the Rustler Formation. The comments column attempts to explain the basis, or lack of basis, for the numbers chosen.

The most likely values chosen in Table 4 lead to 50-year dose commitments from a one-year intake of 0.7 mrem effective and 11 mrem to the bone for the Pecos River water and 590 mrem effective and 9,420 mrem bone of a well outlet. However, doses somewhat above the values in Tables 2 and 3 could occur easily by changing one or two parameters. For example: (1) a saturated (50 mg/l) ^{233}U solution from a breach at 9900 years after closure would lead to a Pecos River dose from ^{233}U over twice as high as the totals in Table 2; (2) a saturated (85 mg/l) ^{90}Sr solution would result in a ^{90}Sr dose about 4 times as much as the Table 2 values for a breach occurring at 200 years after closure; (3) the ^{238}Pu dose from a 0.4 mg/l concentration of heat source plutonium would be 30% higher than the Table 2 total at 100 years. Therefore, it is concluded that if the postulated breach is to occur the values in Tables 2 and 3 are conservative, but far from bounding.

4.4 Additional Thoughts on the Karst Proposition

The proposition that the WIPP site is situated in a karst region is not a new one. Every geologist who has studied the geology of the northern Delaware Basin has described geomorphic and lithologic features which relate to the past dissolution of evaporite rocks in the region. Therefore, the use of the word "karst," which simply refers to the presence of the effects of dissolution of rocks by water in the area, should not by itself arouse strong feelings of the unsuitability or the inadequacy of the WIPP site. The WIPP site

TABLE 4

EFFECT OF PARAMETER VARIATION

Parameter	Value Used	Reasonable Range	Most Likely Value	Comment
Hydraulic Conductivity	50ft/d	1-1000	50	Lower value has been observed. Higher value is well below those for pure karst conditions.
Plutonium Solubility	1.0 mg/l	0.1-1.0	0.4	Value used in Kerrisk (1984) for Nevada HLW Site.
	$5.7x10^{-4}$ Ci/l	$7.6x10^{-6}$ to $1.3x10^{-2}$	$2.3x10^{-4}$ (at 100y) $2.7x10^{-5}$ (at 5000y)	Specific activity can be much higher if Waste dissolved is heat source waste.
Uranium Solubility	1.3 mg/l	1-50	1.3	Value of 50 mg/l used by Dosch (1981) and Kerrisk (1984)
% of Nuclide that is not retarded (K_d=0)	10	1-10	5	Wofsy (1980) concludes 1% reasonable in fractured media. Even small karst channels should be greater.
Time Injection Begins after repository closing	100 yrs.	100-9,900	1,800	40 CFR 191 estimate of maximum frequency of exploratory drilling in salt formations is equal to one borehole per 1750 years at WIPP.

appears to be protected from the advance of blanket dissolution in the area (Neill et al, 1983; Chaturvedi and Rehfeldt, 1984). The relevent question which remains to be answered is, "Are there passages of flow of water through the Rustler Formation that could carry radionuclides to the Pecos River or to a well (in case of a breach of the WIPP repository), in a significantly shorter period of time than assumed so far on the basis of available hydraulic data for the Rustler?" The question does not address the potential mechanisms of migration of the radionuclides from the repository to the Rustler aquifers, but relates only to the efficacy of the Rustler Formation as a barrier, should a breach inject the radionuclides in that formation.

There are no direct indications to date that solution conduits in the Rustler or overlying formations carrying a large amount of water flowing at rapid rates exist within zone II of the WIPP site. To the west, boreholes P-14 and H-6 (Fig. 1) are located in an area where all the salt from the Rustler Formation is missing and the yield and hydraulic conductivities of the Rustler aquifers are substantially higher. Borehole WIPP-33 found solution cavities underground and is situated in a depression which clearly acts as a point of infiltration of surface runoff. Directly above the repository, however, wells H-1 and H-2 are relatively tight while the transmissivity in Culebra at well H-3 is computed to be 15 ft^2/day (Gonzalez, et al, 1984) or a hydraulic conductivity of about 0.7 ft/day. While this does not translate into an alarming rate of flow of water through the Rustler over the repository, sufficient hydrologic investigations have not been completed as yet to provide an adequate representation of permeability distribution in the Rustler at the WIPP site. However, since the karst conduit assumed in the above scenario does not involve a large flow (only about 0.05 gpm) of water, it is not necessary for conduits to be large in order to be significant.

The karst issue was briefly discussed in the 1983 EEG evaluation of the suitability of the WIPP site (Neill, et al, 1985 pp. 81-85) and a number of recommendations were made for work to be conducted by DOE to investigate issues related to karst. Three of these studies (Hunter, 1985; Bachman, 1985 and Snyder, 1985) have been completed and others are at various stages of completion. These studies, their relevance to the karst proposition and recommendations for additional work resulting from an analysis of work completed so far, are discussed in Chapter 5.

5. CONCLUSIONS AND RECOMMENDATIONS

The Rustler Formation overlies the Salado Formation in which the WIPP repository is situated. The base and top of the Rustler are approximately 1300 feet and 1600 feet respectively above the repository horizon. The Rustler contains three discrete water-bearing zones and a possibility of some water moving outside these zones. The recharge area for this water is not known but has been postulated to be a few miles to the north and/or northeast of the WIPP site. Since there is no well-developed surface drainage at the Los Medanos plain where the WIPP site is situated and since the average rainfall in the area is about 13 inches per year, there is a good possibility of at least some recharge to the Rustler aquifers through infiltration at the site. Such infiltration would require openings in the overlying Dewey Lake Redbeds. Perhaps some of the conspicuous topographic depressions at the site represent localized points of recharge.

The measured hydraulic heads for the three discrete water-bearing zones in the Rustler show that in the central part of the WIPP site, there is not much mixing between the three zones, although some water probably leaks downward. The head differences between Magenta, Culebra, and the Rustler/Salado contact zone diminish to the west and become practically zero in Nash Draw. The potentiometric contours indicate the flow of water in the Rustler is to the west and southwest. Some of the Rustler water probably discharges at the salt lake, Laguna Grande de la Sal. Most of the discharge is, however, assumed to take place along the Malaga Bend of the Pecos River where several saline seeps are located. The transmissivity of the Culebra, which is the most prolific water-bearing zone in the Rustler is about 15 to 30 ft^2/day at the center of the WIPP site and steadily increases to the west. In the area between the salt lake and the Malaga Bend of the Pecos River, the water in Rustler occurs in unconfined condition and the transmissivity is about 8000 ft^2/day. A crude maximum estimate of travel time of water from the WIPP site to the Malaga Bend through the Rustler is 4000 years.

Boreholes in the southeastern corner of the WIPP site have encountered several salt beds within the Rustler and a thickness of up to 475 feet. The salt beds are progressively absent from the upper to the lower parts of the formation as one moves to the west. In the western part of the site, all halite from the Rustler is absent, and further west the upper part of the Salado salt has been dissolved. Where salt is missing, dissolution residues are present and the formation has thinned substantially. Water moves with greater ease in areas where salt is absent. There is thus a preponderance of evidence to favor a post-depositional dissolution hypothesis for the Rustler Formation.

The WIPP site is situated in a region which has been affected by karst processes, i.e., the evaporite rocks have been affected by dissolution by unsaturated groundwater. Direct evidence from boreholes and flow tests suggest that the site itself is removed from the area (to the west and south) where such processes have resulted in cavities, collapse, and hydration. Calculations based on geologic evidence suggest that the rate of advance of the solution front will take 4.5 million years to remove the salt overlying the repository (Bachman, 1980). There is some indirect evidence, however, that solution conduits and altered rock may exist in the shallow subsurface at the WIPP site. If so, the rate of travel of water through some preferred pathways from the site to the Pecos River may be much faster than what has been assumed in analyzing the effect of breach of the repository and migration of radionuclides through the Rustler aquifer to the biosphere. The indirect indications of the possibility of karst at the WIPP site consist of gravity anomalies, the lack of surface drainage, the topographic depressions which in some cases roughly coincide with the negative gravity anomalies, and the existence of cavities in the Rustler Formation encountered in borehole WIPP-33 (this borehole is west of the WIPP site, but well east of the Nash Draw boundary and therefore situated in a depression in an area with no other visible signs of karst topography). An analysis of the potential release of radioactivity to the biosphere in case of a breach of the repository when pathways of rapid movement of water may exist in the Rustler shows that such releases could result in radiation doses that exceed environmental standards at the Pecos river and occupational standards in a water supply well.

There are two ways to address the "karst" proposition. One way is to collect additional data on the hydrology of the formations overlying the Salado so that a clearer understanding of the recharge, movement through, and discharge of water through the shallow water-bearing zones is obtained and the disposal of precipitation is better understood.

The following studies are now in progress to better characterize the hydrology of the Rustler Formation. There is a formal commitment from the U. S. Department of Energy to the State of New Mexico in the form of "Modification 1 to the Consultation and Cooperation Agreement" signed in November, 1984, to conduct these studies.

Hydrologic Testing: The well H-3-b-3 started pumping in October 1985 and drawdowns in several wells have been observed. Similar multi-well testing is planned for 1986 at H-11 and at central and northern parts of Zone II. Analyses of these tests will provide more reliable values of transmissivity and may also indicate the presence of high permeability zones.

Tracer Testing: Convergent tracer tests at wells H-2 and H-6 have been previously completed (Gonzalez, 1983). Similar tests will be carried out in 1986 at wells H-3 and H-4, to obtain the effective porosity and dispersity parameters at these locations. A sorbing tracer test will also be performed, at a location which is yet to be chosen, in 1987-88, to obtain reliable values of the "Distribution Coefficient" for use in breach scenario analyses.

Water Chemistry: An extensive and elaborate program to collect representative water samples from different water-producing horizons in the Rustler Formation from about 20 wells is being carried out from 1985 to 1988. These samples are being analyzed for major and minor dissolved constituents as well as for environmental isotopes, to aid in the determination of flow-paths, groundwater velocity and the recharge/discharge areas.

Water Balance Study: A report by Hunter (1985) has been completed and has been reviewed by EEG. The report confirms that serious gaps remain in our knowledge of the area, mechanics, and amount of recharge to the Rustler water-bearing beds, and makes recommendations for additional work to increase the understanding in this area.

Mechanics of Removal of Salt from the Rustler Formation: Based on a detailed mineralogical and sedimentological study of the cores at and near the WIPP site, this study will attempt to explain the pattern of absence of salt layers in the Rustler Formation and its implication to the Rustler hydrology.

Investigation of Suspected "Dolines": Some of the prominent depressions at the site and in the surrounding area will be investigated to address the question of their origin, particularly the suspicion of at least some of these being "dolines". Bachman (1985) investigated one such depression in the SW corner of Sec. 29, T22S, R31E and called it a "blow-out". Investigation of other depressions will directly address the question of the presence of karst features east of WIPP-33 borehole.

Modeling of Rustler Hydrology and Solute Transport: This will be completed by January 1988 and will rely upon additional data being collected during 1985-87.

A review of work completed so far indicates that it is advisable to carry out additional work in this area as outlined below.

1. Re-evaluation of Gravity Data:
   Barrows (1982), Barrows et al (1983) and Barrows and Fett (1985) have interpreted the gravity anomalies at the WIPP site as "...resulting from density (and accoustic velocity) alterations in the vicinity of Karst channels." In the light of additional information now available through detailed study of the Rustler cores, Bachman's field-oriented studies and multi-hole flow tests, the gravity data should be re-evaluated to check the interpretation offered by Barrows and Co-workers and to provide alternative interpretations, if feasible.

2. Interpretation of Electro-magnetic surveys data for Rustler:
   Preliminary indications of the results of the electro-magnetic surveys conducted at the WIPP site for

delineating the Castile Formation brines indicate that some of the EM methods may be particularly suitable for delineating changes in the quantity and quality of water in the Rustler Formation. The results of surveys conducted to date should be analyzed to see which method provides the most useful data for Rustler and then that method should be used over the WIPP site to delineate the spatial (lateral) changes in the Rustler hydrology.

3. <u>Recommendations from Water Balance Study:</u> Hunter (1985) has identified a number of areas where more information is needed to achieve a desirable level of understanding on the recharge, movement through and discharge of water in and out of the Rustler water-bearing horizons. We support the recommendations for establishing a precipitation network at WIPP, investigations of an apparent groundwater mound between the Clayton Basin and Nash Draw, identification of groundwater divide in R-32E, quantification of seepage at Malaga Bend and at Laguna Grande de la Sal, and direct determination of recharge and evapo-transpiration at the WIPP site. All this information will also be needed for a comprehensive hydrologic model of the Rustler Formation.

Another approach to address the Karst proposition would be to not consider the Rustler Formation as a barrier and rely solely on the 1300 feet of salt between the repository and the base of the Rustler to contain the radionuclides in the event of a breach of the repository. This approach would require a very reliable plugging and sealing program and the introduction of engineered barriers for an extra measure of safety. It is recommended that both approaches be pursued simultaneously.

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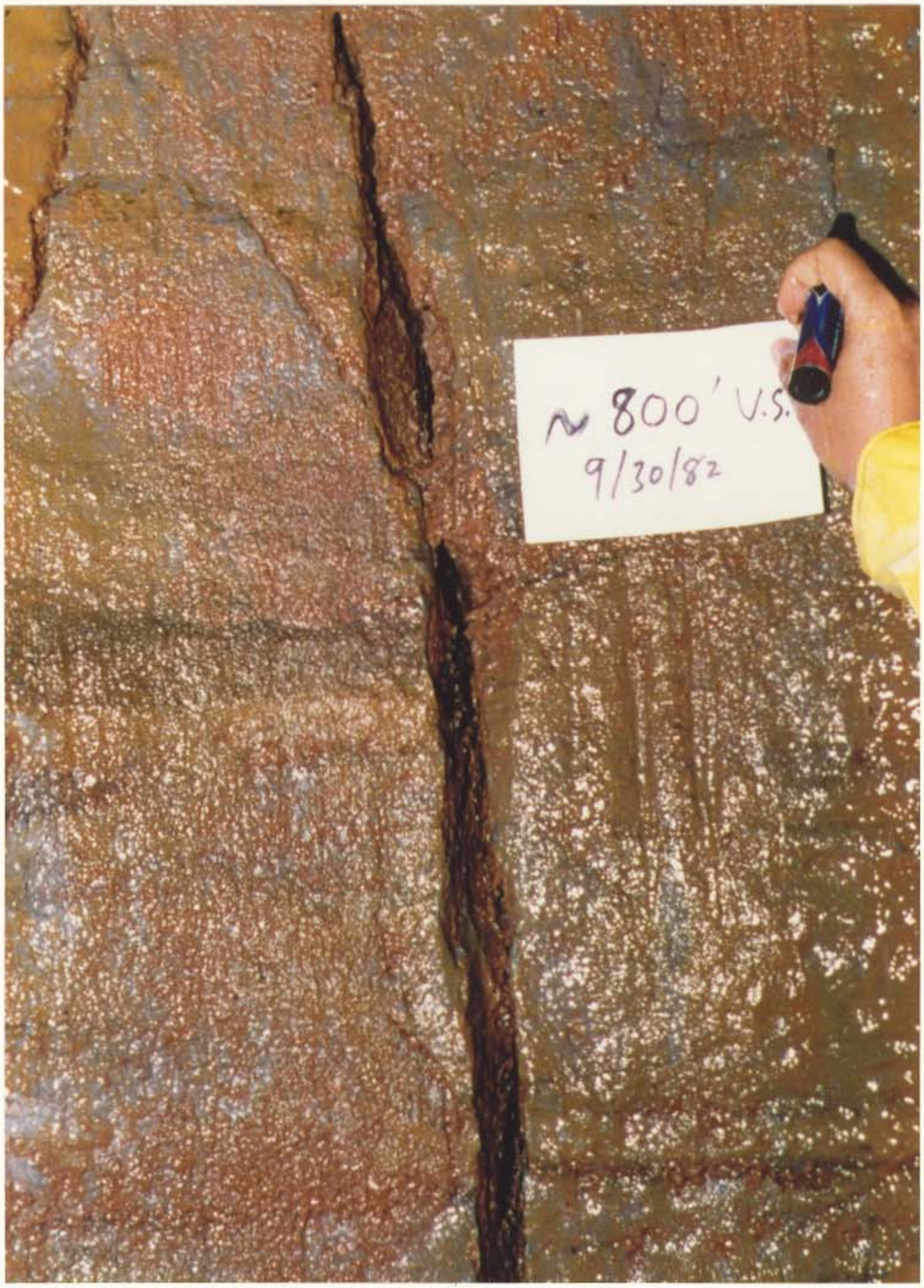

Plate 1. An open fracture in the unnamed lower member of the Rustler Formation.

Plate 2. A closeup of the washout zone just below the Culebra Dolomite in the Waste Shaft.

Plate 3. A closeup of a dissolution residue in the Tamarisk Member in the core of borehole H-11.

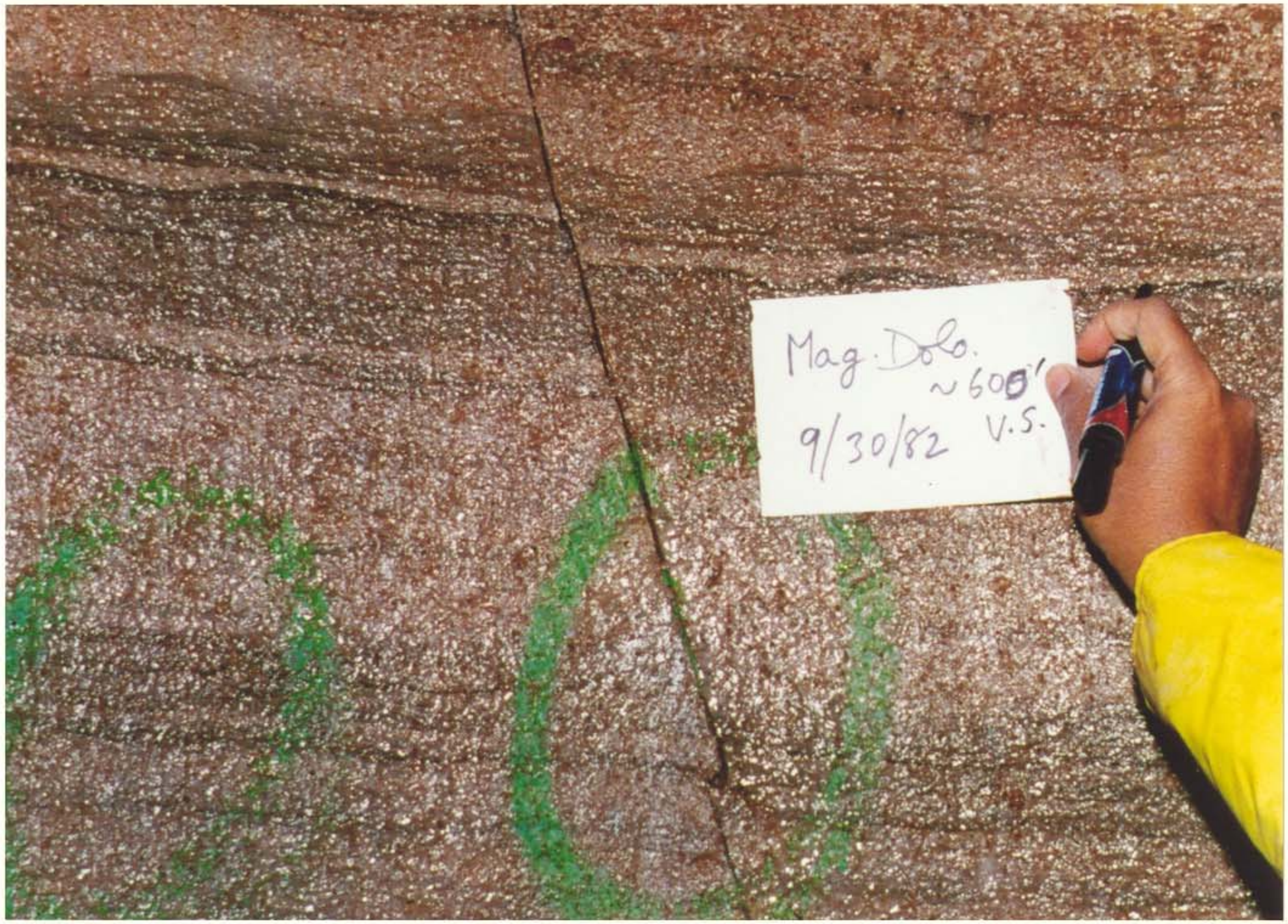

Plate 4. A "fault" in the Magenta Dolomite in the "Construction and Salt Handling" Shaft.

