STATE OF NEW MEXICO
BEFORE THE SECRETARY OF ENVIRONMENT

IN THE MATTER OF THE RENEWED
HAZARDOUS WASTE FACILITY PERMIT
FOR THE WASTE ISOLATION PILOT PLANT

HWB 10-26 (P)

TESTIMONY OF DENNIS W. POWERS, Ph.D.

My name is Dennis Powers, and I will be testifying regarding aspects of the geology at and around the Waste Isolation Pilot Plant (WIPP) site as it relates mainly to geohydrology of the site and compliance with 20.4.1.900 NMAC (incorporating 40 CFR § 270.23(b)) Specific Part B information requirements for miscellaneous units, and 20.4.1.500 NMAC (incorporating 40 CFR § 264.601) Environmental Performance Standards. In some areas, I will refer to positions or information that will be further described or discussed by other witnesses on behalf of the application.

1. Witness Qualifications

I am a consulting geologist under contract to Washington TRU Solutions LLC (WTS) as an independent contractor. WTS is the management and operating contractor (MOC) for the US Department of Energy at the WIPP facility.

My education includes a B.S. in geology from Iowa State University, two years of graduate work in geology at Iowa State University including a minor in ecology, and a Ph.D. in geology from Princeton University. During those years, I participated in several international expeditions conducting geological and paleontological investigations.

I began working on the WIPP project in August, 1975, as a Member of Technical Staff at Sandia National Laboratories (Sandia). Until 1980, my responsibilities were mainly to undertake the geological characterization of the WIPP site after the current location was chosen. From early 1980 to early 1983, I was supervisor of the earth sciences division at Sandia with responsibilities for the staff conducting the geological and hydrological investigations of the WIPP site.

From early 1983 to early 1988, I was a faculty member at the University of Texas – El Paso (UTEP) in the Department of Geological Sciences. Concurrently, I consulted for D’Appolonia Consulting Engineers and later with IT Corporation, with activities ranging from mapping the geology of three WIPP shafts to evaluating the depositional environments and facies relationships of the Rustler Formation. I also was principal investigator on contract work for Sandia through UTEP on evaluating dissolution of the Castile Formation in the Delaware Basin.

Since 1988, I have been an independent contractor with various companies; WIPP-related work has been a substantial part of my practice and has been contracted through IT Corporation, Westinghouse, WTS, and Sandia. During that time, the main activities for the WIPP project have included

- detailed mapping or description of rock units ranging from Salado Formation (Salado) (underground) to the Gatuña Formation (Gatuña) through field work and drilling
- extensive use of geophysical logs to delineate Salado and Rustler units, facies relations, and evaluate dissolution
- surface geologic process evaluation through field work and image examination
- evaluating features, events and processes for use in performance assessment by Sandia

In 1999, I presented rebuttal testimony at RCRA hearings conducted by the New Mexico Environment Department. More recently, I have provided geologic studies related to the Global Nuclear Energy Partnership (GNEP) program as well as for Waste Control Specialists LLC, which has obtained licenses from the Texas Commission on Environmental Quality for a radioactive waste disposal site in western Andrews County, TX.

Through over thirty five years of association with the WIPP project, I have been involved with most aspects of the geology and geohydrology of the WIPP site and surroundings. Over the last ten years, these activities have focused mainly on the geological underpinnings to understand and model groundwater of the Culebra. This includes evaluating the geology of 18 new wells drilled and completed since 2000 and writing a basic data report for each well. I have also prepared several contract reports, as well as published articles, that present information from these wells from field work, and from geophysical log studies. In addition, I have edited, contributed to, authored, or co-authored the following WIPP project-related documents: 13 additional drillhole basic data reports (31 total); 60 reports or articles in which the underlying work was funded by the DOE; and 13 articles related to the WIPP project but not funded directly by the DOE. I have also authored or co-authored eight articles or book chapters and more than 25 reports (not including many proprietary reports) not directly related to the WIPP project.

I am registered as a Licensed Professional Geologist by the State of Illinois and as a Professional Geologist by the State of Texas.

Based on my background, education and experience, I am qualified to render expert opinion on the subject matter of this testimony.

2. Summary of Testimony

This testimony supports the detailed information that has been submitted in accordance with 40 CFR Section 270.23(b). The WIPP is located in a geological setting that will be protective of human health and environment in accordance with NMAC 20.4.1.500 (incorporating 40 CFR § 264.601).