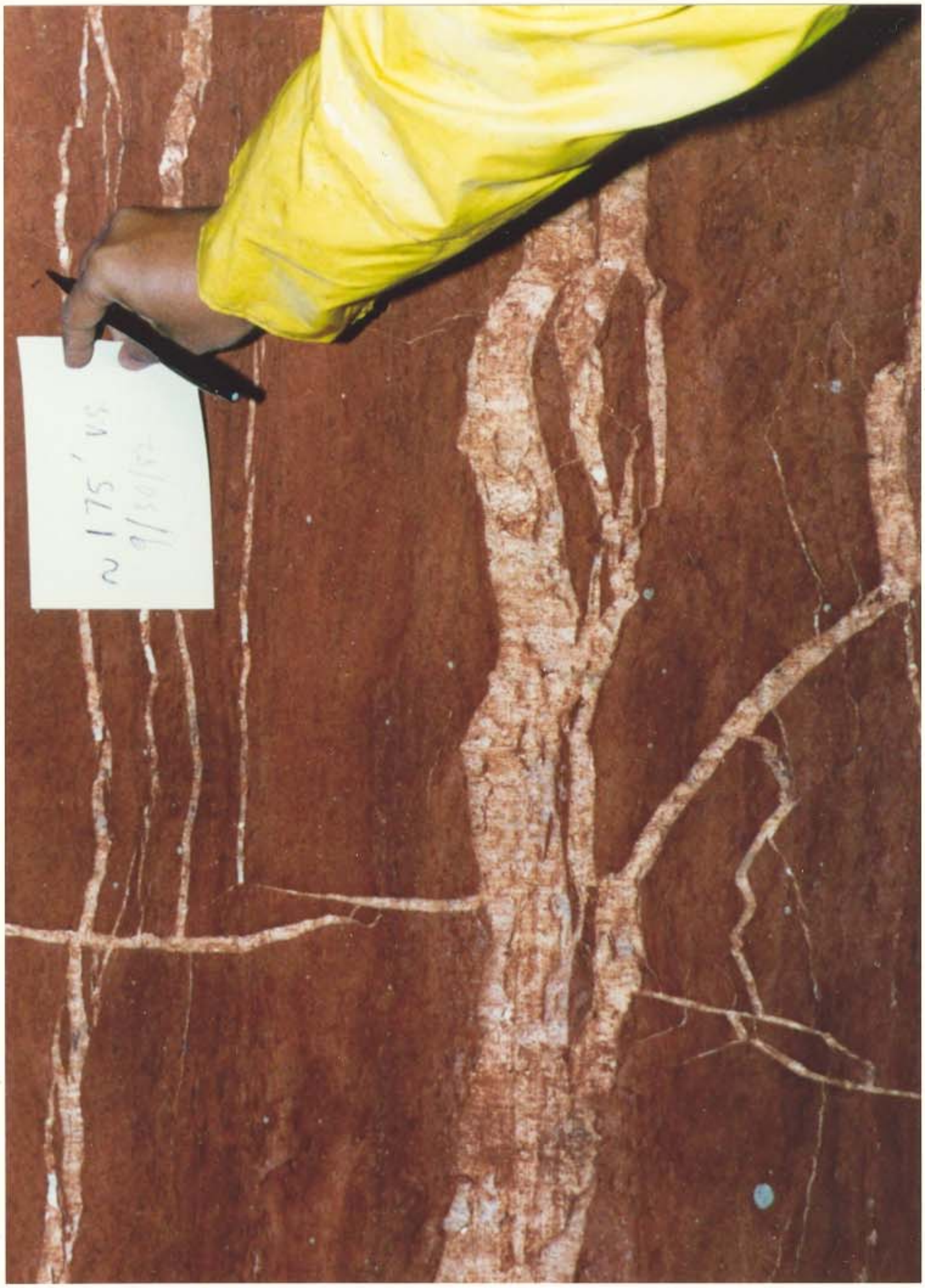

Plate 5. Selenite veins in the Dewey Lake Redbeds.

APPENDIX A

"WIPP Geohydrology - The Implications of Karst", an unpublished manuscript by Larry Barrows, dated May 20, 1982.

WIPP Geohydrology - The Implications of Karst

Larry Barrows

5-20-82

Introduction

Karst refers to a particular type of surface morphology and goundwater hydrology that results from the dissolution or corrosion of rock. The most spectacular and best studied karstlands are in carbonate rocks, but karst also forms in gypsum, anhydrite, and salt.

The WIPP is in one of the largest karstlands of the United States. Karst morphology has been extensively studied by G. O. Bachman and others. The implications of karst hydrology have not yet been considered.

The problem with karst is that shallow groundwater flow is highly irregular in both time and space, through open conduits with a minimum of filtration, and (under the right weather conditions) extremely fast. The Rustler Formation is both the principal aquifer in the region and the principal karst horizon. The Rustler Formation is not a reliable barrier to the migration of contaminated water.

This report results from a review of literature on karst hydrology, inspection of karst features in the field, and discussions with an experienced consultant. The conclusions are based on the referenced literature and should not be judged without a thorough understanding of that material. For minimum background information, the reader is referred to Bachman (1980) and Bogli (1980).

Evidence of Karst

A literature review places the WIPP site within one of the largest karstlands of the United States. Davies and LeGrand (1972) and LeGrand, Stringfield and LaMoreaux (1976) both summarize the important karstlands of the U.S. and include the Pecos Valley of southern New Mexico in their discussions. The maps in these articles (p 470 and p 36, respectively) indicate the WIPP site lies within an extensive karstland. A similar map is reproduced in Milanovic (1981, p 15) and in slightly more detail in Davies (1970, p 77).

Relevant articles on a more local scale include (Morgan (1941), Olive (1967), Gustavson, Hoadley and Simpkins (1981), Vine (1963), and Bachman (1974, 1980, 1981).

Morgan (1941) noted that in the Pecos River drainage basin solution of halite, gypsum, and limestone has controlled the position and efficacy of surface streams and accomplished much of the actual basin excavation. He also notes that over large areas the surface drainage systems have been completely disrupted by development of subterranean drainage through solution channels. The WIPP site is indicated by his map (Fig. 1, p 28) as lying in one of these areas.

More recently Gustavson, Hoadley, and Simpkins (1981) identified rapid karstification of land surfaces overlying areas of active salt dissolution. Their studies are largely conducted in the Texas Panhandle, but simple extrapolations of their regional maps place the WIPP in a karstland.

Olive (1967) discussed solution-subsidence troughs in the outcrop area of the Castile Formation. He attributed the troughs to collapse of solution conduits initially developed along east-trending joints. Although this karstified formation differs from that at the WIPP, the article demonstrates karst development in gypsum in the same semi-arid climate.

G. O. Bachman has conducted extensive investigations of the surface geology of the Los Medanos area to support geologic feasibility studies of the WIPP. The results of this field work and his present interpretation of the Cenozoic history are in Bachman (1980). This report describes dissolution and karst development in the Permian evaporites of the Pecos drainage in the Delaware Basin (including the WIPP site). The affected evaporites include anhydrite, gypsum, halite, and related minerals, and the karst features include collapse sinks, breccia pipes, domes, mounds, caves, and intricate solution passages. Here, and in Bachman (1974), it is suggested that the rate of karstification is dependent on climate with more rapid dissolution and collapse during humid intervals and active fields of windblown sand during arid intervals. The result is an extensive, partially-buried karst plain.

Nash Draw is the most impressive topographic feature in the vicinity of the WIPP site. It is described by Vine (1963) and mapped in detail by Bachman (1981). Processes identified in its formation include near surface dissolution and the related in-filling of solution cavities by surficial sediments. Presently active dissolution of gypsum from the Rustler Formation has resulted in numerous collaps sinks, caves, and tunnels, in a complex karst topography. Caves near the Ken Smith Ranch, near WIPP 26, and near the turn-off from NM

Route 128 to ERDA 10, are large enough to enter (J. Mercer, pers. comm.). Deep-seated dissolution and subsequent collapse of the overlying evaporite section has not been identified.

Karst springs are usually large, few in number, and very irregular in flow. Surprise Spring at the north end of Laguna Grande de la Sal and the brine springs at Malaga Bend are probably karst, although Surprise Spring is affected by waste water from potash refining. The brine springs at Malaga Bend have been studied as part of a salinity alleviation project. The flow is estimated at 0.5 cubic ft/sec, but (more pertinent to karst) it is irregular. Hale, Hughes, and Cox (1954, p 26) noted that short period (hours - few days) water level changes in wells in the spring aquifer accompanied local rain storms. Similar conclusions are indicated from the monthly precipitation table (p 26) and hydrographs in Havens and Wilkins (1979). Particularly notable are the very abrupt changes in all their wells accompanying 6-1/2 in. of rain during August 1966. The significance of such rainfall-related short-period well level oscillations near a karst spring is discussed in Milanovic (1976).

The evidence for regional karstification is extensive, and there is no reason to preclude karst conditions from the immediate vicinity of the WIPP site. The following observations indicate that karst conditions do exist at the site:

- the Rustler Formation isopach
- solution-controlled anisotropic heterogeneous vugular porosity
- closed topographic depressions
- the WIPP 33 cavities
- the gravity field
- lack of surface runoff
- the water balance

An isopach of the Rustler Formation is given in Powers and others (1978, Figure 4.3-8) and more recently in the USGS contribution to Barrows and others (in preparation). These maps show the isopach thinning from 450 feet in the southeast corner of WIPP site Zone IV to 275-300 feet in the northwest corner. There is a strong correlation between the isopach thinning and downward progression of surfaces defined by borehole encounters of the uppermost halite, the uppermost anhydrite, and the lowermost gypsum. These relations have been attributed to the downward and eastward progression of dissolution in the formation by Powers and others (1978, p. 4-41) and by Snyder in Barrows and others (in preparation). The Rustler Formation thinning is an example of a complex interstratal blanket karst involving halite, anhydrite-gypsum, and, to a lesser extent, dolomite.

The interpretation that dissolution progresses downward and eastward is inconsistent with confined southwesterly flow in the Rustler Formation. If the flow were confined, then dissolution should proceed from the recharge area where fresh water first enters the formation. This is demonstrated by a laboratory model of halite karst development described by Bogli (1980, p 210). A more likely process involves easterly progressing karst development with downward infiltration of fresh water through feeders in the overlying Dewey Lake Formation to karst channels in the Rustler Formation.

The borehole measured hydraulic characteristics reported by Gonzalez (1982) are consistent with an interstratal phreatic karst. The measured transmissivities vary over five orders of magnitude within the site (0.001-100 ft^2/day) and up to 1250 ft^2/day in Nash Draw. Transmissivity and the isopach thinning of the Rustler Formation generally increase from east to west. Where measured, the transmissivities are anisotropic with reported ratios of 2.1:1 and 2.7:1. The potentiometric gradient is well below the ground surface, of low average gradient, and irregular. The core descriptions of the aquifers (Schreiber, 1982) indicate primarily vugular porosity.

There are a large number of closed topographic depressions at the WIPP site. These are best seen with stereoscopic viewing of the site aerial photographics or by inspection of the site topographic maps (2 ft. contour interval) (Bechtel, 1981). The largest of the depressions are: in sec. 9, R31E, T22S; at WIPP 14; and at WIPP 33. The one in section 9 is briefly discussed in Powers and others (p 4-7, Fig. 4.2-1b) and by Griswold (1977, p 13, Fig. 34). The depression at WIPP 33 is discussed in the WIPP 33 Basic Data Report (SNLA and USGS, 1981).

The smaller depressions may be windblown. However, the larger depressions are not reasonably attributed to the wind. They are generally round instead of elongate in the prevailing wind direction, symmetric instead of having windward and leeward sides, and have hummocky sandy bottoms instead of a pebble-strewn wind scour. They are also partially coincident with the negative gravity anomalies and one (WIPP 33) was found to be underlain by cavities.

The larger of the depressions are reasonably interpreted as alluvial dolines. Following M. Sweeting (1973, p 46) or A. Bogli (1980, p 61) alluvial dolines form when loose surficial material is washed into solution cavities in the underlying rocks.

Borehole WIPP 33 (SNLA and USGS, 1981) encountered four cavities totaling slightly over 20 feet in the Forty-niner and Magenta Dolomite Members of the Rustler Formation. These cavities are direct evidence of karst. They demonstrate the relation between alluvial dolines, negative gravity anomalies and karst channels in the Rustler Formation.

The surface of the doline at WIPP 33 is floored with loose sand. There are matted leaves and debris indicative of shallow flooding but no evaporite crust. One of the few small arroyos at the site drains into the depression.

A negative gravity anomaly at WIPP 33 was indicated by the regional gravity survey. Additional reconnaissance high-precision gravity profiles resolved a 0.6 milligal negative anomaly with a double half width of 900 ft. This anomaly cannot be reasonably attributed to the 44 ft of Holocene fill encountered in WIPP 33. The top of the causative body should be at or above 450 ft, and the anomaly is too large to be due directly to the cavities .

The WIPP gravity survey is a classic demonstration of the utility of microgravity in karstlands. The field parameters were initially selected to resolve low-amplitude, broad-wavelength anomalies originating from structures within the Castile Formation. Instead of the anticipated signals, the survey revealed a complex pattern of high-amplitude, and short-wavelength negative anomalies. These are presently interpreted as resulting from density (and acoustic velocity) alternations in the vicinity of karst channels. The interpretation and preliminary data are in Barrows and others (in preparation, section 3.3). It consists of the following elements:

Borehole WIPP 34 is in a normal gravity field. WIPP 13, WIPP 14, and WIPP 33 are in negative gravity anomalies. The depths to shallow stratigraphic horizons in all the boreholes are normal.

One of the negative gravity anomalies is coincident with a time-structure syncline at the reflection time of the Rustler Formation (seismic line 77X2). Assuming stratigraphic depths are normal, the seismic time-structure syncline can be produced by lateral velocity variations in the overlying Dewey Lake Formation. The magnitude of the required velocity variation is comparable to that indicated by measurements in uphole velocity surveys at WIPP 13 and WIPP 34. The density variation implied by this measured velocity variation is, along with the thickness of the Dewey Lake Formation, sufficient to account for the negative gravity anomaly.

Boreholes WIPP 14 and WIPP 33 are in alluvial dolines. The two dolines are coincident with negative gravity anomalies.

Gravity interpretations are inherently ambiguous. However, the anomalies are large, real, and must originate at shallow depths. The boreholes did not encounter stratigraphic features which could cause such anomalies, and alteration in the vicinity of karst channels is the simplest interpretation yet proposed. Microgravity surveys in other karst areas (Arzi, 1977 and Omnes, 1977) have also detected negative anomalies which are too large to be entirely due to the cavities. These are interpreted as partially resulting from rock alteration near the channels.

The morphology of semi-arid environments is normally the product of intermittently running water. Arroyos, piedmonts, and playas are characteristic features. The WIPP site has almost no surface runoff and is characterized by a gently-sloping, slightly hummocky plain blanketed with partly stabilized windblown sand and sand dunes. This morphology is evident on the detailed WIPP topographic maps (Bechtel, 1981). The maps show numerous small closed topographic depressions scattered over the site area.

The lack of erosional morphology is not due to inadequate precipitation. There are about 12 inches of annual rainfall most of which falls between May and October. Ed. L. Reed and Associates (1977) provided a study of the surface hydrology in the Los Medanos Area. They indicated an intensity distribution of 1.6 inches and 4 inches for the 2 year and 100 year (resp.) recurring 6 hour storms; and 2 inches and 5 inches for the 2 year and 100 year (resp.) recurring 24 hour storms. They also calculated anticipated runoff using criteria established by the U.S. Soil Conservation Service. The 100 year, 24 hour storm should cause 990 acre feet of runoff from the 30 sq. mile WIPP site. Instead of running off, the precipitation collects in the small topographic depressions and rapidly soaks into the ground.

The absence of surface runoff is characteristic of a karstland. "Mature karst" has been defined as the stage when subsurface drainage is sufficiently developed to accommodate nearly all surface runoff (Bogli 1980, p. 47).

Further karst indications can be inferred from the steady-state water balance equation

$$\text{Inflow} = \text{Outflow}$$

Despite its simplicity, this expression is fundamental to hydrology and must be satisfied by any model or any part of a model (Ward, 1967, p. 19).

Consider the soil at the WIPP site. The inflow is simply 1 foot of precipitation per year (Powers and others, 1978, p. 6-4). Outflow is split between percolation to the groundwater system and evapotranspiration.

Insufficient information exists to establish the division between evapotranspiration and downward percolation. Efficient evapotranspiration should be favored by the semi-arid climate, deep water table and generally dry precursory conditions. Percolation to the ground water system should be favored by sparse vegetation, intense rainstorms, and transmissive soils. The soils are at least transmissive enough to allow infiltration of the larger storms.

Geohydrology Associates, Inc. (1978, p. 48) discussed various studies pertinent to establishing the percentage of total precipitation that is evapotranspirated. They needed the value to calculate the water budget at the potash mines and concluded that 96% evapotranspiration is reasonable. Their report describes many surficial karst features in the area. However, they did not assume karst hydrology in modeling the groundwater movement.

Assuming 96% evapotranspiration, then 0.04 foot of water per year is added to the groundwater system. Further assuming the Rustler aquifers are fifty feet thick with an average effective porosity of 10% (Powers and others, 1978, p. 6-22), then enough water is added to completely refill the aquifer every 125 years.

It follows that the groundwater must be removed from the system on an average of 125 years (some faster, some slower). Calculations based on borehole-measured parameters and a particle-tracking model for a nonabsorbing tracer yield extremely long travel times around 40,000 years (Gonzalez, 1982). There is a basic inconsistency between these two approaches. Appealing to an evapotranspiration efficiency approaching 100% is both unsubstantiated and unnecessary. It is subsequently shown that in a karstland boreholes are expected to indicate values which are not representative of the area. The calculated very long travel times are then both understandable and wrong.

Implications

The WIPP site is reasonably described as a karstland. Regional karst is evident in the surface morphology and has been so identified by Morgan (1941), Olive (1957), Davies and LeGrand (1972), LeGrand, Stringfield and LaMoreaux (1976), G.O. Bachman (1974, 1980, 1981), Powers and others (1978, section 6.3.6) and Gustavson, Hoadley and Simpkins (1981, p 130-137). Locally the Rustler Formation is an example of a complex, interstratal, blanket karst involving halite, gypsum-anhydrite, and dolomite. Karstification of the Rustler Formation is evident from the Rustler isopach, solution-controlled anisotropic heterogeneous vugular permeability, the gravity field, the WIPP 33 cavities, closed topographic depressions, lack of surface run-off, and considerations of a reasonable water balance.

Implications to WIPP follow from the characteristics of karst hydrology. The English literature on karst hydrology is limited but adequate to form some general conclusions. This literature includes two text books (Bogli, 1980 and Milanovic, 1981), a couple of published symposia (Yevjevich, 1976, and Tolson and Doyle, 1977) and several articles. It should be noted that karst hydrology is a newly developed area of research and not much was published in English before the last half decade.

The hydraulic characteristics of a karstland result primarily from the dissolution or corrosion of rock. Secondary processes include the transport of insoluble material through solution conduits and the incasion or collapse of underground cavities. The processes are discussed at length in Chapter 14 of Bogli (1980).

Karstlands develop in phases. During the initial phase a hydraulic gradient forms in a corrodible but unaltered country rock. Water flows slowly through interstices and open joints and corrodes or dissolves the rock. One or two of the pathways will be slightly more permeable, carry slightly more water, and grow faster than the other pathways. As they grow, the hydraulic gradient decreases and alternate pathways become increasingly inactive. The end result is a highly irregular regional network of primary solution conduits within a larger volume containing generally inactive stagnated secondary pathways. Average transmissivities should be highly anisotropic in the direction of the original gradient (Mandel, 1966, p 5).

The initial stage of karstification lasts until the subsurface drainage is sufficiently developed to accommodate all of the surface run-off. The karstland is then defined as "mature" (Bogli, 1980, p 47). During maturity, corrosion enlarges the conduits, the water table drops towards the level of the drainage springs, and the number of springs decreases as the more aggressive conduits capture increasingly larger proportions of the total flow. Finally in old age the cavities collapse. In this sense, karst development at the WIPP should be regarded as mature.

The preceding discussion is independent of the size of the volume considered. In a karstland, flow through any representative volume is expected to be dominated by a few throughgoing conduits and there should be no spatial scale at which the average hydraulic properties vary gradationally. Because of this inherent heterogeneity, continuum models should not apply. This includes the use of an anisotropic continuum for a "fracture flow" model. For further discussion of the physical conditions necessary to use the anisotropic continuum approximation see Maini, Noorishad, and Sharp (1972, paper Il-E. 8 p.).

Another implication of the karstification process is that borehole-measured transmissivities and storativities should not be representative of the area. A borehole which misses one of the active corrosion conduits should show values which are much less than the average. This applies to almost all boreholes in a karst terrain because the area of active conduits is only a small part of the total area. Conventional borehole measurement can still be made in a karstland. Mandel (1966, p 6) notes that even in well developed karstlands there can be a regular distribution of groundwater potentials and a "cone of depression" around pumping wells. In this sense, karst may be indistinguishable from classical porous aquifers.

A karstland can normally, but not always, be subdivided into three hydrological zones based on the position of the water table (Bogli, 1980, Ch 6). The largely inactive vadose zone includes feeders in which groundwater flows downward towards collecting channels. The high-water zone is that region which is alternately flooded and empty, and the phreatic zone remains completely flooded. All three zones should be present where corrodible rocks extend from depth to the surface (e.g., Nash Draw). At the WIPP site the corrodible Rustler Formation is beneath the Dewey Lake Formation and entirely saturated with water (interstratal phreatic karst). When penetrated by wells, water rises several hundred feet into the relatively impermeable Dewey Lake Formation (i.e., an artesian aquifer). Other karstlands in which saturated corrodible rocks are covered by non-soluble formations include the Athabasca carbonate and evaporite karst in Alberta, Canada (Ozoray, 1977, p 85-98), the partially covered Silver Springs basin in Florida (Faulker, 1976, p 137-164), and the Santa Rosa area of New Mexico (M. Sweeting, 1973, p 299). Artesian conditions in karstlands have been noted along the northern cost of Puerto Rico (Giusti, 1977, p 149-167), in Yugoslavia (Milanovic 1976, p 165-191 and 1977, p 357-358), in portions of the Silver Springs basin (Davies and LeGrand, 1972, p 477), and the Roswell Artesian Basin of New Mexico (Davies and LeGrand, 1972, p 502; Bean, 1942).

The velocity of groundwater in a karstland is very irregular. Milanovic (1981 ch 5) reviews the background and present concepts of karst water and its zonation by velocity. At one extreme are old and nearly stagnant waters occupying pores in the remaining unaltered country rock and in abandoned pathways which are no longer part of the primary system. Bogli (1980, p 82) notes several occurrences of stagnated karst waters, one of which was dated at 3400 $\pm$400 yrs. At the other extreme are the waters in the primary system. A few direct velocity observations have been made by spielogists observing the flow of water along cavern floors. Most velocity measurments are made indirectly by injecting a tracer into the karst watercourse, usually at a swallow hole, and observing the arrival at a spring. This "velocity" is the linear distance divided by travel time and does not account for irregularities in the flow path.

The measured tracer velocities are, by groundwater standards, very fast. Milanovic (1981, p 135) gives a histogram and discussion of 281 tests conducted in the Dinaric Karst of Yugoslavia. The measured velocities ranged from 0.002 to 55.2 cm/sec with an average of 5 cm/sec. The linear travel distances are 10 to 15 or more kilometers. Bogli (1980, p 78-79) reports flow velocities ranging between a few meters per hour and 1/2 km/hour (0.08 to 14 cm/sec). Comparable velocities were discussed by the participants in the 1975 U.S.-Yugoslavian symposium on karst hydrology and water resources (Yevjevich, 1976, pp 170, 176, 186-187, 240). At a reasonable karst velocity of 1 cm/sec water in the primary system can move 30 km in about one month.

The observed character of karst flow also differs significantly from more conventional groundwater. First, velocity is not proportional to the potentiometric gradient. Milanovic (1981, p 138) gives a plot of the measured tracer velocities versus the gradient between the end points. There is no detectable relation on the plot despite the wide range of both variables. Bogli (1980, Ch 5) notes that there is no direct relationship between the velocity of flow and the gradient. It follows that models based on a linear or Darcy relation should not be applied to a karstland.

Second, karst velocities are found to be dependent on surface conditions with relatively slow movement during the dry season and rapid movement during heavy rains. In fully arid climates, permanently static karst water-bodies can be found (Bogli, 1980, p 85). This dependency of velocity on surface conditions results from variable flow regimes more than an increase in the gradient. Torbarov (1976, p 121) demonstrated at least two, and probably three, flow regimes using the decomposition of water recession curves. The calculated hydraulic characteristics (i.e., transmissivity and effective porosity) of the regimes differ. Further considerations of multiple flow regimes in a karst are given by Milanovic (1976, p 184), Yevjevich (1976, p 213), Ramljak, et al (1976, p 240) and Bogli (1980, Ch 5).

Karst results from the dissolution or corrosion of rock in a complex groundwater system which is extremely irregular in both space and time. The chemical properties of karst waters are correspondingly complex. Faulkner (1976, p 149) and LeGrand, Stringfield and LaMoreaux (1976 p 44) note chemical stratification of karst water with generally more dissolved solutes at greater depths. Chemical analysis of nine samples from the Puerto Rico karst are given by Guisti (1977, p 149-167) and for six samples for the Athabasca buried karst by Ozoray (1977, p 85-98). These last two papers illustrates the broad range of chemical compositions of karst waters. Further discussion of geochemical studies are in Thrailkill (1976, paper 34) and Petrik (1976, paper 29).

Faulkner (1976, p 137-164) reported the analysis of a karst system discharging at Silver Springs, Florida. This article may reasonably represent the extent to which hydraulic analysis can be applied to a complex and largely inaccessible karstland like the WIPP site. The analysis used flow net techniques to model the known flow rate from the spring. Sufficient well data were available to contour the potentiometric surface. Recharge was by infiltration of local rainfall. Aquifer thickness, effective porosity, and isotropic transmissivities were assumed. The flow net analysis indicated transmissivities of 10^3 to 2.36×10^6 meters squared per day and velocities between 0.05 to 23 meters per day, with an average of 2 to 3 meters per day. The author notes that the calculated velocity approximations must be used with care because of complications due to the presence of solution channels (p 158). He also notes that while flow net analysis of the freely flowing karst spring yielded results representative of the basin, conventional pumping tests may necesarily analyze a small part of the aquifer that is not representative of the larger segment (p 159).

Practical problems of waste disposal in a karstland result from the irregular, very fast movement of contaminated groundwater through open conduits. Authors who have identified karstlands as unreliable waste disposal environments include LeGrand (1973), LeGrand, Stringfield and LaMoreaux (1976, p 32), Yevjevich (1976, p 220), Turk (1976, paper #30 and p 861), Pokrajcic (1976, paper #31), Preka (1976, paper #32), Faulkner (1976, p 859), Petrik (1976, p 860), Corovic (1976, p 860, p 862), Vineyard (1976, p 861), Herak and Stringfield (1972, p 515), Milanovic (1981, p 3), Richter (1977, p 305), Sendlein and Palmquist (1977, p 323), and Davies and LeGrand (1972 p 480), Malatino and Lloyd (1977, p 307).

Conclusions

- The WIPP site is regionally and locally a karstland.
- Representative hydraulic characteristics cannot be measured at boreholes.
- Continuum models should not be used to establish minimum flow times. This includes the use of an anisotropic continuum approximation of fracture flow.
- Flow in the Rustler Formation is expected to be highly irregular in both space and time, through open channels with a minimum of filtration, and (under the right weather conditions) extremely fast.
- The Rustler Formation is not a reliable barrier to the migration of contaminated water.

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APPENDIX B

Consultants' Reports and Correspondence
with Harry LeGrand 1982-83

HEALTH & ENVIRONMENT department

"Equal Opportunity Employer"

STATE OF NEW MEXICO

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July 8, 1982

Mr. Joseph McGough
Project Manager on WIPP
WIPP Project Office
U. S. Department of Energy
Albuquerque Operations Office
P. O. Box 5400
Albuquerque, NM 87115

Dear Mr. McGough:

We have invited Mr. Harry LeGrand, a Hydrogeological Consultant and an authority on fracture flow hydrology to consult with us during the week of July 12. To facilitate Mr. LeGrand's acquisition of the maximum information on the questions concerning the fracture flow hydrology of the northern Delaware Basin, we have made the following arrangements with the appropriate TSC and Sandia staff people:

1. Dr. Larry Barrows will visit with us in Santa Fe on Tuesday, July 13th at 9:30 a.m. to discuss the results of gravity survey at the WIPP site.

2. Dr. Don Diego Gonzalez and Dr. Jerry Mercer will accompany us on a visit of the WIPP site and vicinity on Thursday, July 15th. We will visit the site of the hydrological tracer tests as well as the WIPP shaft and WIPP-12 locations on 15th morning.

3. Dr. S. J. Lambert will also accompany us on the field trip on 14th afternoon (San Simon Sink and Bell Lake) and on 15th (WIPP site, WIPP-12 in the morning; Nash Draw and Malaga Bend in the afternoon).

We truly appreciate the cooperation of all involved.

Sincerely,

Jack M. -for- McNeil

Robert H. Neill
Director

cc: William F. Jebb, WIPP Construction Manager
Chuck Little, Lead Engineer
Dennis Powers, Sandia Lab
TSC, IEA
Jerry Mercer, USGS

✓2-037-AG14-24

Harry E. LeGrand
Hydrogeologist

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FMN

July 22, 1982

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JUL 2? 1982

ENVIRONMENTAL
EVALUATION GROUP

Mr. Robert Neill, Director
Environmental Evaluation Group
320 Marcy Street
P. O. Box 968
Santa Fe, New Mexico 87504-0968

Dear Bob:

Attached is a copy of my informal report on the hydrogeology of the WIPP area, with special reference to karst hydrology.

The report represents a summary of some key thoughts that I have after spending the week of July 12 at your office in Santa Fe and at the Site.

I gained optimum value from the data and findings of reports furnished me, and the gracious help you and your colleagues offered allowed me to get a fairly good grasp of the subject. If some of the interpretations in this report show a lack of understanding of the subject on my part, please let me know so that the best ultimate interpretations are not clouded.

I was impressed with the high caliber of work conducted by EEG and by all agencies involved; the fine cooperation between agencies is commendable.

It was a pleasure to be with you and your co-workers during the week.

With all good wishes -

Sincerely,

Harry

Harry E. LeGrand

HEL:ul
Attachment

HYDROGEOLOGIC CONSIDERATIONS AT THE WIPP SITE

With Special Emphasis on Karst Hydrologic Features and Processes

(An Informal and Preliminary Report)

by

Harry E. LeGrand

July 22, 1982

INTRODUCTION

This informal report summarizes my thoughts about some hydrogeologic features of WIPP resulting from my trip to Santa Fe and to the site area during the week of July 12, 1982. The comments below center chiefly on dissolutional phenomena and related ground-water flow systems. More particularly, I have tried to determine the similarity of the Delaware Basin dissolution features with the typical karst features where limestones and dolomites have been subjected to dissolution. Some thoughts are expressed on potential ground-water flow patterns that are not clearly defined by the existing data. A variety of other thoughts are also offered.

For the purpose of simplicity, I will not delve into the geochemistry related to dissolution mechanism and will make no distinction between the soluble capabilities of limestone, dolomite, gypsum, and halite. Steve Lambert has ably done this in his recent report. I will stress dissolution in general terms in relation to ground-water circulation systems in certain formations and settings.

My thoughts should be considered as tentative in view of the fact that I was not able to fully absorb and synthesize all the key data that those on the project have so skillfully collected.

GENERAL CHARACTERISTICS OF LIMESTONE KARST AND COMPARISON WITH WIPP KARST

Karst regions are widespread in the United States and also in many parts of the world. They are characterized by soluble rocks at or near land surface. These rocks, chiefly limestone and dolomites, may be etched in many ways on the land surface and have solution openings, such as caverns, beneath the ground where circulating water has been able to move into the rocks and to discharge from them.

Carbonate-rock terranes are not entirely water bearing, as some parts of the rock system either are impermeable or are above the zone of saturation. In the development of a karst system, some parts of the formations are not in the path of water movement, and these parts may remain relatively impermeable. In those parts where an aquifer has developed and where the permeability is high, the slope of the water table is flattened, and a permeable unsaturated zone remains. Thus the permeable zones commonly extend above and below the water table.

Surface features commonly present are:

(1) rolling topography with enclosed depressions, or sinks

(2) thin soils or bare rock

(3) scarcity of surface streams

(4) escarpments and topographic difference with respect to less soluble rocks (limestone almost everywhere being noticeable above or below adjacent insoluble rocks).

Where circulation of water and solution of the carbonate rocks have progressed fully, there is a tendency for the aquifer to have some of the following characteristics:

(1) a channel or artery network type of permeability, especially near the water table

(2) rapidly decreasing overall permeability with increasing depth below the water table

(3) an exceptionally high zone of permeability in valleys

(4) a very permeable and cavernous unsaturated zone

(5) salty water in the lower and less permeable part of the aquifer

(6) moderately low storage of freshwater in long periods of fair weather.

A comparison of the hydrogeologic setting in the vicinity of WIPP with a typical limestone karst setting reveals some similarities and some differences. Some similarities are:

(1) enclosed depressions, or sinks

(2) an escarpment separating an upland from a dissolution subsided lowland

(3) caves

(4) variable permeability related to the degree of circulation and dissolution from place to place.

WIPP differs in some of the following ways:

(1) artesian conditions beneath the upland (presumably water-table conditions only in Nash Draw)

(2) inappreciable recharge of water to stimulate circulation and dissolution

(3) concurrent subsidence with development of solution openings

(4) predominance of thin sheet-like, or stratabound, circulation and dissolution, and absence of large springs.

PHILOSOPHY OF DOWN-DIP WATER MOVEMENT

Anderson has postulated a down-dip movement of water in his proposed upper Castile Brine aquifer. He says that recharge for this "brine aquifer" could be from the Pecos River and discharge into the Capitan Reef in the low northeast part of the basin. If my calculations are correct, this would put the recharge area at an elevation of about 2,950 feet and the discharge level in the Capitan at about 3,200 feet (pre-development Capitan water level). This appears to be an uphill flow of water.

There is almost always a general tendency to project a down-dip flow of water within inclined strata. Much of this confined water does tend to go downdip where the surface slope is also in a downdip direction and where overlying confining beds allow upward leakage. (Upward leakage is the common tendency and leads to a down-dip hydraulic gradient also.) The setting above the escarpment at Livingston Ridge doesn't fit the normal down-dip movement of water. (First, there is no recharge of significance at the high part near Livingston Ridge,) and the Rustler, Salado, and Castile formations don't crop out at high places immediately west of the scarp. Second, the confining beds to aquifers are so impermeable that they don't allow enough upward leakage to cause a down-dip drop in head.

Having no recharge and no leakage out to a discharge area would suggest a static, or no-flow, condition. Certainly, the Salado and Castile formations beneath the upland and underneath WIPP closely approach this because (any semblance of an aquifer within them would be confined with no significant source of recharge or discharge available.)

MOVEMENT OF WATER IN THE RUSTLER FORMATION

Circulation of water in the Rustler formation is more apparent because its water is seeking a discharge zone in the lower end of Nash Draw, into Salt Lake, or into the Pecos River at Malaga Bend. These general discharge areas are confirmed by the water level contours, which show a west and south drop in head. If it can be demonstrated that no recharge to the Rustler is from downward leakage from the Dewey Lake Red Beds, some recharge apparently is coming from a northern source.

The water-level map of the Rustler does not suggest a two component system of water movement, but the land surface topographic positions of parts of the Rustler indicate a different artesian and water-table setting from place to place. Only the Culebra and beds below are confined all the way to Malaga Bend. All beds in the Rustler are confined beneath the Site and almost to the edge of the escarpment. From the edge of the escarpment and in Nash Draw extending down to Salt Spring and on to the Pecos River at Malaga Bend, the Magenta and other upper beds of the Rustler are close to the land surface and under water-table conditions.

This conversion of some of the beds from a confined position to a water-table position has some significance. Where water has been confined under artesian pressure there is a tendency for slower movement of water than under water-table conditions because of poor means of discharge. (Since good circulation leads to enlargement of fractures by dissolution, it follows that the Rustler, under confined conditions east of the escarpment, should have, in general, minor or insignificant openings.) The extremely low values of hydraulic conductivity in the Rustler beneath WIPP and higher values in areas to the west support the generalization that cavities do not form readily under artesian conditions. This generalization applies also to limestone karst regions of the world; in almost all cases the cavities in karst areas were formed under water-table conditions even though some caverns have since been buried by overlying deposits and are now confined. As to halite and gypsum, Lambert and others have noted no appreciable lag time between the incipient development of cavities and subsidence of overlying material; this concurrent development of open space by dissolution and subsidence of overlying material prevents any long "pipe-line" type of openings to carry water.

Permeability in the Culebra does increase under the Livingston Ridge as much as two miles east of the escarpment, still under artesian conditions. Yet, there is no indication of the increased permeability of the Culebra toward or beneath Nash Draw that could be due to interconnected cavities. As I recall, the Culebra aquifer is still under artesian conditions as it approaches Salt Lake, but its water is beginning to leak upward in the southern end of Nash Draw. The discharging water of the Culebra is responsible for much of the salty water entering the Pecos River at Malaga Bend.

It is difficult to determine the remaining source of the salts at Salt Lake and Malaga Bend. The Rustler beds above the Culebra beneath Livingston Ridge that are buried beneath the Dewey Lake Red Beds extend westward into Nash Draw where they are near land surface. I assume that the disarranged near-surface beds in Nash Draw are composed of alluvium, colluvium, and residue of gypsum, halite, and dolomite beds; nearly flat-lying undisturbed soluble beds lie not far below. The surface beds are more permeable than the Dewey Lake Red Beds on the upland area to the east. There must be some semblance of a water-table system in Nash Draw. Recharge through downward diffused seepage and through the caves in sinks leads to southward movement of water to Salt Lake.

The top of the soluble Rustler beds in Nash Draw are in the path of southward moving ground water. Thus, the relatively shallow sheet dissolution on the top Rustler beds in Nash Draw account for much of the salty water reaching the Pecos River and Malaga Bend. Because of the near-surface position of some Rustler beds in Nash Draw and because of better recharge facilities in Nash Draw, some of the Rustler water in Nash Draw could be very young; the Rustler water beneath the Dewey Lake Red Beds under the upland should be old.

POSSIBILITY OF FAST KARST WATER MOVEMENT IN THE RUSTLER FORMATION

Characteristics of limestone karst areas and comparison of limestone karst with halite-gypsum karst features have been discussed earlier. Larry Barrows, in an oral discussion, cited examples of fast movement of water through open channels in some limestone karst regions; he posed the question that if similar conditions exist in the halite-gypsum-dolomite karst, the Rustler formation might not be a barrier to the migration of contaminated water.

The processes of karst development to produce continuous channels for relatively fast movement of water, described by Barrows, are correct. They would apply to the Rustler formation as a "worse-case" situation if there were no constraints. (However, the constraints are mostly predominant,) as mentioned earlier in this report and cited in the "fracture flow" report by Don Gonzalez and in the "dissolution" report by Steve Lambert. Some of the constraints to fast flow include: inherently low permeability with inertia to keep it that way, confined flow that restricts movement, concurrent slumping or compaction with enlargement of fractures by dissolution, and lack of nearby discharge areas. The data confirm the existence of these constraints east of the escarpment except in the vicinity of WIPP 33.

WIPP 33 is somewhat unusual in that a cavity or soft zone was drilled through in the Rustler. The well is located in an enclosed sink. The enclosed sink, the four cavities totaling slightly more than 20 feet, and negative gravity anomalies at the site, give support to Larry Barrows' thesis of significant karstification.

From my own observations in many karst regions, I don't find it surprising to find solution channels and increased permeability beneath dissolution escarpments even though fluvial processes appear to be dominant. As early as 1948, Steve Herrick and I described the mechanism of escarpment retreat and the development of permeability in a study of a limestone terrane in southwest Georgia. (Like an advancing army against enemy lines, the attack is not even and broad but rather as advancing prongs. The advancing prongs in this case are zones of greater permeability where fractures have been enlarged preferentially by dissolution.) I assume that one of these prongs has advanced as far east as WIPP 33. I would not expect any appreciable dissolution prong to extend more than about two miles into the upland. The data on hydraulic conductivities generally support this limit of increased permeability. The data show very low values of hydraulic conductivity in the central WIPP zone, essentually indicating that no significant dissolution reaches this zone.

Unless additional data indicate otherwise, it is reasonable to assume that a postulated solution channel underlies WIPP 33, that it decreases in size and importance eastward and does not exist in the central 2-mile WIPP zone, that it continues westward toward the escarpment, and that it is obliterated in Nash Draw.

If WIPP 33 has located a solution channel extending westward to the escarpment, are there others? Since WIPP 33 is located in an enclosed depression and since gravity anomalies exist there, the presence of cavities and an extended solution channel is reasonable. Unless other surface sinks in the escarpment area are mapped and unless geophysical anomalies suggest subsurface cavities, we may assume that other dissolution channels are not present or significant.

While the WIPP Program is now in a stage of trying to reduce uncertainties, there still remains an uncertainty of possible moderate significance about postulated channel flow of water in a part of the Rustler formation westward from the 2-mile zone to the escarpment. Further studies in the Livingston Ridge area may be justified. A test to determine how WIPP 33 would take induced water has been suggested. A terrain evaluation to locate possible depressions near the escarpment may also be useful.

DEEP DISSOLUTION PHENOMENA EAST OF THE WIPP SITE

Sinks and chimney-like subsided areas generally beneath the buried Capitan Reef have been puzzling, and Anderson and Lambert have made special studies of them. The fact that (1) some rather deep soluble but nearly impermeable beds are involved and (2) no surface or near-surface karst indications extend to a possible surface discharge area in the Delaware Basin leads logically to the conclusion that the circulation system in the more permeable but deep Capitan Limestone in the buried reef area is involved.

In spite of useful studies already made concerning deep dissolution, there remain some uncertainties. (If these unusual and interesting features are confined to the general reef area and associated with the reef in origin, as it now appears, they may be more of academic than of practical concern.) However, it would be helpful to focus more thinking on Bell Lake Sink and Slick Sink, which lie inland several miles from the inner reef margin. Is there a permeable prong of Capitan Limestone extending inward to Bell Lake Sink and Slick Sink? It seems unlikely that the effect of dissolution collapses at these two depressions could extend to the WIPP Site, but we need to explore the possibility further.

BRINE POCKETS IN THE CASTILE FORMATION

My experience in brine behavior in deep burial situations is limited, and I did not explore this subject. It is obvious to me that the high-pressured brine pockets, such as that found in ERDA 6, do not represent a brine aquifer. To be an aquifer, there must be a recharge area, transmission area, and discharge area. The brine pockets have none of these. They should not be termed brine reservoirs but may properly be considered isolated pods or pockets entrapped perhaps as a result of the tectonic compressive stresses when the Delaware Basin was tilted. The subject is important and needs further study.

CONCLUDING REMARKS

The WIPP Site is in a region of complex hydrogeology that results in a setting almost unique in composite terms. Both conventional studies and specialized approaches have been necessary to minimize the questions and uncertainties. One might question the WIPP Site as a candidate for a waste-storage plant if the hydrogeology is complex and if uncertainties, however small, still persist. On the contrary, the best candidate for the waste should logically be in an unusual setting.

We start with the premise that if there were no moving ground water anywhere, radioactive and other hazardous wastes could be buried in the ground almost anywhere without harm. Thus, the ever-present and ever-moving ground water is the major concern in all cases. Even if a zone at depth is found where water is not present, an additional requirement would be that no aquifers lie above or below this zone of "no-water occurrence or movement." These constraints essentially eliminate all simple and conventional hydrogeologic settings.

The point to be made is that only an unusual hydrogeologic setting, such as the WIPP Site, is likely to be an acceptable one. It follows that complex hydrogeology that requires special study surrounds such a setting. This is true with the WIPP Site, where three unresolved uncertainties still exist.

These uncertainties are: (1) the extent or degree to which dissolution channels may extend in the Rustler eastward from the escarpment, as postulated by data at WIPP 33, (2) the existence and nature of high-pressure salt-water pods, as found in ERDA 6, and (3) the origin and implication of

San Simon Swale, Bell Lake Sink, and Slick Sink depressions east of the Site. These three uncertainties are being addressed, and adequate knowledge about the degree of severity and their pertinence to the safety of the facility should be known in the coming months. The probability of any of these uncertainties becoming a major problem seems slight; yet, in view of the overall need for complete success of waste isolation, further considerations of them are merited.

HEALTH ENVIRONMENT department

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STATE OF NEW MEXICO

ENVIRONMENTAL EVALUATION GROUP
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(505) 827-5481

August 2, 1982

Dr. Larry J. Barrows
Organization 7111
Sandia National Laboratories
Albuquerque, NM

Dear Larry:

Attached is a copy of the preliminary report on karst hydrology at the WIPP site by Harry LeGrand. Please let me have your comments on it as soon as possible. We are sending it to you since many of his comments relate to issues raised by you at our meeting here last month. Obviously, his comments are very preliminary and, therefore, should not be released to anyone else.

With best wishes-

Sincerely,

Lokesh Chaturvedi

LC:eg

Enclosure

August 6, 1982

Lokesh,

Attached are my comments on the preliminary karst hydrology report by Harry LeGrand. I hope you find them useful.

Let me first say that he has done a good job with a large amount of material in the short time available. His contribution to the WIPP investigations is both sorely needed and appreciated.

Agreed that our geo-hydraulic situation is exceedingly complex and not analogous to a classic humid carbonate karstland. Applying research results obtained in other areas to the semiarid northern Delaware Basin is equivocal. However, I continue to support the material and conclusions of my previous report.

My karst sudy did not consider implications of the Rustler core descriptions given by Ferrall and Gibbons. (I had inadvertently overlooked their report). I think their indications of a strata-bound karst in the three non-dolomitic members of the Rustler are important.

Sincerely,

Larry Barrows

(Typed from handwritten original.)

First some general comments

1. There is no physical reason to preclude karst development from the site and good evidence that it does exist. This includes:
   - The Rustler Formation isopach
   - The Rustler Core descriptions
   - The negative gravity anomalies
   - Lack of surface runoff
   - the water balance
   - alluvial dolines (e.g. WIPP 14)

2. The Culebra Dolomite may not be the primary water transport horizon. The Culebra is more uniformly porous than other members and it is the most reliable source of well water. However, the core descriptions (Ferrall and Gibbons) indicate strata-bound karst in the non-dolomitic members and at the Rustler/Salado contact. Halite and gypsum/anhydrite are considerably more soluble than carbonates.

3. The Dewey Lake may not be an aquiclude. At WIPP-33 it is transmissive enough to accommodate intense but infrequent flow from the small arroyo that drains into the sink. Dewey Lake cores (WIPP 19, WIPP 14) show numerous cross-cutting selenite veins. Maybe these were once open to water flow? Maybe some are still open? If not, I would expect more runoff from the occassional storms and more development of a shallow perched water table.

   Incidently a potash corehole (#115 in sec. 13 of T19S, R30E) encountered 100 feet of open (water filled) cavity plus 40 feet of mud and silt in the Dewey Lake. This was followed by a normal Rustler section.

4. The potentiometric surfaces have generally low gradients but they are not simple. The three maps in Mercer and Gonzalez (Magenta, Culebra, Rustler/Salado) show the Culebra below the Magenta over most of the site but above it to the north. Similar cross-over exists between the Culebra and Rustler/Salado surfaces. Perhaps the heads indicate relative proximity of the water-yielding aquifers to karst conduits in adjacent strata.

The Culebra potentiometric map in the fracture flow report (Fig. 16) needs to be redrawn. This map is largely predicated on the tightest (most unreliable?) hole (p-18) and ignores WIPP-30, H9, and H10. My work map is considerably more convoluted.

More specific comments referenced to Harry's report

Page 3, last two lines

The Dewey Lake is generally tight and does not yield water to wells. When porous levels of the Rustler are penetrated, water rises several hundred feet into the Dewey Lake but is still well below the surface. It isn't clear that these "artesian" conditions demonstrate a confined aquifer.

The available recharge is 12"/year falling as intense but sporadic storms. Most (e.g. 96%) is evapotranspirated but this leaves enough for circulation and dissolution. Presumably the karst was more active in past fluvial periods (see "Bachman")

Page 4

WIPP-33 showed 20+ ft. of cavity beneath 450 ft of overburden. Subsidence may not be sufficient to choke off solution conduits.

The springs at Malaga Bend and Salt Lake are irregular, seasonal but not necessarily small.

Page 6-8

The question of confinement is important but difficult. At the site, downward infiltration is implied by the dissolution interpretation of the Rustler isopach thining.

As I understand it, hydraulic confinement in the Culebra beneath Salt Lake is based on artesian flow from a borehole in the lake. We need to know more about the duration of flow, salinity-corrected heads, seasonal fluctuations. The extensive dissolution of all members of the Rustler and of the upper Salado at this location seems inconsistent with total confinement. Perhaps "partially-confined" is a better description.

Page 9, 3rd paragraph

The cavity indications at WIPP-33 include lost circulation, full' out' on a long arm caliper, and the televiewer. I don't think "soft zone" is a good description

Page 10, 1st paragraph

The "advancing army" may be more like a gorilla war in which local partisans progressively corrode a soluble social order.

Page 10, 2nd paragraph

Why not interconnect the WIPP-33 cavities with those in Nash Draw?

Page 10, last paragraph

WIPP-14 is in an alluvial doline abut 700 feet wide and 10 feet deep. This depression is: round instead of elongate in the prevailing wind direction, symmetric instead of showing windward and leaward sides, and has a hummocky sand filled bottom instead of a pebble-strewn wind scour. It is not attributable to the wind. WIPP-14 is also in a negative gravity anomaly similar in amplitude and wavelenght to that at WIPP-33. The WIPP-14 negative anomaly extends east-west across all of sections 8 and 9.

Both WIPP-14 and WIPP-33 encountered normal depths to stratigraphic horizons. At WIPP-33 there were cavities in the Rustler, at WIPP-14 there is extensive hydration of anhydrate to gypsum (based on densilog comparison of WIPP-14 with WIPP-34 about 1000 ft. to the west).

I agree with the interpretation that Livingston ridge is a solution escarpment but suggest the site area is a karst plain whose irregularities have been largely filled in by drifting sand.

Page 12

I ran two reconnaissance gravity profiles over Bell Lake Sink. These data indicate a complex, near-surface density structure. If further investigations are made, I suggest using gravity to locate several drilling targets. Given the subsurface complexity indicated by our present gravity data, it is doubtful that a single hole would adequately characterize the sink.

HEALTH & ENVIRONMENT department

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(505) 827-5481

August 20, 1982

Mr. Harry LeGrand
331 Yadkin Drive
Raleigh, NC 27609

Dear Harry:

Here is a copy of the comments from Larry Barrows on your report. Also attached is the Ferrall, Gibbons' report cited by Larry in his letter.

Please bring the report back with you when you come here. We are looking forward to seeing you here during the second week of September.

Yours sincerely,

Lokesh

Lokesh Chaturvedi

LC:eg

Harry E. LeGrand
Hydrogeologist

331 Yadkin Drive

Raleigh, N. C. 27609

Telephone (919) 787-5855

Rob

October 9, 1982

OCT 1_ 1982
ENVIRONMENTAL
EVALUATION GROUP

Mr. Robert H. Neill, Director
New Mexico Environmental Evaluation Group
320 Marcy Street
P. O. Box 968
Santa Fe, New Mexico 87504-0968

Dear Bob:

Attached are two copies of the informal report prepared as a result of my visit during the week of September 6.

I hope my interpretations are correct. I have tried to use some of the key conclusions of other workers as a basis to recast some thoughts in terms of karst processes and of development of permeability.

This has been a very interesting experience for me. The fine cooperation and hospitality extended by you and your colleagues made the work very pleasant.

With very best wishes to all -

Sincerely,

Harry LeGrand

Harry E. LeGrand

HEL:ul

Attachments

ASPECTS OF KARST HYDROLOGY AT THE WIPP AREA

(An Informal and Preliminary Report)

by

Harry E. LeGrand

October 8, 1982

(modified slightly November 10)

INTRODUCTION

This informal report expresses some of my thoughts about some hydrogeologic features of WIPP resulting from my trip to Santa Fe and to the site area during the week of July 12 and the week of September 6, 1982. The comments below center chiefly on karst, or dissolutional, phenomena and related ground-water flow systems. More particularly, I have tried to determine the similarity of the Delaware Basin dissolution features with the typical karst features where limestones and dolomites have been subjected to solution. Some thoughts are expressed on potential ground-water flow patterns that are not clearly defined by the existing data. Dissolution is stressed in general terms in relation to ground-water circulation systems in certain formations and settings.

It is proper that karst hydrology be considered in the scope of studies of WIPP because development of permeability results from karst processes. The great range in permeability in the Delaware Basin is a major concern. Most of this range of permeability is caused by the different action of karst processes in space and time.

This report discusses general characteristics of the more typical and widespread limestone karsts and compares these characteristics with those of gypsum and halite karst in the Delaware Basin. Special features of permeability are outlined in relation to causes and effects. The ground-water circulation system from recharge to discharge area is also a part of karst phenomena and also must be addressed. An effort will be made to reconstruct parts of the hydrogeologic history of the area. This approach has been fruitful in past studies in understanding the distribution of permeability and patterns of ground-water flow.

It has been established that there is a considerable range in hydraulic conductivity from one stratigraphic unit to another. It has also been established that the hydraulic conductivity ranges greatly from east to west in specific units. To simplify areal descriptions of hydraulic conductivity and other features in this report, three areal zones are identified. These are (1) Nash Draw, (2) Upland West, and (3) Upland East. Upland West is a zone three or four miles wide east of and above the Nash Draw scarp; it corresponds generally with the area refered to as the "dissolution front" by Snyder, Jones, and others. Upland East includes most of the WIPP site and the area to the east; it is a zone represented chiefly by inherently low hydraulic condictivity throughout the Rustler Formation.

It should be noted that the boundary between Upland East and Upland West is quite arbitrary and that other workers should adjust it to the most likely zone. The fact that this boundary is not now definite does not take away the important and necessary distinctions to be made between Upland West and Upland East.

My thoughts should be considered as tentative in view of the fact that I may not have fully absorbed and synthesized all the needed data. The skillful collection of data by others and their sound interpretations appear to leave little room for expression of new ideas. Many of the conclusions of others are restated or placed in another context to provide linkage with thoughts that I have.

GENERAL CHARACTERISTICS OF LIMESTONE KARST AND COMPARISON WITH WIPP KARST

Karst regions are widespread in the United States and also in many parts of the world. They are characterized by soluble rocks at or near land surface. These rocks, chiefly limestone and dolomites, may be etched in many ways on the land surface and have solution openings, such as caverns, beneath the ground where circulating water has been able to move into the rocks and to discharge from them.

Carbonate-rock terranes are not entirely water bearing, as some parts of the rock system either are impermeable or are above the zone of saturation. In the development of a karst system, some parts of the formations are not in the path of water movement, and these parts may remain relatively impermeable. In those parts where an aquifer has developed and where the permeability is high, the slope of the water table is flattened, and a permeable unsaturated zone remains. Thus the permeable zones commonly extend above and below the water table.

Surface features commonly present are:

(1) rolling topography with enclosed depressions, or sinks

(2) thin soils or bare rock

(3) scarcity of surface streams

(4) escarpments and topographic difference with respect to less soluble rocks (limestone almost everywhere being noticeable above or below adjacent insoluble rocks)

Where circulation of water and solution of the carbonate rocks have progressed fully, there is a tendency for the aquifer to have some of the following characteristics:

(1) a channel or artery network type of permeability, especially near the water table

(2) rapidly decreasing overall permeability with increasing depth below the water table

(3) an exceptionally high zone of permeability in valleys

(4) a very permeable and cavernous unsaturated zone

(5) salty water in the lower and less permeable part of the aquifer

(6) moderately low storage of freshwater in long periods of fair weather

A comparison of the hydrogeologic setting in the vicinity of WIPP with a typical limestone karst setting reveals some similarities and some differences. Some similarities are:

(1) enclosed depressions, or sinks

(2) an escarpment separating an upland from a dissolution subsided lowland

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(4) variable permeability related to the degree of circulation and dissolution from place to place

WIPP differs in some of the following ways:

(1) artesian conditions beneath the upland (presumably water-table conditions only in Nash Draw)

(2) inappreciable recharge of water to stimulate circulation and dissolution

(3) concurrent subsidence with development of solution openings

(4) predominance of thin sheet-like, or stratabound, circulation and dissolution, and absence of large springs

DISSOLUTIONAL PERMEABILITY IN UPLAND EAST, UPLAND WEST, AND NASH DRAW

Upland East

Upland East, as shown in general terms on Figure 1, includes the central part of the WIPP Site. In Upland East inherently low hydraulic conductivity exists throughout the Rustler; there is no evidence of significant solution in the halite, anhydrite, and dolomite beds. The two dolomite units - the Magenta and Culebra contain some fracture permeability but not to the extent of considering them aquifers in the normal sense. Artesian, or confined, conditions exist in all the Rustler beds and in deeper formations.

Upland West

Upland West extends from the scarp facing Nash Draw to the Upland East boundary. It represents a belt bordered on the east by an apparent abrupt zone in which the hydraulic conductivity of the Culebra Dolomite is distinctly reduced. This boundary is shown by Gonzalez in figure 5 of the "Culebra Fracture Report;" it is indicated in this figure by the "no-halite zone" below the Culebra.

In aggregate, the rocks of the Rustler Formation are relatively impermeable. Yet, the Magenta and Culebra dolomites have hydraulic conductivity significantly higher than those in Upland East. Also, there is sufficient permeability at the base of the Rustler near the scarp to the extent that this zone has been called water-bearing. The increased hydraulic conductivity in these three zones appears to be due directly or indirectly to dissolution. Near the scarp the Rustler halite has been dissolved away, as have some overlying anhydrite layers. The dolomite beds are persistently present and apparently have been only partly removed by solution action. The increased hydraulic conductivity of the Culebra, relative to Upland East, may be due chiefly to increased fracturing resulting from slight subsidence of the dolomite as a result of removal of these zones of underlying anhydrite and halite. Gonzalez and others have touched on this point. Artesian conditions exist in all the Rustler beds except in the uppermost beds at the edge of the scarp at Nash Draw.

Nash Draw

The linear extension of many of the Rustler beds to the west of the scarp has been interrupted by solutional processes and collapse of less soluble beds in Nash Draw. The Rustler halite beds have been dissolved away, as well as much of anhydrite-gypsum. Parts of the Magenta and Culebra dolomite beds have also been removed by solution action. In many places in Nash Draw only down-slumped remnants of the dolomites exist. The upper 50 feet of material in Nash Draw in most places may be difficult to map because of down-slumping and disarranged former beds of the Rustler, which now may be called residuum. Although not explicitly stated in any reports I have read, water-table conditions probably prevail in much of Nash Draw within 50 feet of land surface; artesian conditions prevail in the underlying beds.

Dissolutional History and Mechanisms

Having stated some key conditions in Upland East, Upland West, and Nash Draw, we turn attention to the hydrologic history and to the development of permeability.

To develop permeability through dissolution it is necessary for the rock to have been in a ground-water circulation system - a system having a recharge area, transmission zone, and a discharge area. A discharge area is of primary importance. The greater the circulation of water, the greater the dissolution, and, conversely, the greater the solution, the greater the circulation of water.

In looking for a discharge area, it is logical to look at the lowest part of a basin in or near a perennial stream. The Pecos River in the vicinity of Malaga Bend would be the presumed discharge area, even without looking at supporting data. This general discharge area at the lower end of Nash Draw, and including Salt Lake, is confirmed by the water level contours of the Magenta, Culebra, and the Rustler-Salado contact. All show a south or west drop in head.

Recharge to the three more permeable units of the Rustler has been considered only in general terms, and understandably so. Recharge on Upland West and East by downward recharge from the overlying Dewey Lake Red Beds is often considered, but the extremely low hydraulic conductivity of these beds reduce the likelihood of appreciable recharge. All three Rustler units of concern have higher heads to the north, supporting the consensus that the general recharge area is northward, perhaps in Clayton Basin.

The potentiometric maps of the three water-bearing zones show the general flow patterns in Upland West and East, but our knowledge of flow patterns in Nash Draw is poor. The work underway and planned for Nash Draw will help in better understanding the processes and history of dissolution in the WIPP region.

The development of permeability in Nash Draw and in Upland West has resulted indirectly from the presence of the Pecos River. The downcutting of this river between Carlsbad and Malaga Bend through moderately recent geologic time has produced a line sink, representing the discharge zone and promoting circulation of the mineralized waters. Thus, we have some aspects of a typical karst setting in nearly flat-lying soluble beds - a perennial stream representing a base-level control, bordered by a low solution plain and a distant scarp that has retreated away from the stream.

This type of limestone karst setting is developed under water-table conditions. The Pecos River setting of gypsum-halite karst is also under water-table conditions to some extent. The best opportunity for sufficient solution to occur to lower the elevation in Nash Draw would be a water-table system in which the top gypsum bed is involved. The top gypsum bed is of younger age in northern Nash Draw, of course. The dolomite beds, being less soluble and thinner in aggregate than the evaporite beds, are less responsible for the existence of Nash Draw. It is likely that considerable soluble evaporites are being removed under confined conditions through upward leakage through the fractured Culebra near Malaga Bend.

In a general sense, we can classify the solutional mechanisms into three groups as follows:

(1) solution channels and prongs from enlargement of fractures

(2) stratabound solution

(3) sheet solution

Solution channels and prongs from enlargement of fractures commonly occur under water-table conditions where fractures are in the path of circulating water. As in typical limestone karst areas, some fractures continue to enlarge until they reach a true cavernous situation. Larry Barrows, in an informal presentation, described this typical karst development as it may apply to the WIPP area. The cavernous localities in Nash Draw have developed in such a manner.

Much of the solutional development near edges of scarps is through enlargement of fractures. As early as 1948, Steve Herrick and I described the mechanism of escarpment retreat and the development of permeability in a study of a limestone terrane in southwest Georgia. Like an advancing army against enemy lines, the attack is not even and broad but rather as advancing prongs. The advancing prongs in this case are zones of greater permeability where fractures have been enlarged preferentially by dissolution. I assume that one of these prongs has advanced as far east as WIPP 33. I would not expect any appreciable dissolution prong to extend more than about two to three miles into the upland area.

The puzzling question of regional dissolution in the Delaware Basin bedded evaporties has been discussed ably by Steve Lambert. The core study of the Rustler by Ferrall and Gibbons attempts to account for a space requirement, so necessary for circulation of water. The absence of halite and some anhydrite beds in Nash Draw and Upland West certainly indicate intrastratal dissolution under artesian conditions over a larger area than would appear reasonable to me. Whatever the detail mechanism of intrastratal dissolution may be, the process should be so slow that the advance of the action into Upland East may be many tens of thousands of years away.

The fact that the dissolved beds do not leave open spaces to act as aquifers is not merely academic. The blanket subsidence of overlying beds in the voids from the dissolved evaporite beds tends to increase the fracturing of the overlying Culebra and Magenta dolomite beds, as several workers have reported. The hydraulic conductivity of the dolomites is highest in Nash Draw, is moderately low in Upland West, and very low in Upland East. Thus, this range in hydraulic conductivity is indirectly the result of stratabound dissolution of evaporite beds.

The sheet solution, mentioned earlier, is restricted to the shallowest water movement in Nash Draw. Whether under water-table or artesian conditions, this shallowest water in Nash Draw moves somewhat as sheet flow over relatively impermeable evaporite beds; this water carries dissolved material toward Malaga Bend. This sheet flow and solution, supported by recharge in Nash Draw and in Clayton Basin to the North, tends to maintain the low-lying surface plain of Nash Draw. This sheet solution has no significant or direct relation to concerns of the WIPP Site.

FLOW PATTERNS

Emphasis thus far has been put on development of permeability through karst processes. Circulation of water from a recharge area to a discharge area is of primary importance. In a gross sense, the Rustler waters move from a recharge area in the north to a discharge area near Malaga Bend in the Pecos River. In considering the Magenta Dolomite, the Culebra Dolomite, and the Rustler-Salado contact zone, we see that each of these water-bearing zones have somewhat different flow patterns in Nash Draw, Upland West, and Upland East.

Only beds below the Culebra are confined all the way to Malaga Bend. Mercer and Gonzalez have projected a general three-element flow pattern for the Culebra. One element of flow is southward in Nash Draw; another element of flow is more southeastward under Upland West before turning southwestward toward Malaga Bend; the third element, in which very little movement occurs in the impermeable beds, water moves even more to the southeast through Upland East. The direction and degree of flow of Culebra water in Upland East are subjects about which there is not complete agreement.

The water-level map of the Magenta shows a pronounced west and southwest flow from Upland West to Nash Draw. This is understandable because the Magenta is close enough to the land surface near the scarp that upland leakage into overlying beds surely occurs in the east side of Nash Draw. There are no springs near the scarp in Nash Draw, but water from the Magenta can leak upward into a water-table system in Nash Draw.

We are not certain about the Magenta water as it passes from Upland West into Nash Draw. Some stays in the Magenta as long as it is a tangible unit and not dissolved away or crumbled in Nash Draw. To what extent does some of the water leak up into clayey or poorly permeable beds? To what extent does some move through open gypsum caverns? These questions may not be critical to the concerns about the WIPP Site, but they are significant. Great changes in hydraulic conductivity from place to place and uncertainties of flow paths make it difficult to determine the travel time of Magenta water from the WIPP Site to Malaga Bend or to some undesirable place in Nash Draw.

SUMMARY

Approaching the features of the WIPP Site from the viewpoint of karst development leads one to see some similarities and some differences with conventional limestone karsts. The karst analysis is helpful because it places the subject in terms of processes and stages of permeability development that conventional data collection and analysis may omit.

Three key areal zones should be distinguished even though they have overlapping relations. These are Nash Draw, Upland West, and Upland East. Upland East is underlain by soluble beds of inherently low permeability, essentially isolated from sufficient circulating water for dissolution to occur. It is bordered by Upland West, where some dissolution of evaporite beds and where some fracture permeability in dolomite beds are recognized. Nash Draw seems far removed geographically from concerns of the WIPP Site, but it is underlain by a significant part of the ground-water transmission system leading from the Site.

The stratabound dissolution features of some evaporite beds under artesian conditions aren't a limestone karst characteristic. It appears that we must rely more on data collection, observations, and inferences for conclusions and less on past experiences of similar situations.

The boundary between Upland West and Upland East has been mapped on the basis of sharp changes in hydraulic conductivity and on the basis of presence or absence of Rustler halite. The boundary may also approximately coincide with the eastern limit to which both stratabound dissolution and prong karst solution may have extended. Upland East is considered to be the zone in which inherently low permeability exists.

The persistence of the Magenta and Culebra dolomite beds from Upland East through Upland West and into Nash Draw is noteworthy. In many karst areas such thin dolomite beds would be dissolved away more readily. It makes sense, as others have stated, to conclude that increased fracture permeability to the west is due to slight subsidence of the beds following solutional removal of some underlying evaporite beds.

FIGURE 1. (LeGrand)

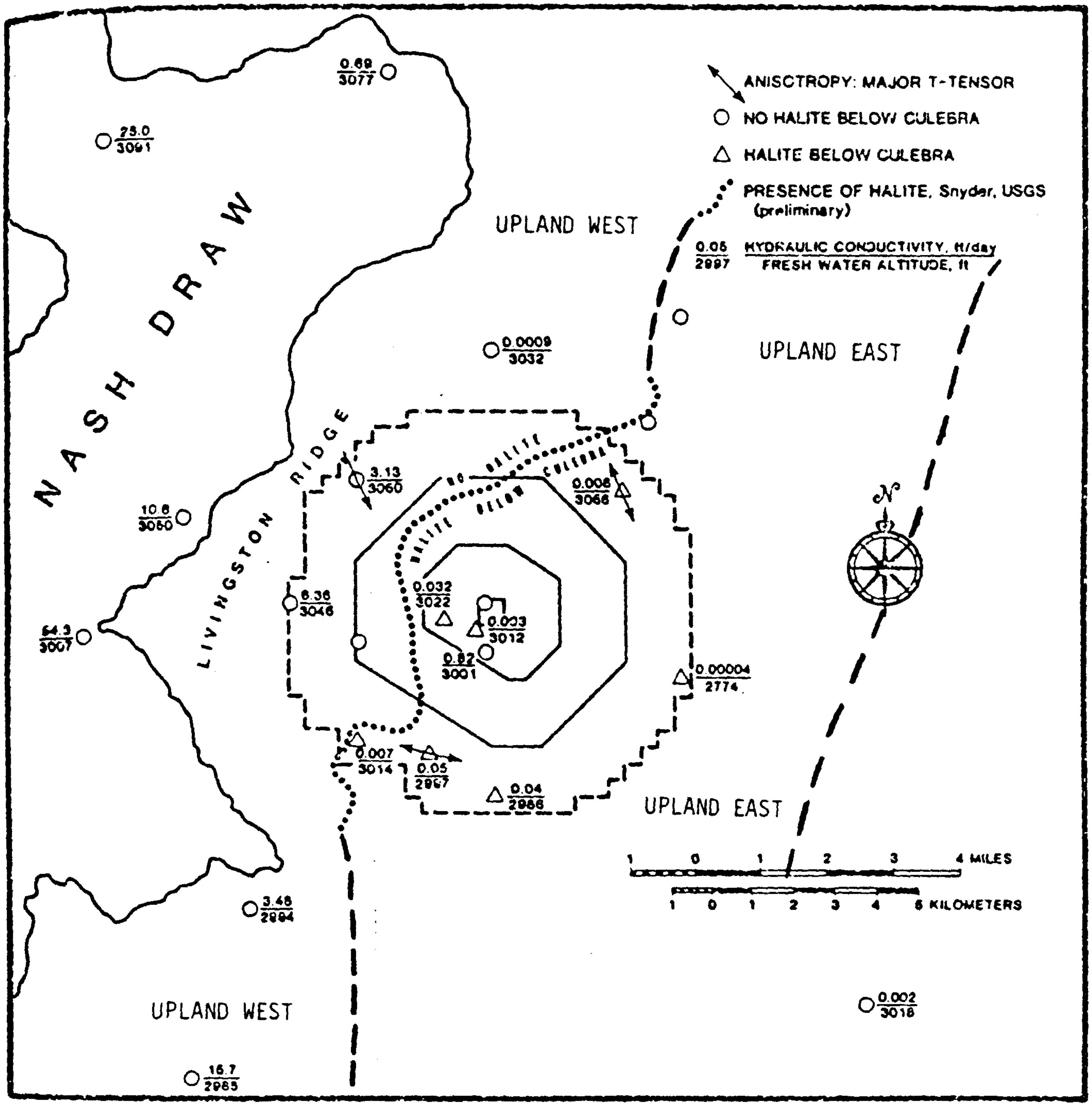

Figure 15. Variation in K, Anisotropy, Fresh Water in the Culebra Dolomite and the Presence of Salt Where Hydrogeologic Testing Has Occurred at the WIPP

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STATE OF NEW MEXICO

ENVIRONMENTAL EVALUATION GROUP
320 Marcy Street
P.O. Box 968
Santa Fe, NM 87504-0968
(505) 827-5481

HEALTH & ENVIRONMENT department

October 15, 1982

Harry E. LeGrand
Hydrogeologist
331 Yadkin Drive
Raleigh, NC 27609

Dear Harry:

Thank you for your letter of October 9, 1982 transmitting your report entitled "Aspects of Karst Hydrology at the WIPP Area." After studying your report, we will get back to you if we have any questions.

We have enjoyed working with you and look forward to a continuing relationship as issues relating to karst hydrology continue to develop at the WIPP site.

Sincerely,

Bob

Robert H. Neill
Director

RHN:eg

Prof 5-1
LeGrand

HEALTH ENVIRONMENT department

"Equal Opportunity Employer"

STATE OF NEW MEXICO

ENVIRONMENTAL EVALUATION GROUP

320 Marcy Street
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(505) 827-5481

October 29, 1982

Mr. Harry E. LeGrand
Hydrogeologist
331 Yadkin Drive
Raleigh, North Carolina 27609

Dear Harry:

Lokesh went down the 6' diameter ventilation shaft at the WIPP site two weeks ago. Here are some photographs of the Dewey Lake Redbeds and various horizons in the Rustler formation, which would be interest to you. The description for each is written on the back side of the photos.

Please return these to him after you have looked at them.

We have received your preliminary report dated October 8. We would like to make the following comments for your consideration in preparing a "final" version of your report.

1. Since Larry Barrows raised this question in a formal way through a paper, we would like to address as many of the points raised by him as possible. The points raised by Larry which you have not addressed are: the lack of surface runoff at the WIPP site in spite of an average of 12" per year rainfall, the evidence for solution conduits from gravity surveys, the Rustler formation isopachs and dolines such as at WIPP-14. The bottom line of all this is whether or not we should accept the transmissivity and porosity values determined from flow tests and tracer tests (as reported in the fracture flow report by Gonzalez) as representative values for the WIPP site. If not, should we conclude that "there is no direct relationship between the velocity of flow and the gradient (from which) follows that models based on a linear or Darcy relation should not be applied to a Karstland" (Bogli, 1980, quoted in Barrows' paper, p. 15)?

In order to help you answer these questions, I am enclosing the following material.

- A simple map showing locations of all WIPP, H and P boreholes. This map also has a range/Township grid on it so that you can locate the features identified in Barrows' paper and his comments on your first draft.

- A copy of GCR Fig. 4.3-8 and a more recent map drawn by U.S.G.S., showing Rustler isopachs. Barrows has discussed these on p. 5 of his report.

- A Bouger gravity anomaly map prepared by Larry Barrows. According to Larry, the negative anomalies seen in this map "result from density alternations in the vicinity of karst channels" (p. 7, Barrows, 1982). In the ventilation shaft near ERDA-9, there are washed out zones below Magenta and Culebra aquifers which produce water. Two of the enclosed photographs clearly show this.

2. You have used the "Halite/No Halite below Culebra" boundary drawn by Snyder as the hydrologic boundary between fractured, high permeability Rustler aquifers and the tight aquifers to the east. But there are four drillholes to the east of this boundary which show "No halite below Culebra" (shown as circles in your Fig. 1). Two of these holes are in the center of the WIPP site. Also, a well to the west of this boundary shows k=0.0009 ft/day and the wells to the east of this boundary show a range of k from 0.82 ft/day to 0.00004 ft/day. Does this boundary really have any meaning in terms of hydrologic properties of the Rustler aquifers?

3. On page 6 of your report, you have speculated on the water-table conditions in Nash Draw within 50 feet of land surface. David Updegraff has condensed the available information on this subject from the basic data reports for holes WIPP-25 through WIPP-29. His memo is attached.

4. Figure 15 of Bachman (1980) report indicates that the Magenta is missing at Malaga Bend and the Culebra outcrops along the Pecos river. This would seem to suggest that water-table conditions exist in the Rustler formation along the Pecos river. We are pointing this out to you in connection with your statement, "...but the Pecos river setting is characterized to a great extent by artesian conditions." (P.8, para 2).

5. On page 9 of your report, you seem to imply that the boundary between high and low hydraulic conductivity zone is moving to the east. If this is true, would it change the southeasterly hydraulic gradient in the uplands to a south or southwesterly gradient parallel to Nash Draw in the future?

We will be happy to pay your consulting fees at the usual rate for an additional 2 to 3 days for finalizing your report. Payment will be made through a subcontract with New Mexico Tech. A form for payment is enclosed.

Sincerely,

Robert H. Neill
Director

cc: Dr. Marx Brook, NM Tech

STATE OF NEW MEXICO
HEALTH ENVIRONMENT

MEMORANDUM

DATE: October 21, 1982

TO: Lokesh Chaturvedi

FROM: David Updegraff DU

SUBJECT: Water Table Conditions in Nash Draw

I have studied your verbal request for my opinion regarding water table conditions in Nash Draw. Harry LeGrand in his report dated 8 October, 1982, is not clear as to what he means by water table conditions, i.e. water table conditions in the dolomites, water table conditions in the alluvium, water table conditions in the residuum or some combination of the aforementioned.

The data for WIPP-25 through WIPP-29 generally indicate the following:

1. Culebra is confined along Livingston Ridge and in the northern part (edge of the dog bone) of Nash Draw. The Culebra just to the north of Laguna Grande de la Sal appears to be unconfined. The unconfined water level in the Culebra may extend to the caves that we visited in July, 1982, but there is no data to either confirm or deny this.

2. The Magenta, where it both exists and contains water, is confined. This occurs at points along Livingston Ridge and in the northern part (edge of the dog bone) of Nash Draw.

3. There does not appear to be any data that supports or denies water table conditions in the Holocene deposits, Pliestocene deposits or Dewey Lake Redbeds that exist in Nash Draw.

The above statements are only valid for Nash Draw north of the east-west highway (Route 128) running across Nash Draw.

Data for Nash Draw south of the highway is non-existent. However, the data for WIPP-29 indicate that the Culebra is hydraulically connected to Laguna Grande de la Sal. The Culebra may be unconfined in this area.

ADM 031 Issued 6/78

The following is a summary of the data:

Hole	Member	Depth Below Ground Surface	Water Level Depth Below Ground Surface	Comment
WIPP-25	Magenta	302 - 328	160	Confined
	Culebra	447 - 472	165	Confined

Note: 17' of Pliestocene deposits and 215' of Dewey Lake Redbeds overlie Rustler at this location. No data on water levels for these formations are available.

Hole	Member	Depth Below Ground Surface	Water Level Depth Below Ground Surface	Comment
WIPP-26	Magenta	70 - 99	dry	-
	Culebra	186 - 209	146	Confined

Note: 10' of Holocene deposits overlie Rustler at this location. No water level data are available for these deposits.

Hole	Member	Depth Below Ground Surface	Water Level Depth Below Ground Surface	Comment
WIPP-27	Magenta	175 - 193	102	Confined
	Culebra	292 - 318	105	Confined

Note: Dolomitic part of Magenta appears to be gone; only silt and clays remain. Rustler overlain by 79' of Holocene deposits and Mescalero caliche, and 73' of Deway Lake Redbeds at this location. No water level data are available for these formations.

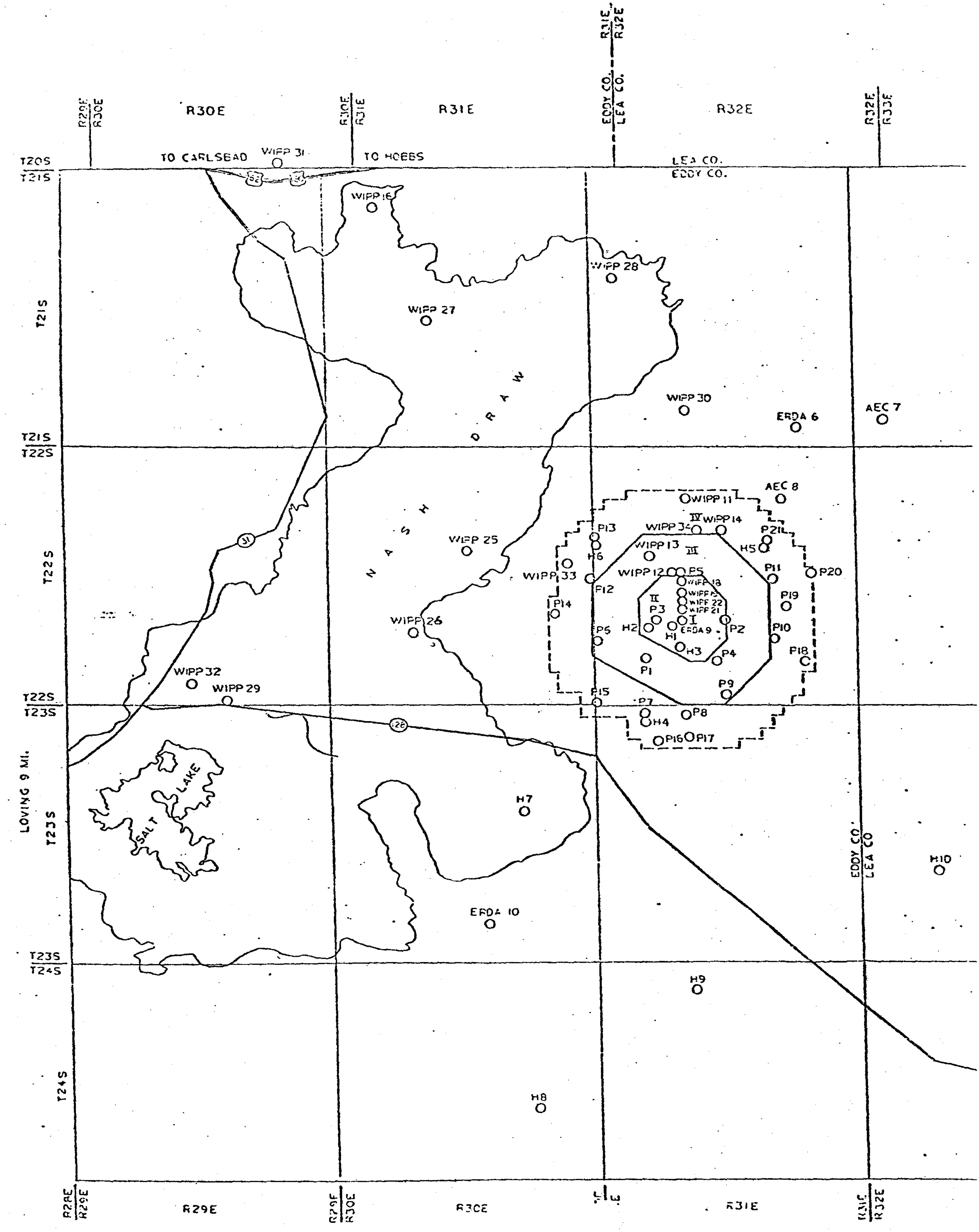
Hole	Member	Depth Below Ground Surface	Water Level Depth Below Ground Surface	Comment
WIPP-28	Magenta	285 - 310	202	Confined
	Culebra	420 - 446	277.2	Confined

Note: 12' of Holocene deposits and 203' of Dewey Lake Redbeds overlie the Rustler at this location. No water-level data are available for these formations.

Hole	Member	Depth Below Ground Surface	Water Level Depth Below Ground Surface	Comment
WIPP-29	Magenta	Not present	-	-
	Culebra	12 - 42	10	Unconfined

Note: 12' of Holocene deposits overlie Culebra at this location. 8' of the 12', which directly overlies the Culebra is a limestone. The core long does not state explicitly that the limestone is fractured, but the zone of non-recoverable core and the neutron porosity log indicate it's possible.

A well location map is attached.


R29E / R30E
R30E
R30E / R31E
R31E
EDDY CO. / LEA CO.
R31E / R32E
R32E
R32E / R33E
T20S / T21S
TO CARLSBAD
WIPP 31
TO HOBBS
LEA CO. / EDDY CO.
WIPP 16
WIPP 28
WIPP 27
T21S
NASH DRAW
WIPP 30
ERDA 6
AEC 7
T21S / T22S
AEC 8
WIPP 11
WIPP 14
WIPP 34
P13
P21
WIPP 13
H5
WIPP 25
H6
T22S
WIPP 33
WIPP 12
P5
P11
P20
P12
WIPP 18
WIPP 22
WIPP 21
P19
P14
P3
ERDA 9
WIPP 26
P6
H2
H1
P2
P10
H3
P4
P18
P1
WIPP 32
WIPP 29
P9
T22S / T23S
P15
P7
P8
H4
P16
P17
LOVING 9 MI.
SALT LAKE
T23S
H7
EDDY CO. / LEA CO.
H10
ERDA 10
T23S / T24S
H9
T24S
H8
R28E / R29E
R29E
R29E / R30E
R30E
R31E
R31E / R32E

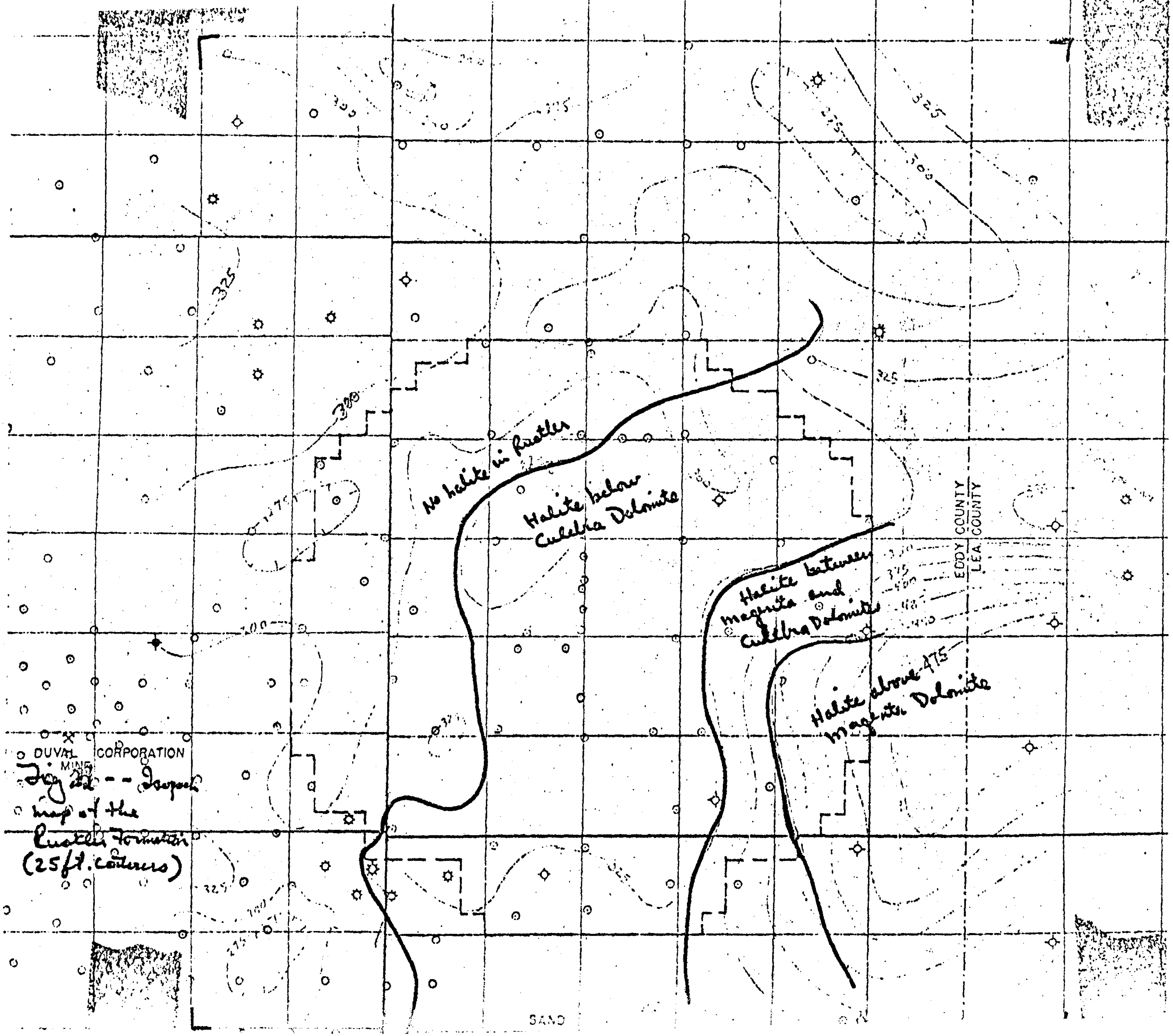


Fig 22 -- Isopach map of the Rustler Formation (25 ft. contours)

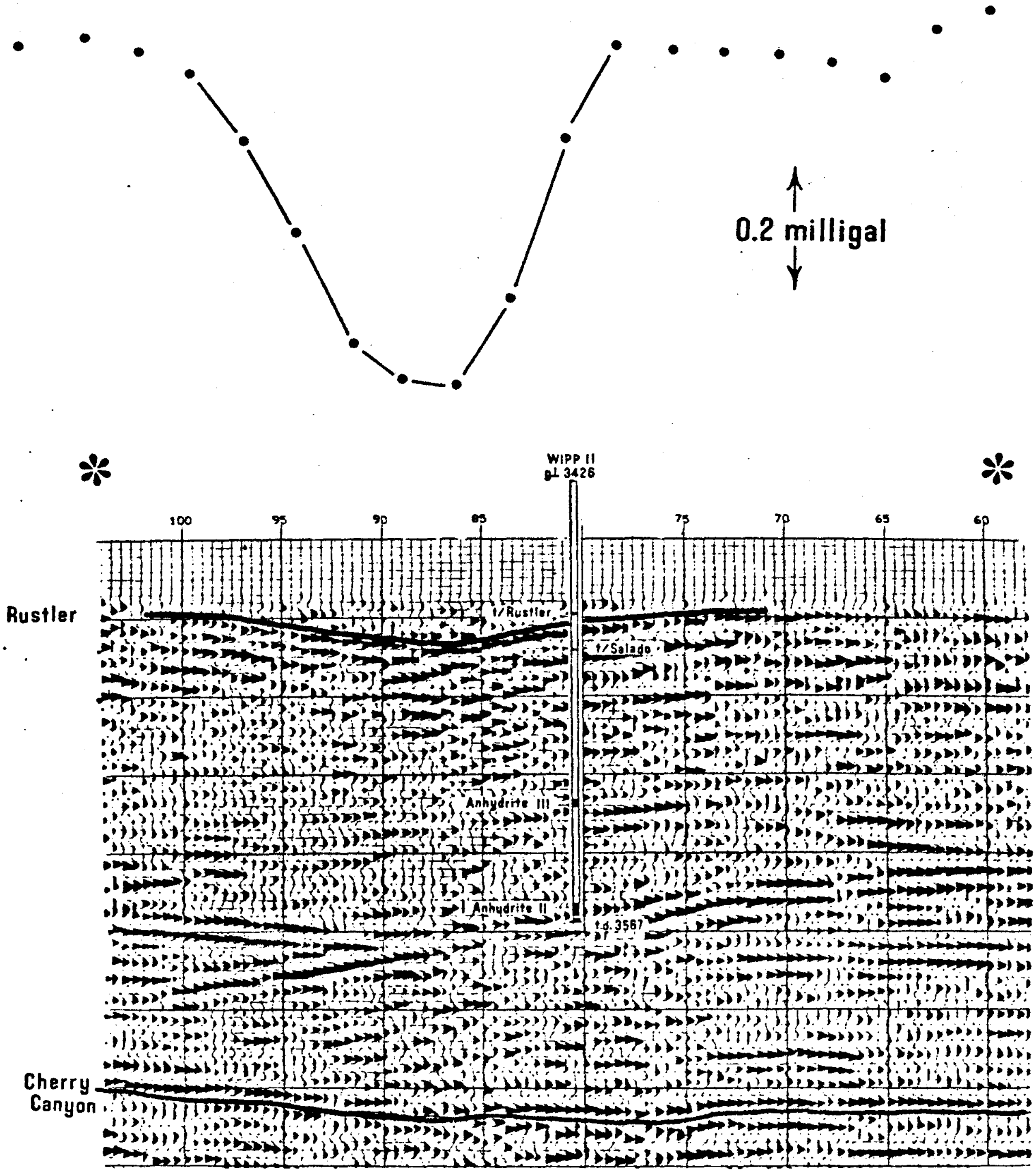
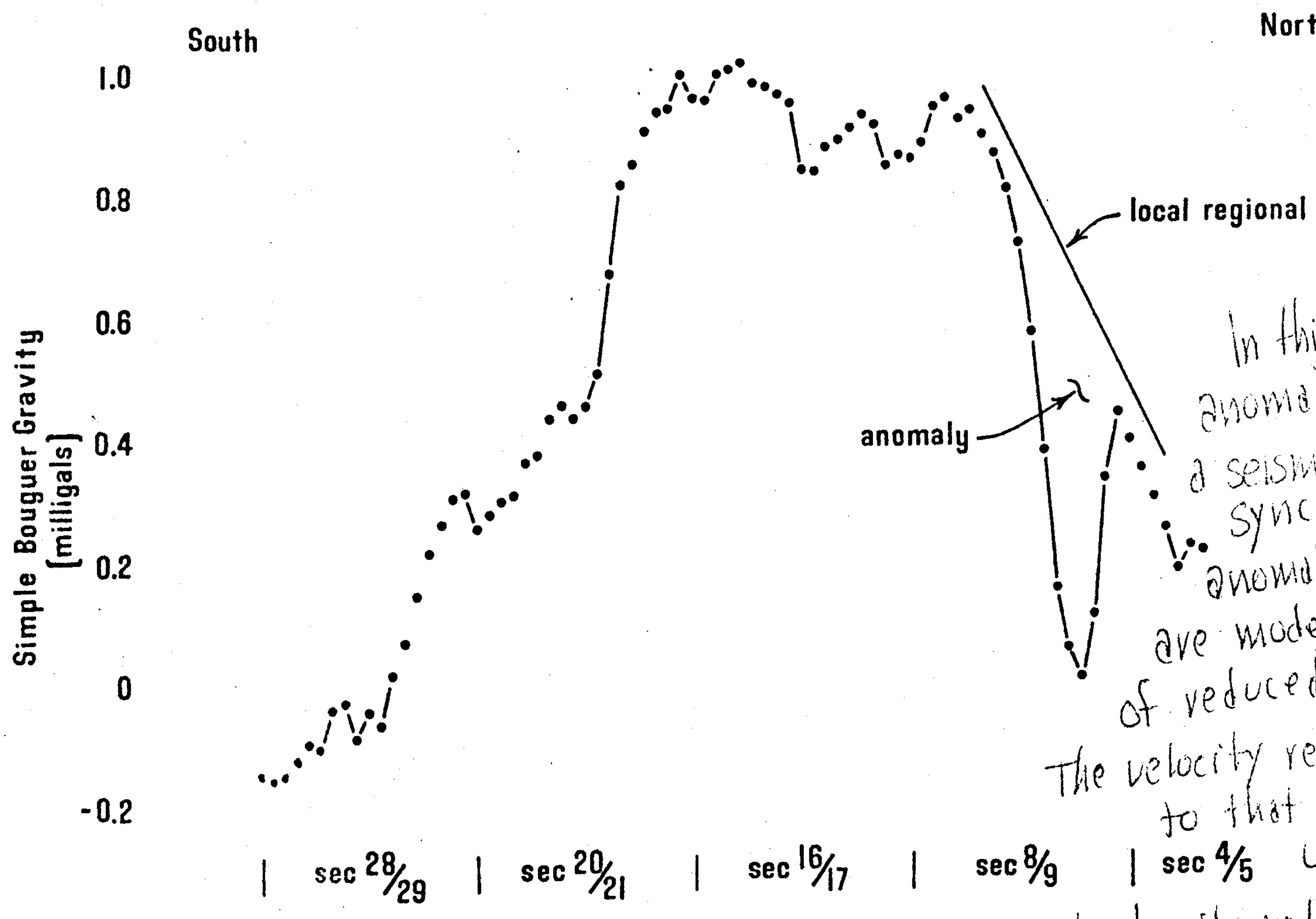


Fig. 3.2.2-2. Seismic line 77X2, shotpoints 58-105 and the coincident gravity anomaly from gravity survey line G. The darkened Rustler seismic event was calculated from a model of the gravity anomaly.



In this case the gavity anomaly is coincident wi[th] a seismic time-structure syncline. Both the gravi[ty] anomaly and the syncline are modeled with a block of reduced density & velocity. The velocity reduction is comparabl[e] to that observed in uphole velocity surve[y]. The density reduction is consistent with that inferred by the veloci[ty] reduction.

WIPP Gravity Survey – Line 'G'.

Fig. 3.2.2-1. Simple Bouguer gravity along survey line G. The broad 1 milligal positive anomaly is discussed in section 3.1. The shorter wavelength negative anomaly is coincident with a seismic time-structure syncline on line 77X2.

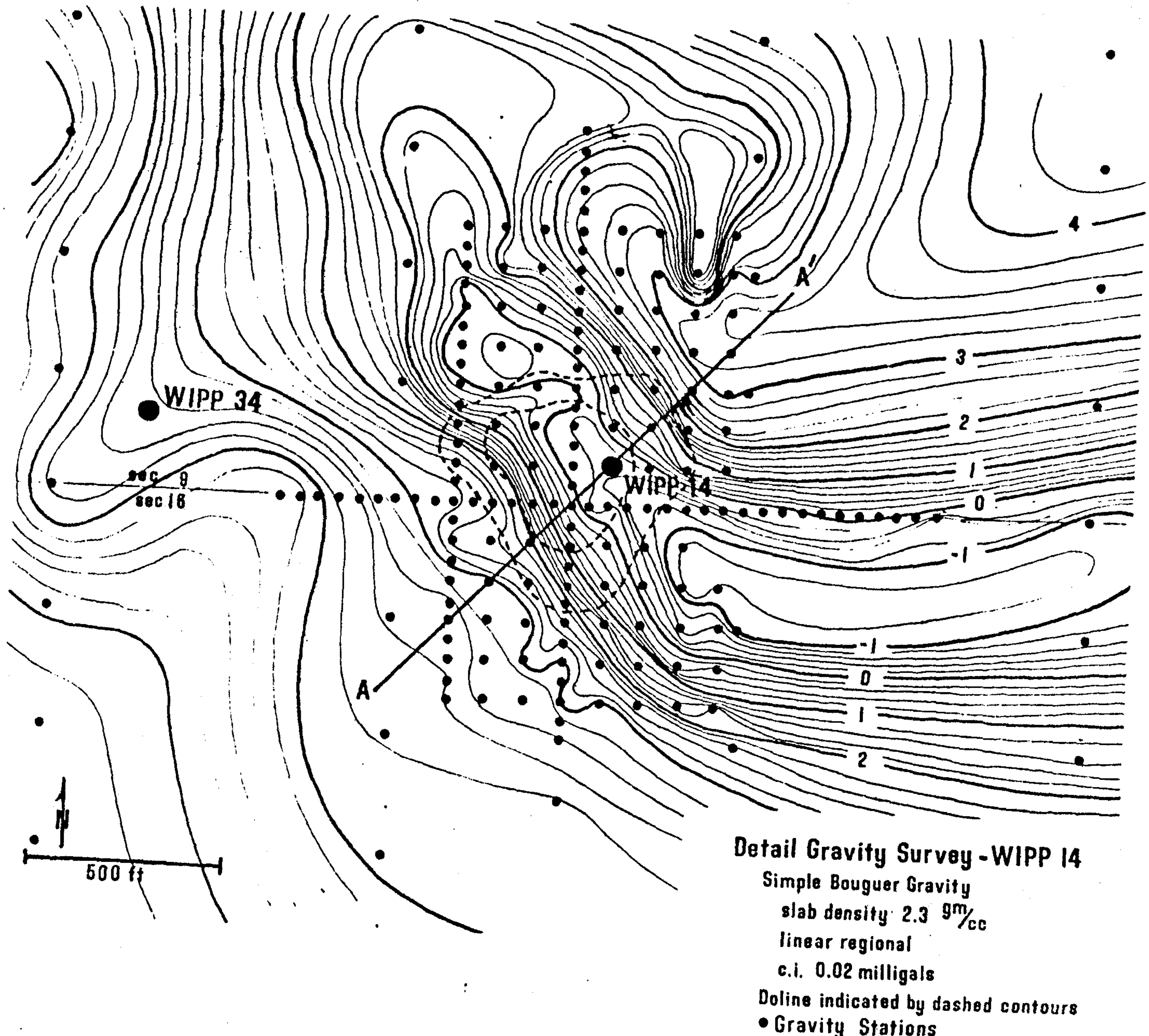
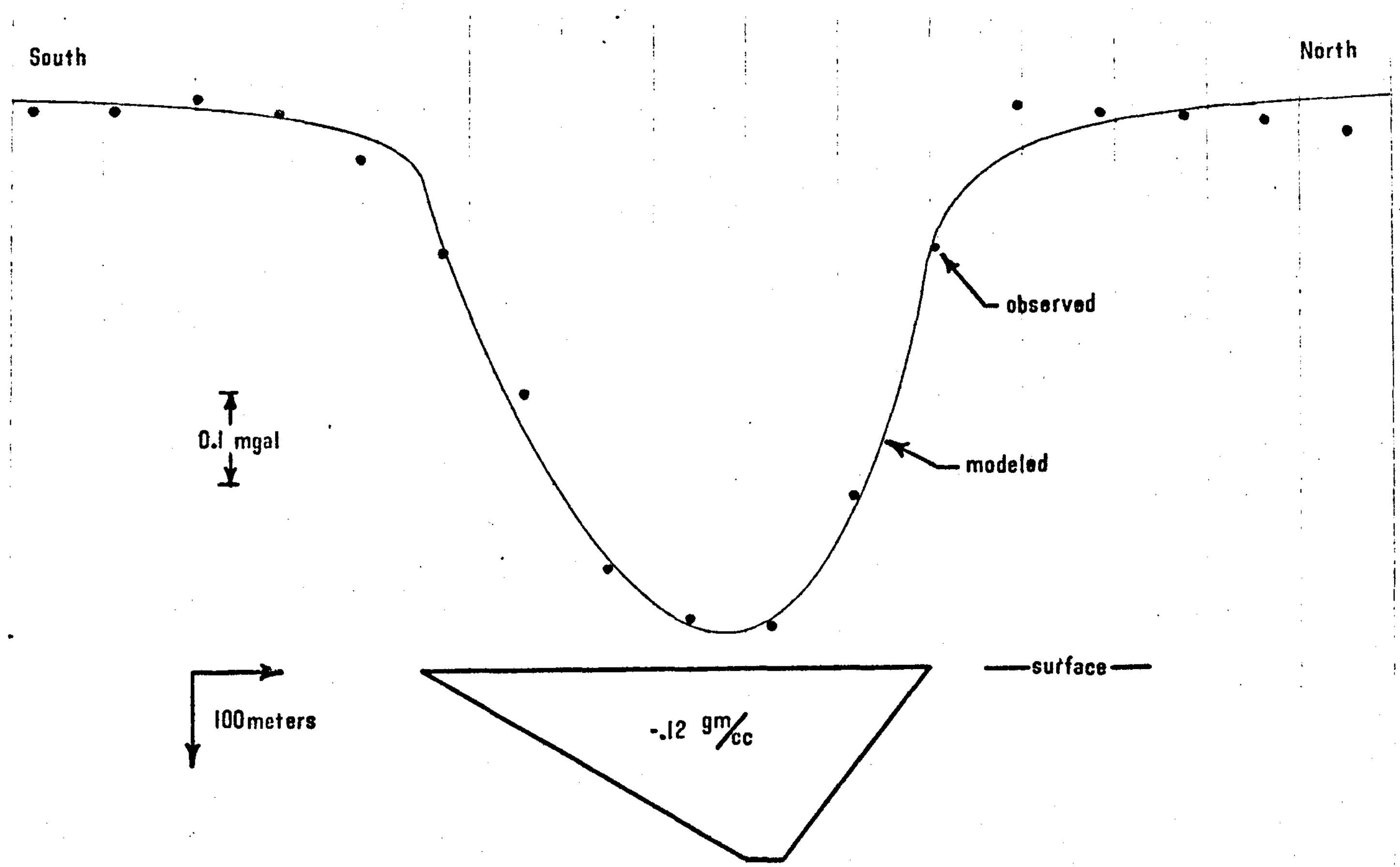
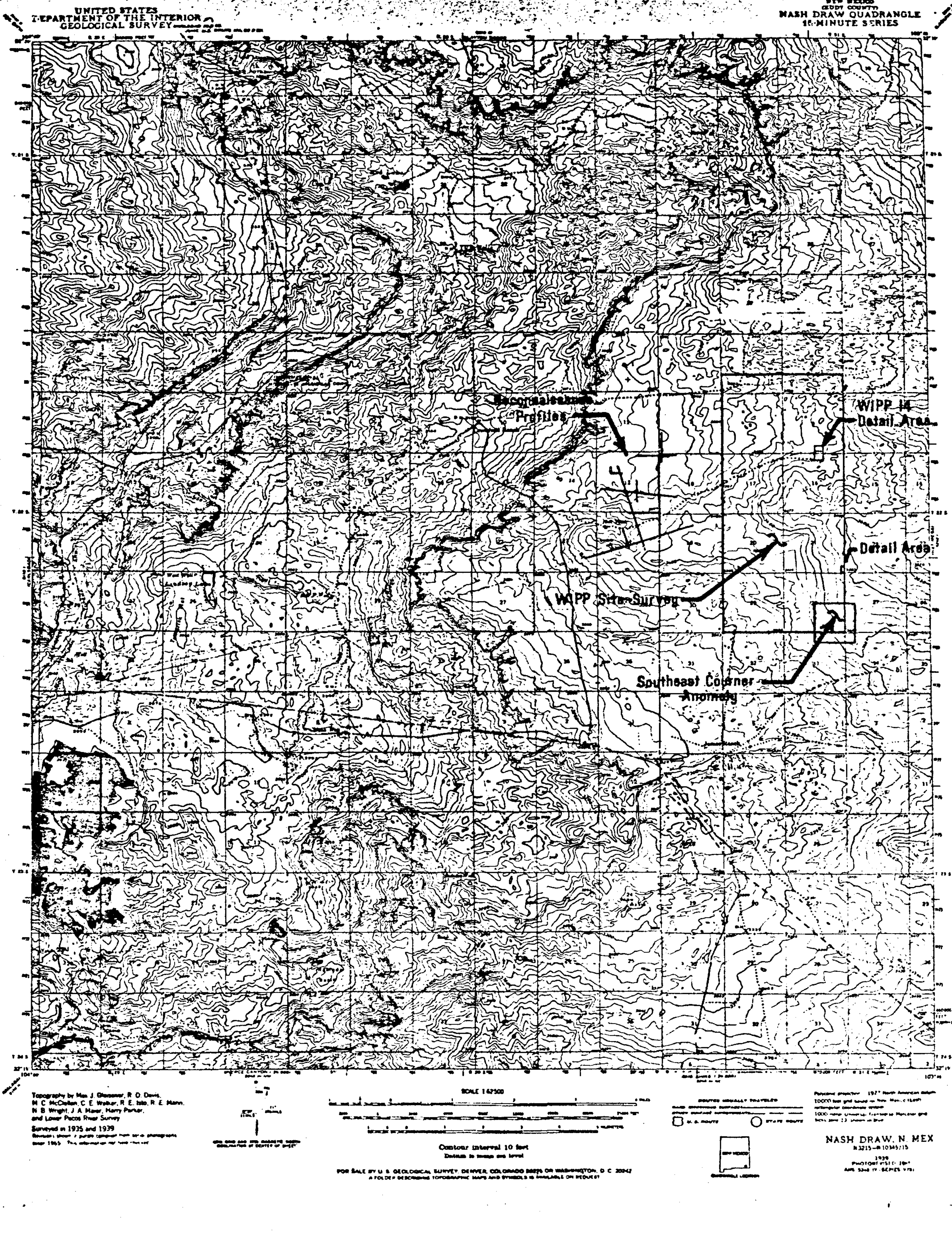


Fig. 2.2-2. Simple Bouguer gravity at the WIPP 14 anomaly. The area of the detailed survey is indicated on Fig. 1.3.2-1.



Line 'G' Anomaly - Model and Observations.

Fig. 3.2.2-3. A model of the gravity anomaly on line G. The maximum depth of the body is near the top of the Rustler Formation and the density contrast is consistent with that implied by the Dewey Lake velocity variation between WIPP 13 and WIPP 34.


UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
NEW MEXICO
(EDDY COUNTY)
NASH DRAW QUADRANGLE
15-MINUTE SERIES
Reconnaissance Profiles
WIPP 14 Detail Area
Detail Area
WIPP Site Survey
Southeast Corner Anomaly
Topography by Max J. Gleissner, R. D. Davis, M. C. McClellan, C. E. Walker, R. E. Isto, R. E. Mann, N. B. Wright, J. A. Maier, Harry Parker, and Lower Pecos River Survey
Surveyed in 1935 and 1939
SCALE 1:62500
Contour interval 10 feet
Datum is mean sea level
FOR SALE BY U. S. GEOLOGICAL SURVEY, DENVER, COLORADO 80225 OR WASHINGTON, D. C. 20242
A FOLDER DESCRIBING TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST
NASH DRAW, N. MEX
1939

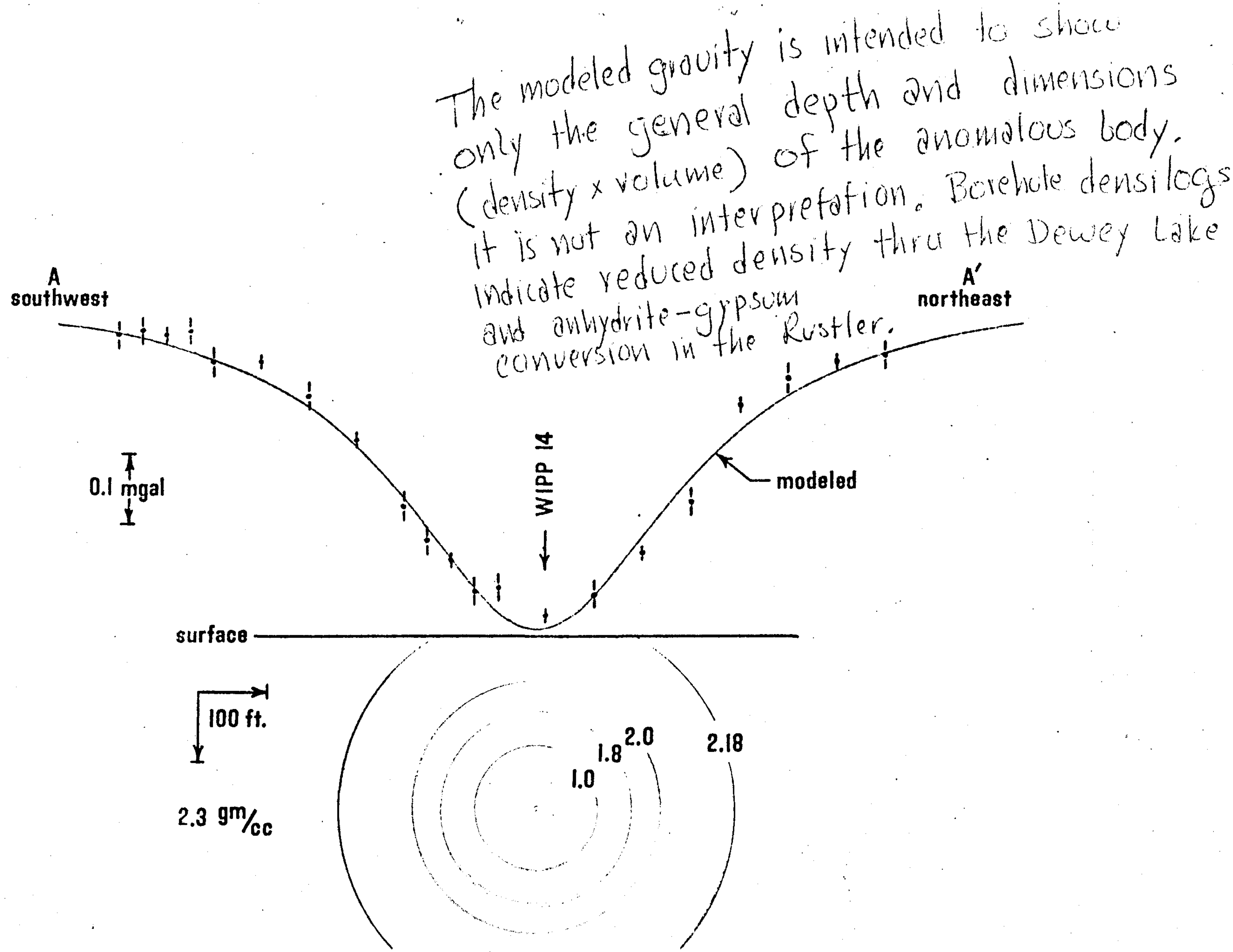


Fig. 2.2-3. A gravity profile across the WIPP 14 anomaly. The modeled gravity comes from any of the indicated horizontal cylinders and is intended to show the approximate magnitude of the density structure necessary to cause the anomaly.

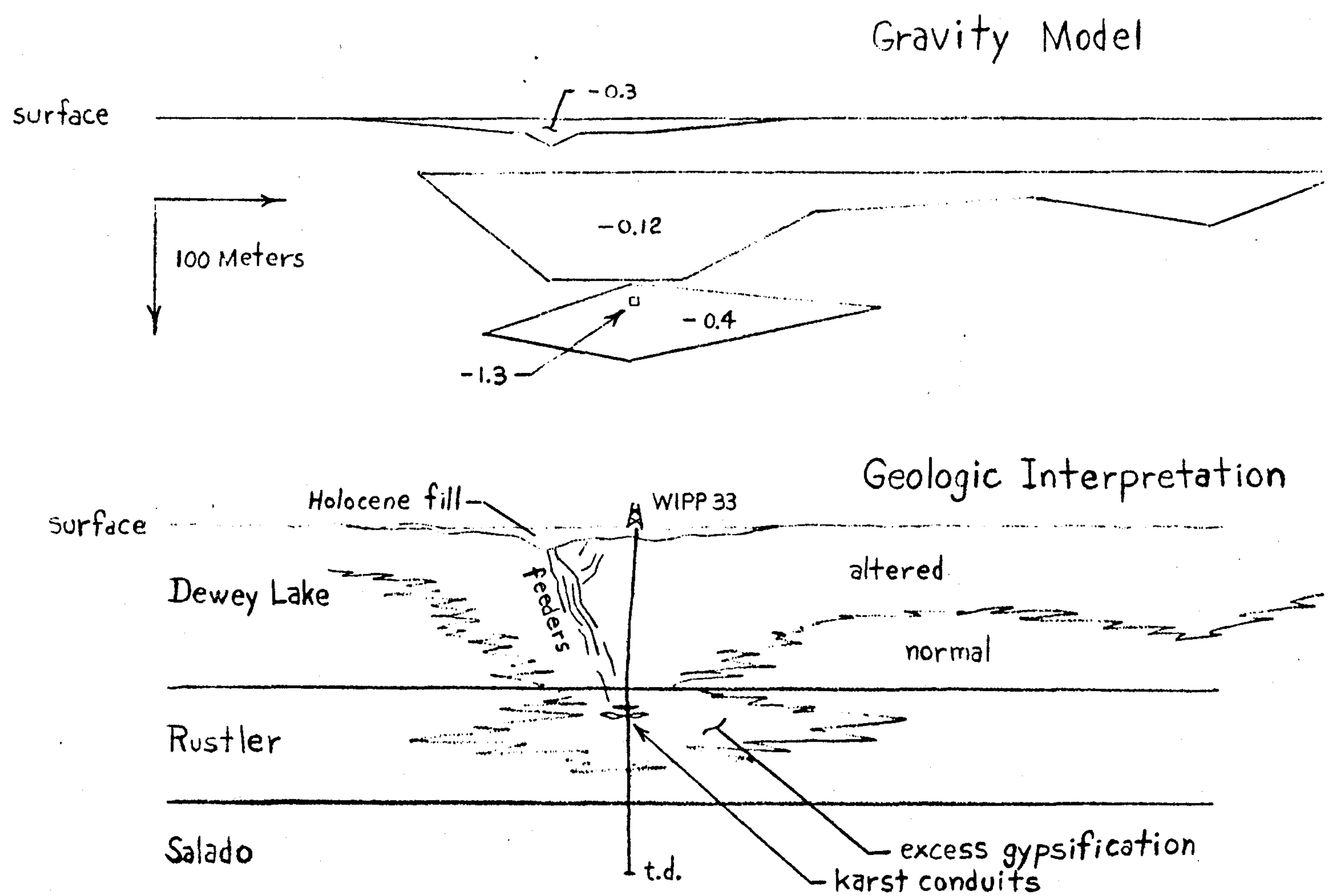


Fig. 3.2.3-2. Density model related to the profile on Fig. 3.2.3-1 and the corresponding geologic interpretation.

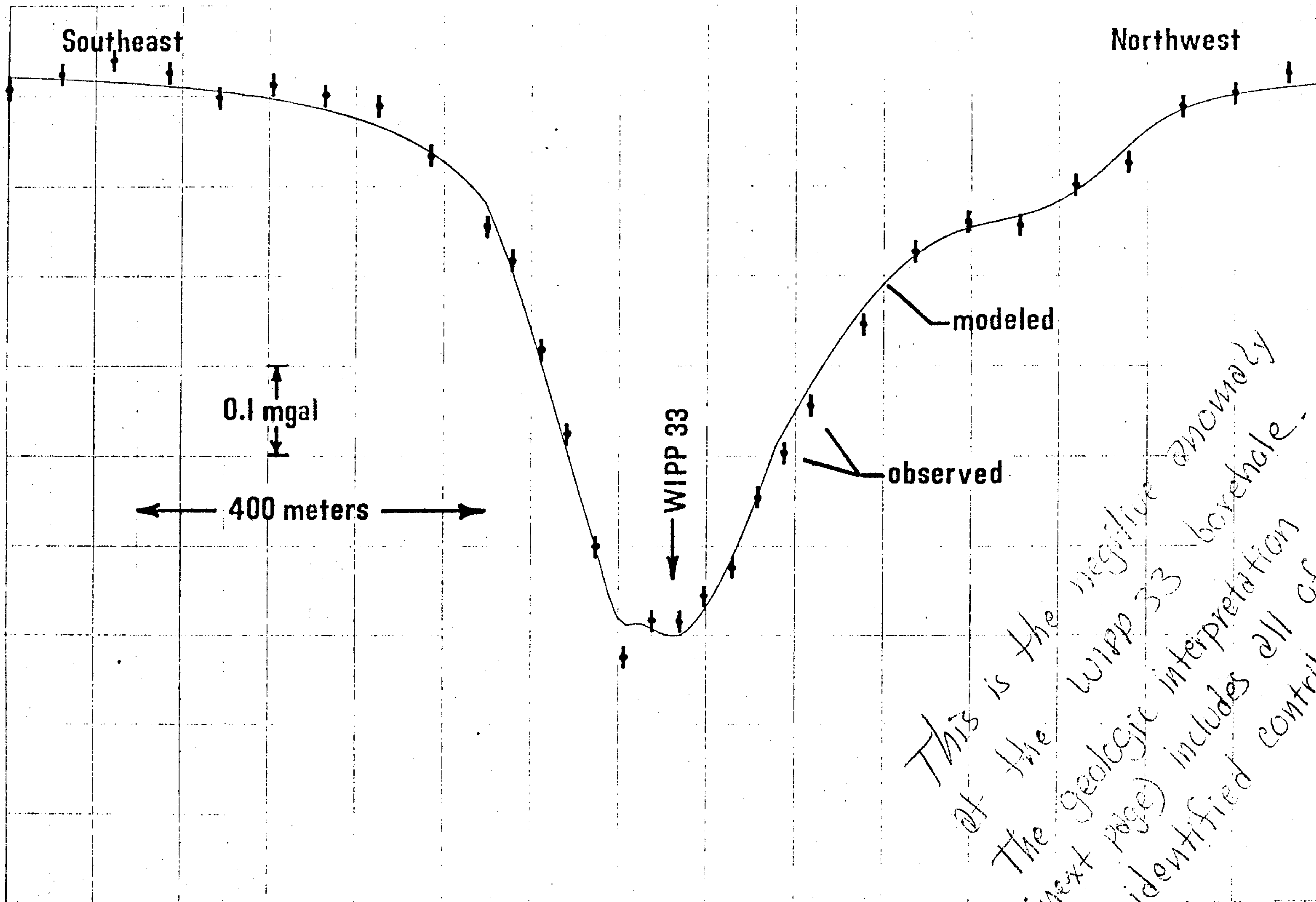


Fig. 3.2.3-1. Observed and modeled gravity along the pipeline trail crossing the WIPP 33 anomaly.

This is the negative anomaly
of the WIPP 33 borehole.
The geologic interpretation
(next page) includes all of
the identified contributing
factors,

Harry E. LeGrand
Hydrogeologist

331 Yadkin Drive
Raleigh, N. C. 27609

Telephone (919) 787-5855

November 5, 1982

Dr. Lokesh Chaturvedi
New Mexico Environmental Evaluation Group
P.O. Box 968
Santa Fe, New Mexico 87504-0968

Dear Lokesh:

I am returning the photographs you sent me. They show very clearly some of the permeability relations in the various zones.

As I mentioned on the phone yesterday, I plan to work on the questions asked in the recent letter from E.E.G. I will try to put some of my answers into a revised portion of my paper, and I will answer the other comments in an informal memorandum.

I hope that I can answer all the questions satisfactorily.

Sincerely,

Harry

Harry E. LeGrand

Enclosure

Harry E. LeGrand
Hydrogeologist

331 Yadkin Drive

Telephone (919) 737-5855

Raleigh, N. C. 27609

November 12, 1982

RECEIVED
NOV 16 1982
ENVIRONMENTAL EVALUATION GROUP

Mr. Robert H. Neill, Director
Environmental Evaluation Group
320 Marcy Street
P.O. Box 968
Santa Fe, New Mexico 87504-0968

Dear Bob:

I have worked on my report of the WIPP Site as related to comments in you letter of October 29.

The probing questions and comments in your letter are appropriate. Rather than completely rewriting my October 8 report to include responses to EEG comments, I have made only minor changes. In a separate memorandum I try to address the EEG comments. Within the short working period, this is simpler for me to do. I would have preferred to have had references at the end of the text, but I didn't have adequate bibliographic material. Incidentally, I think that Sandia or EEG should prepare an annotated bibliography of WIPP work; it would be useful and would require little effort, I suppose.

The only changes made in my October 8 report are:

Page 2 - Adding of first paragraph in partial response to your item 2.

Page 8 - A new paragraph in response to your item 4.

Page 9 - 9th line - "two to three" miles

Page 10- Third paragraph, change to "only beds below the Culebra" in response to your item 2.

As your letter indicated, the somewhat divergent conclusions of Larry Barrows' report and the Gonzalez fracture report need to be addressed. I am pleased to comment on this subject within my area of expertise.

Sincerely,

Harry LeGrand

Harry E. LeGrand

Attachments

MEMORANDUM

November 10, 1982

TO: Robert H. Neill

From: Harry E. LeGrand

Subject: Reconciling karst phenomena with fracture flow studies in the Rustler Formation

Two somewhat divergent approaches toward understanding the distribution of permeability in the Rustler Formation have arisen as a result of the fracture-flow report by Gonzalez and the karst report by Barrows.

One of the first issues to be considered is that of the source and extent of recharge on the upland areas. Several workers believe that the relatively low precipitation and the tightness of the Dewey Lake Red Beds prevent any appreciable recharge to the Rustler. They point out the overall drop in head southward indicates that area of the Clayton Basin may be the primary recharge area. Barrows demonstrates that the sporadic heavy storms and the absence of surface runoff results in some movement of water through the Dewey Lake Red Beds to recharge the Rustler.

I have mixed reactions on the subject of recharge. There are reports that the Dewey Lake has no water. We know that the Magenta is under confined conditions and that its water rises into the Dewey Lake Red Beds. It's a shame that the Dewey Lake hydrology can't tell us something about recharge. It surely has a water table, but it might take years for it to be expressed in a well. Without head measurements of the Dewey Lake to compare with those of the Magenta, we must look elsewhere for means of determining recharge characteristics. Some recharge apparently is from the general area of the Clayton Basin, but I don't know if there is any appreciable recharge from local precipitation at the WIPP Site.

Whether we use the terms Upland West and Upland East, trying to define a boundary between incipient karst on the west and seemingly unaltered rocks on the east is essential. The Barrows' karst approach is applicable to the west and the Gonzalez fracture approach more suitable to the east.

Conceding that my initial boundary "Halite/no Halite below Culebra" is not precise, we should try to do better to find the boundary that is real. It would appear that much of the fracture permeability of both dolomite units is due to down slumping into space formerly occupied by halite or gypsum. Perhaps the lower hydraulic conductivity of the Magenta relative to the Culebra is due to its rigidity and failure to subside into the voids. The void space beneath the Magenta in the ventilation shaft suggests this rigidity. Those voids or washed-out zones below the Magenta and Culebra are probably discontinuous but rely on the fractured dolomite to transmit water.

Gonzalez skillfully used a delicate technique in his fracture-flow study. In spite of his careful work, it appears to me that he was dealing with micro values, so indirectly obtained that some of the derived values may depart greatly from true values. At any rate, I don't know how to interpret the anisotropy reported. The anisotropy in Upland West (wherever we put its eastern extent) of inherent fractures is surely overshadowed by a greater degree of anisotropy from karst processes. I have expressed this condition in several of my karst publications, and Barrows states on page 13 "Another implication of the karstification process is that borehole-measured transmissivities and storage storativities should not be representative of the area. A borehole which misses one of the active corrosion conduits should show values which are much less than the average. This applies to almost all boreholes in a karst terrain because the area of active conduits is only a small part of the total area."

As indicated in my karst report, solution prongs, or linear zones of high conductivity, in or near the dolomite beds should extend eastward from the scarp of Nash Draw. I wouldn't have expected them to extend more than about two miles eastward from the scarp. Yet, Barrows' evidence of solution conduits at WIPP-14 would lead me to believe that at least one prong extends this far eastward. It is a little surprising that the thick cover of Dewey Lake Red Beds would reveal subsidence, such as the dolines, described by Barrows.

Emphasis in the fracture report was on the Culebra rather than the Magenta. I have been puzzled by the higher hydraulic conductivity of the Culebra because its deeper burial and seemingly poorer discharge facilities might hamper circulation of water and solution in it and in the adjacent beds. The voids below the Magenta in the ventilation shaft suggests that we should give this upper zone more attention.

Some attention should be focused on the quote by Barrows (page 15) - "Bogli (1980, Ch 5) notes that there is no direct relationship between the velocity of flow and the gradient. It follows that models based on a linear or Darcy relation should not be applied to a karstland." Since most karst areas are under water-table conditions, the water table is depressed locally along solution prongs or linear cavernous zones. These zones are interspersed with large zones of relatively impermeable rock. Thus, the gradient and rate of flow ranges greatly over local areas. The Darcy relation should be used with caution or should take into consideration these ranges of conditions. To some extent, these conditions should apply to the confined setting in the WIPP area.

Considering the wide range of permeability and its unusual distribution, I think that we are fortunate to have the divergent approaches that Gonzalez and Barrows have followed. Conclusions that can be derived from these approaches need to be pondered, studied, and reconciled. My discussion in this memorandum only partly reconciles the differences. An informal group discussion of conditions and processes acting should help to further understand the relations that are important.

We don't seem to have a good grasp of the mechanism of stratabound evaporite dissolution under confined conditions. I haven't run across references on this particular subject in the conventional karst literature. Perhaps we are dealing with a very unusual subject if we must rely on the fractured dolomite beds to transmit the dissolved evaporite material to a discharge area; I don't think that confined evaporite beds can transmit water very far.

The Barrows' study, the range in hydraulic conductivity in Upland West, and the open spaces found in the ventilation shaft point to the need for pursuing further thoughts about karst hydrology.

To end this memorandum on a philosophical note, I am repeating the last three paragraphs on my paper entitled "Perspective on Karst Hydrology." This paper is a part of the Stringfield Symposium to be published in February as a volume by Elsevier.

> "Before massive new data-collecting programs get under way in karst regions it is wise to review all pertinent karst principles. An overview of existing information should be made and the geologic and hydrologic history should be conceptually reconstructed. The stage of karst development in each segment of the study area should be interpreted so that some good approximations of the distribution

of permeability can be made. Until all useful inferences are drawn from existing information, effort spent on collecting new data may be questionable.

The uneven distribution of permeability and the seemingly unpatterned solution openings can best be considered in the context of the principle of indeterminacy. The averages of certain features are determinate, but each specific case may be indeterminate. An individual case may be considered only in a statistical sense. There are too many unknowns in the range of combination of values of the interdependent variables to predict precisely certain features of hydrology in a karst setting. For example, the existence of a cavity at a certain place and depth may be indeterminate prior to drilling.

The best way out of the dilemma of indeterminacy is to learn more about the processes operating in a variety of karst settings so that we can reduce the range of uncertainties. Fortunately, we can reach a high plateau of knowledge if we use existing data and if we make full use of good inferences. Thus, it may be foolhardy and unduly expensive to demand precision in cases where indeterminacy is involved, especially if best inferences are likely to be successful. Reducing the range of uncertainties for the needed answers should be a major objective in karst hydrology. This objective is in line with the Stringfield approach of fundamental karst hydrogeology."

HEALTH & ENVIRONMENT department

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February 3, 1983

Dr. Larry Barrows
Organization 7111
Sandia National Laboratories
Albuquerque, NM 87185

Dear Larry:

Here are all the reports from Harry LeGrand on the karst question.

Please let us know what you think.

Sincerely,

Lokesh Chaturvedi

LC:jdc

Enclosures

February 11, 1983

Dr. Lokesh Chaturvedi
N. M. Environmental Evaluation
Group
P.O. Box 968
Santa Fe, NM 87503

Dear Lokesh:

As you requested, I have reviewed the material provided by H. LeGrand and am sending you my comments.

In his memos (October 8 and November 10, 1982) Harry refers to a geohydrologic distinction between Upland West and Upland East. Karst conditions are presumed to dominate in Upland West and fracture flow is presumed to dominate in Upland East. I have reviewed the evidence for such a subdivision. In my opinion the subdivision is not supported by our present data and the entire area should be regarded as a karst plane.

Topography: I have examined the Nash Draw quad and the two concentric sets of surrounding quads. The maps show numerous closed topographic depressions and very little surface drainage most of which disappears into shallow sinks. These conditions exist in all directions from the site. As I noted in my karst report, the area receives about 12 inches of annual precipitation and the 100 year recurring storm is 5 inches in 24 hours. The lack of surface runoff is not due to a lack of rain.

The small closed depression in the southwest corner of Sec 3, T22S, R31E is interesting. This sink is over 20 feet deep and several hundred feet across. Standing on the rim one can look around at the surrounding dune fields and down into the sink. The depression extends into the plane and cannot be regarded as a remenant feature produced by its chance enclosure by drifting dunes. It is also not attributable to a wind blow-out. More likely sufficient sand has blown in to the sink to fill it several times over. The simplest interpretation is an alluvial doline formed when loose surficial material washes through cracks in the underlying rock into solution conduits. The alluvial doline does not involve subsidence of strata overlying the solution conduits. It does require that the intervening rocks be transmissive to both water and the sand it carries. The implication is that the Dewey Lake must be locally transmissive even it if is generally tight to wells.

There are additional depressions scattered across the plane and across the site itself (check the Bohannan-Huston detailed site topo maps).

Rustler Isopach: The Rustler Formation thins from about 450 feet in the southeast corner of the site to 300 feet along the western edge. The thinning is accompanied by downward progression of surfaces defined on the top of salt, top of anhydrite, and lowermost gypsum. The only reasonable explanation is progressive dissolution by groundwater infiltrating from above. Depositional facies variations are inconsistent with the great areal extent of the formation and the remarkable lateral persistence of the dolomite members and certain sand/silt marker beds.

The Rustler Isopach indicates two things. First it provides additional evidence for the downward infiltration of ground water. Second, even though this may be a very complex, stratabound, phreatic process involving halite and anhydrite/gypsum, it should still be regarded as "karst."

In Nash Draw there are caves in gypsum, at WIPP 33 there were cavities in both the gypsifferous Forty-Niner member and the Magenta Dolomite member. The solution residues described by Ferrall and Gibbons are in the three non-dolomite members. Perhaps it is inappropriate to focus too much attention on only the Culebra and Magenta Dolomites.

Hydrological Data: If there is a distinction between a karstic Upland West and a fracture flow Upland East, then there should be a marked difference in hydrological properties between the two areas. The measured conductivities range over five orders of magnitude and there is a general increase from east to west. However there is no clear bimodal distribution which could be used to distinguish two differing flow regimens and there is overlap in the values (H-1 versus H-3).

The potentiometric surface provides proof that we are not dealing with two distinct flow regimens. If there were open karst conditions in the west and very tight fracture flow conditions in the east, then there should be a marked change in gradient between the two areas. Otherwise constant flow would not be maintained. Mathematical models involving highly variable storativity and variable rates of infiltration could be constructed. However, considering the differences between karst and fracture flow, it seems unlikely such a situation would exist in a natural setting.

The potentiometric contour map in the fracture flow report (page 42, Figure 16) needs to be redrawn. I have enclosed my sketch maps. One includes the 2774' at P 18 and one omits this hole on grounds it is too tight to give a valid reading. The data are from Table 1 of the fracture flow report.

In summary, I have reinspected the topographic maps, formation isopachs, core descriptions, gravity data, reported transmissivities, and culebra potentiometric surface. Nothing in this material indicates a distinction between a karstic upland west and an upland east characterized by slow fracture flow. The evidence indicates to me that the site is situated on a karst plane in the immediate midst of a larger regional karstland

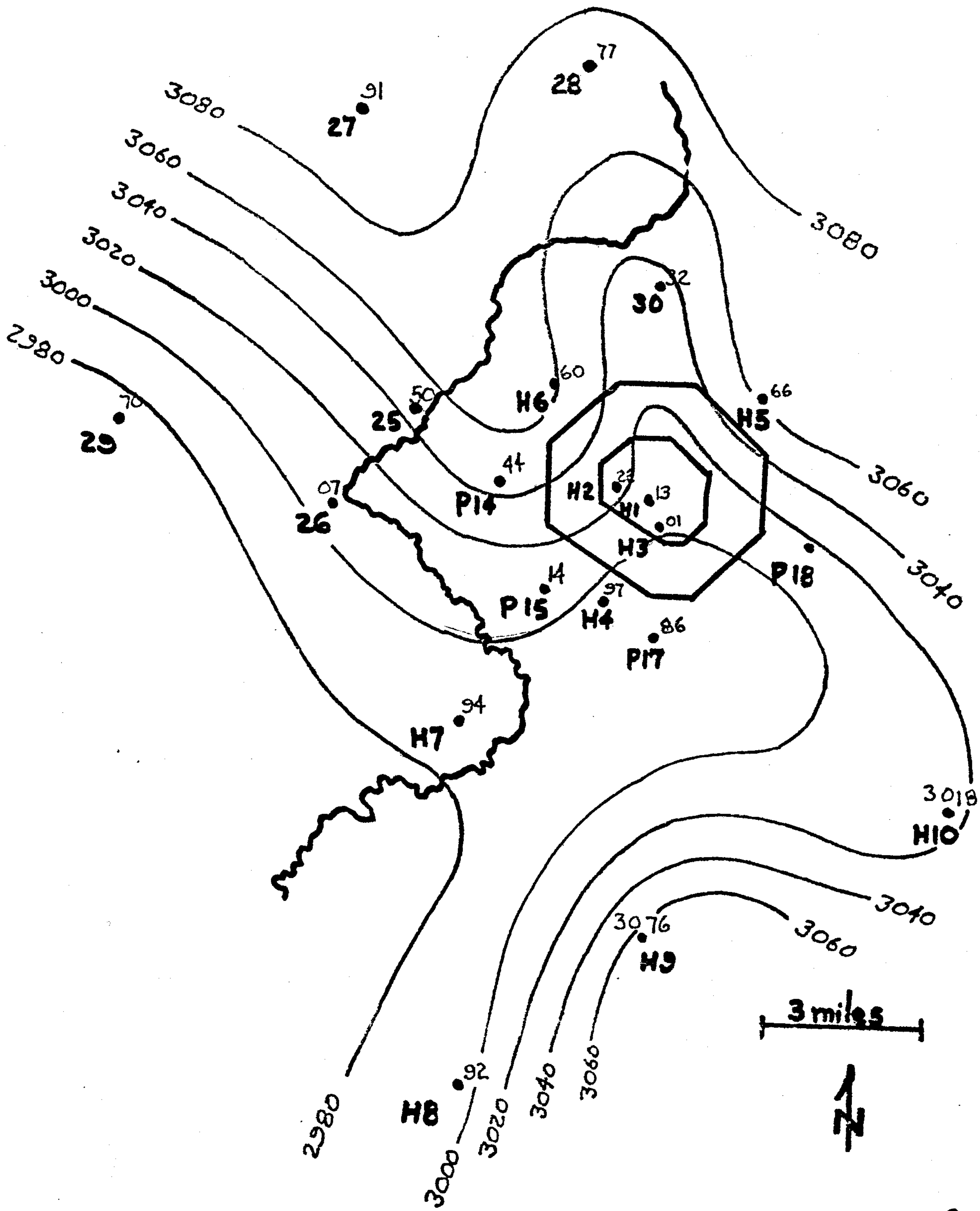
The bottom line is the need to establish groundwater travel times between the site and spring. This parameter is an important part of the site evaluation program. The fracture flow approach implies travel times of tens of thousands of years. Karst implies potentially very rapid velocities. If karst cannot be clearly disproven then the travel time is indeterminate. Until, and if, it is disproven, the Rustler Formation cannot be regarded as a reliable barrier to the migration of contaminated water.

Sincerely,

Larry Barrows

Lawrence J. Barrows

LJB:ds


3080
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27 91
28 77
30 32
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H6 60
H5 66
29 70
26 07
P14 44
H2 22
H1 13
H3 01
P18
P15 14
H4 97
P17 86
H7 94
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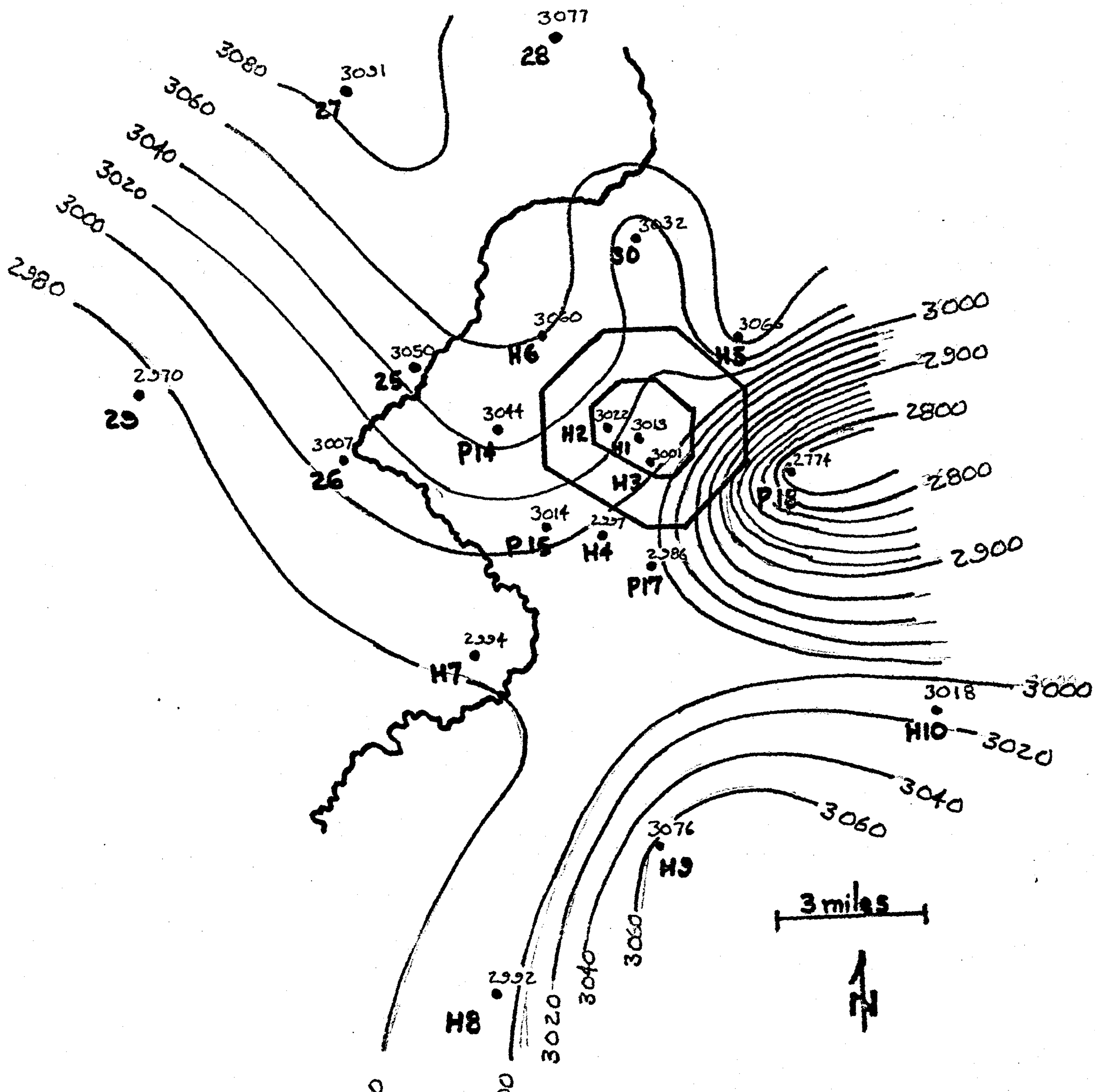
H9
H8 92
3 miles
N

without P-18



with P-18

note: P-18 conductivity 0.00004 ft/day
Head at this hole is significantly below Melaga Bend, Lee county hydo heads, the Delaware mountain Group.

Harry E. LeGrand
Hydrogeologist

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RHN

March 13, 1985

Mr. Robert H. Neill, Director
Environmental Evaluation Group
P. O. Box 968
Santa Fe, NM 87503

Dear Bob:

Attached is the informal report I promised to send you concerning the topics included in the meeting at Carlsbad on March 7 and 8.

It was a pleasure to participate in this constructive meeting. In view of the many unsettled issues remaining about karst, dissolution breccia, and ground water flow, I would be interested in participating in a future conference or informal meeting if one should develop.

I am impressed by the work of EEG and by the approach that you and your colleagues have taken to meet your objectives.

Sincerely,

Harry

Harry E. LeGrand

Enclosure

AN INFORMAL SKELETAL REPORT RELATING TO THE EEG SPONSORED MEETING AT CARLSBAD, MARCH 7 AND 8, 1985

by

Harry E. LeGrand

INTRODUCTION

The comments and questions that follow relate to topics that were of interest at the Carlsbad meeting. The key topics were: (1) evidence for and against non-deposition of halite in parts of the Rustler Formation, (2) characteristics of dissolution residues and breccia, (3) permeability in the Rustler, (4) stratabound dissolution, (5) age of the Rustler water, and (6) recharge and discharge of Rustler water. The topics are still open-ended in part as to resolution. I have only attempted to pose some questions that need further attention and to offer some provocative thoughts. The questions and comments are not necessarily presented in an orderly manner.

A PARTIAL LIST OF QUESTIONS THAT SHOULD BE ADDRESSED

The following questions do not necessarily require precise answers. The point to be made is that very serious effort should be required to answer them.

What is the best available explanation for certain anomalies, such as the depressions at WIPP 33 and WIPP 14?

Why is the predominant permeability concentrated in or near the Magenta and Culebra Dolomites, in spite of the fact that dolomite is less soluble than halite and gypsum?

Are there zones of higher permeability extending eastward from Nash Draw?

Why does the Rustler permeability decrease eastward in general?

If the Rustler water below the WIPP site is very old (at present not seriously questioned), is it chiefly trapped Permian water that now resides in the Rustler? Is the Rustler water a good mixture of Permian water and later recharge water? Recharge water under present conditions? From the Clayton basin? From downward seepage through the Dewey Lake Beds?

How do recharge to, movement through, and discharge from the Rustler apply to halite removal?

How does stratabound dissolution relate to the missing halite?

If halite is removed, does gentle subsidence of overlying material almost completely preserve the bedding of the subsided unit? Is it possible to have preserved bedding in one place and crumpled or dissolution breccia elsewhere?

If dissolution breccia occurs and if halite has been dissolved away, what is the mechanism? Is the mechanism reflected in the character of the cores?

What are the total reasons for postulating the removal of halite in parts of the Rustler?

What are the useful inferences that can be drawn from attempting to reconstruct the geologic and hydrologic history of this part of the Delaware Basin?

GENERAL COMMENTS

For stratabound, or intrastratal, dissolution to occur there must be a circulation system for the water to move; the circulation system requires a discharge area and a recharge area. The discharge area in this case -- the Pecos Valley -- is less puzzling than are the mechanics of recharge and circulation of water.

Lack of consensus or convincing evidence leaves open the source of recharge from (1) the Clayton Basin, (2) broad general seepage through the Dewey Lake Beds, or (3) through fracture openings in the Dewey Lake Beds. Some original entombed water from underlying formations has passed through the Rustler. If there is no recharge to the Rustler, does the present Rustler water represent the older water buried in Delaware Basin? The accepted conclusion that past humid climates provided more water for recharge still leaves the question that potential recharge water may have difficulty getting into the Rustler.

The permeability of the Rustler, chiefly confined to the Magenta and Culebra Dolomites, is epigenetic. It is related in some way to dissolution of halite and gypsum beds. It is necessary to determine or to conjecture how the permeability is developed and how water moves to the discharge area. Lambert has correctly postulated stratabound dissolution as a major element. Stratabound dissolution applies especially to the Rustler beneath the WIPP site and westward into Nash Draw.

It is necessary to postulate some scenarios to understand how stratabound dissolution relates to permeability and also to the removal of halite in parts of the Rustler. The permeability of the Magenta and Culebra is considered not to be inherent but developed by fracturing of these beds as a result of dissolution subsidence of halite and gypsum beds.

First, permeability started to develop earliest near the Pecos River, where water could discharge and circulate. Dissolution of the halite and gypsum beds, and the resulting development of permeability, has continued near the discharge area since the entrenchment of the Pecos River (well back into the Pleistocene, at least). The intrastratal dissolution and drainage have progressed eastward in the soluble beds as long as a continuous intra-stratal flow of water occurred through interconnected openings. East of the WIPP site continuous openings toward the westward discharge area might not occur. Thus, it is understandable that permeability in general decreases eastward.

We must develop an acceptable scenario to explain how stratabound dissolution works, why permeable zones occur at certain horizons, and dis-solution breccia occurs in some places and not in others.

The presence of halite and gypsum in an undersaturated water that flows to the discharge area allows openings to enlarge. At any stage, the vertical enlargement may be small relative to the lateral enlargement along a bed. As the lateral spread of the opening increases, the overlying beds gradually and gently subside, thereby decreasing the vertical dimension of the opening. As more halite is removed, the remaining pillars of salt are dissolved and crumpled into dissolution breccia.

As others have postulated, the Magenta and Culebra Dolomite units have been involved even though they are not the soluble beds of primary concern. The dolomite beds may provide a bridging effect and perhaps a local incipient fracture permeability that could trigger or aid the stratabound dissolution of the halite beds. Sagging of the dolomite beds gently into void layers has increased the fracture permeability as we have it today.

Action in the stratabound soluble beds is continually changing locally from place to place and time to time. After a solution opening has enlarged slightly in the vertical direction and after it spreads laterally, subsidence of the overlying beds closes the openings. The conversion of anhydrite to gypsum causes a volume increase of the gypsum bearing rocks, to further decrease the size of openings. Thus, a dissolution opening may be in a closing stage while a nearby opening is in an enlargement stage.

It seems reasonable that many openings are flattened and closed. In this case, flow of water would be blocked for many years until a new opening would allow the water to get back into the flow system. Such a "stop and go" flow system may seem to be unreal. During the stratabound dissolution process, some water would be retained while other water moves into the dolomite beds, where flow presumably is continuous.

The procedures indicated above could explain some anomalies, such as great local changes in permeability and in the quality of water. This erratic or discontinuous flow system may apply in the Rustler beneath the WIPP site and eastward. It is difficult to visualize a flow system that would allow water to flow continuously through any of the Rustler beds in the vicinity of P18, for example.

We tend to cling somewhat faithfully to the water level maps of the Magenta and Culebra and to the normal interpretations that can be drawn from them. Yet, we should leave open the probability that these maps would be modified or reinterpreted if better information or inferences were applied.

It is incorrect to say that it doesn't matter whether halite has been removed by dissolution from the Rustler beneath the WIPP site. If the halite has been removed, the pattern and degree of permeability and overall flow of water in the Rustler should be different than otherwise. Permeability and ground water flow are the key items; the existing data don't tell us enough about them, and, therefore, we need to use the inferences about permeability that halite dissolution could yield.

The questions and comments above are intended to be provocative and to point out that a closer weave between facts and inferences is still needed. Regardless of how the questions may bear on the integrity and safety of the repository, the final decision makers and the super critics will expect a better consensus of thought on Rustler characteristics than now exist.

APPENDIX C

"Field Trip Notes for a Karst Hydrology Field Trip" prepared by Larry Barrows for an EEG sponsored Field Trip 5/11/83.

April 7, 1983

Lokesh:

As requested, I have assembled my recommendations for a karst geomorphology field trip. You might consider starting with a brief indoor session to review regional topographic maps, the Rustler Formation isopach and core descriptions, reference literature, and hydrogeologic implications.

Larry Barrows

NOTES FOR THE KARST HYDROLOGY FIELD TRIP BY LARRY BARROWS

WPCV-16-3

Stop #1

Surprise Spring - north end of Laguna Grande de la Sal

I interpret this spring as the probable outlet for both Nash Draw and the site area. During late May 1982, John Fett (gravity surveyor) and I estimated the flow thru a recently constructed drainage trench to be a few thousand gallons per minute. S. Lambert (1983, p. 35) reports 115 to 125 gpm so either the rate is highly irregular or we inspected different outlets. Lambert also reports less salinity in the spring than in a nearby test hole (WIPP29). He interprets this as indicating isolation between the Culebra Dolomite and the spring. I interpret it as a chemical distinction between water in the primary system of karst conduits (the spring) and that in the stagnated inactive rock. The water level in the test hole is very near that in the spring.

Stop #2

Gypsum Caves - turnoff to Gnome Site

These caves and drainages demonstrate solution conduits in gypsum. The rocky, soil-free terrace and swallow holes are typical karst features. I think the rocks are of the Forty-Niner Member of the Rustler Formation.

Stop #3

WIPP33 - section 13 T22S R30E

Borehole WIPP33 was drilled to establish the origin of this closed topographic depression. The hole encountered normal depths to stratigraphic horizons. All halite has been leached from the Rustler Formation and almost all anhydrite has been hydrated to gypsum (Anhydrite is present in Nash Draw holes further to the west). There were four cavities totalling slightly over 20 feet in the Forty Niner and Magenta Dolomite Members.

A small arroyo drains into the depression from the southeast and has cut the access road. The bottom of the depression shows debris indicative of occasional shallow flooding but no evaporite crust as expected in an undrained playa.

This depression is reasonably interpreted as an alluvial doline formed when loose surficial material washes into solution conduits in the underlying rock.

Gravity shows a 0.6 milligal negative anomaly centered over the depression.

Stop #4

Topographic Depression - SW corner, Sec 3, T22S R31E
This depression is about 500 feet across and 20 feet deep. It extends into the surrounding plane and is surrounded by partially-stabilized sand dunes sitting on the plane. Wind and water carry loose sand into the sink.

I interpret this depression as an alluvial doline similar to the one at WIPP33. It demonstrates active karst processes well east of Livingston Ridge and shows the Dewey Lake Formation should be locally transmissive to both sand and water.

This feature is just outside the gravity survey area.

Stop #5

WIPP14 - section 9, T22S R31E
This depression was identified as "interesting" by the gravity surveyor. He recommended surveying a detailed grid here prior to conducting the main site survey. This detailed survey indicated a 0.4 milligal negative anomaly with a double half-width of 450 feet (shallow source).

Initial Speculation included: a breccia pipe, fault zone, low density intrusive, and buried stream channel. Shortly before drilling WIPP14, the lateral velocity variations (WIPP13 versus WIPP34) and negative anomaly at WIPP33 (proprietary regional survey) were recognized and karst processes were also suggested as a possible origin.

Borehole WIPP14 encountered normal depths to stratigraphic horizons. The upper 97 feet was poorly indurated and the densilog shows abnormally low densities in the Dewey Lake and Rustler Formations. At least some of the anomalous Rustler Formation is attributable to conversion of anhydrite to gypsum.

The WIPP14 gravity anomaly is reasonably explained by the poorly indurated surficial material and the low densities in the Dewey Lake and Rustler Formations. These density variations are not attributable to either buried stream channels or depositional facies. They are interpreted as due to rock alteration in the vicinity of karst conduits. These negative gravity anomalies and interpretation are similar to those from other karstlands. (Colley, 1963; Omnes, 1977).

Stop #6

Topographic Depression - SW corner, Sec 30, T22S R31E This dimple is evident on the detailed site topographic maps (1 inch=100 feet, 2 foot contour interval). It is about 100 ft across and 8 ft deep.

I though this an appropriate location to discuss the lack of surface runoff, character of the rainfall, and implications of the water balance.

Harry E. LeGrand
Hydrogeologist

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Telephone (919) 787-5855
Raleigh, N. C. 27609

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RW

May 17, 1983

Mr. Robert H. Neill
New Mexico Environmental Evaluation Group
P.O. Box 968
Santa Fe, New Mexico 87503

Dear Bob:

The following comments are offered as a result of our meeting in Carlsbad last week.

Much of the discussion and concern centered on the subject of karst. I noticed that there were a few smirky comments about karst from persons other than EEG. I think the term karst is a bit confusing. To some people, it implies something sinister and mysterious. Even in the WIPP Summary Report, karst is treated as somewhat of an afterthought on page 20 under the subject of Ground Water, whereas dissolution received a major heading. Since karst really represents solutional processes and effects, perhaps it is not necessary to use the term "karst" at all.

Focusing on solutional processes and effects, we still must develop a reasonable conceptual model in the area I referred to as Upland West, which is almost the same as the zone of "no halite below the Culebra." Larry Barrows' views and my views are along moderately similar lines; they have merit whether the term karst is used or not. The point to be made is that ground-water flow studies must take into consideration the processes and effects of dissolution. The ground-water flow models that Sandia and the U.S.G.S. are considering cannot be valid in Upland West without first considering a conceptual model that takes into account the effects of dissolution. In Upland West the data points are too sparse to conventionally model the great changes in hydralic conductivity. Normal interpolation in this region would not be valid in a flow model. A question arises as to whether we can pick out the key anomalies by logical reasoning. We cannot simply use a deterministic model from the data points.

I suppose that the ultimate concern is the rate of flow of water in the dolomite beds all the way to a discharge area. The dissolutional, or karst, processes certainly would affect the rate of flow toward the discharge areas. Thus, it is very difficult to determine the time of travel of contaminants to a discharge area. Perhaps the few new wells to be put in and some good "concensus interpretation" may help to throw more light on this subject. All in all, I don't see anything alarming regarding karst that would retard the reasonable decision that EEG will make by June 1. However, some views on karst still need to be reconciled in the months ahead.

You and your EEG colleagues conducted the meeting in a proper and fair way. If I can be of further help, please let me know.

Sincerely,

Harry

Harry E. LeGrand