A long history of general geological stability of the WIPP site and detailed studies of the geology over the last 35 years demonstrate that the WIPP site is an excellent location for the disposal of transuranic mixed waste. Thick deposits of evaporite rocks provide protection for the public and the environment and are a testament to the lack of circulating water at the disposal depth in the Salado Formation. Extensive study of the overlying Rustler Formation provides quality information for understanding potential pathways for monitoring.

The WIPP site is located in a region of general tectonic stability with a well-established geologic history. Drilling and detailed studies of the geology since 1999 refine knowledge of factors that affect the hydrology of the Culebra, which is considered by the Applicants, the U.S. Environmental Protection Agency (EPA) and the NMED to be the most important water-bearing unit overlying the disposal horizon with respect to isolation of TRU mixed waste in the WIPP repository. These factors include overburden (depth), dissolution of upper Salado halite, halite in Rustler members, and gypsum fill of porosity in the Culebra. Lateral relationships within, and the depositional origins of, the formations overlying the WIPP repository disposal horizon have been confirmed or refined by the additional work. The elevation of the Culebra can be mapped and used to estimate overburden across the site area. Demonstrated continuity of beds of the Salado and Rustler Formations permits evaluation of the effects of post-depositional dissolution of upper Salado salt near Nash Draw. Understanding the depositional origins also contributes to a proper evaluation of the limits of halite in the Rustler as a factor in Culebra properties. Drilling and coring also reveal additional information about the distribution of gypsum within the Culebra, and this is a factor in the hydraulic properties of the unit. Finally, mapping and further investigations in part of Nash Draw show how runoff may be focused at internally drained areas. While individual major rainfall events are related to increases in Culebra hydraulic pressure, the location of recharge is not certain.

The rock system at WIPP is well characterized and provides confidence in meeting the regulatory conditions for isolation for TRU mixed waste. It is my professional opinion that the data developed over the years at the WIPP site clearly demonstrate that the geologic characteristics at the WIPP site and surrounding area will prevent releases of waste constituents to the ground water or subsurface environment, thus ensuring protection of the human health and environment in compliance with NMAC 20.4.1.500 (incorporating 40 CFR §264.601).

3. Detailed Testimony

INTRODUCTION

My testimony supports and supplements information in the Renewal Application and highlights some of the advances in geology at and around the WIPP site since 1999, when the initial Hazardous Waste Facility Permit (HWFP) was issued by the State of New Mexico for the operation of the WIPP facility. Although the geological data are valued independently, they are mainly important to understanding the hydrologic processes at the WIPP facility and isolation of TRU mixed waste over the long term.

Since the original HWFP hearings in 1999, the most significant geohydrological advance has been the formulation of a revised conceptual model of geohydrology of the Culebra (e.g., Holt and Yarbrough, 2002; Powers et al., 2003). This conceptual model shows the relationships between the hydraulic properties of the Culebra and geological conditions that can be ascertained between borehole test points. Thus geological factors that have a regional distribution provide the information that can be used to estimate hydraulic properties (in particular, transmissivity) between borehole test points. This advance provides a sound basis for modeling the behavior of fluid flow in the Culebra.The Culebra is considered the most significant hydrologic unit with respect to evaluating long-term isolation of TRU mixed waste at the WIPP facility.

As a necessary corollary, several geological studies were undertaken to provide more control over important geological factors, beginning with Powers (2003). A program plan (Sandia National Laboratories, 2003) was prepared that laid out a series of boreholes that could be located, drilled, logged for geological data, and completed as monitoring and/or pumping wells as part of testing and refinement of the conceptual model.

The field program was initiated in 2003 with the drilling, logging, and completion of borehole SNL-2 (Powers and Richardson, 2003a). The last well in this series (SNL-17A) was drilled and completed in 2006 (Powers, 2009d). Some non-drilling studies in Nash Draw were concurrent (e.g., Powers, 2006a, 2006b; Powers et al., 2006a), and they will be briefly described.

The Renewal Application refers to reports and articles (e.g., Beauheim et al., 2007; Holt et al., 2005; Powers and Holt, 2000; Powers, 2003; Powers et al., 2003, 2006a, 2006b) that summarize many of the findings of the geology and hydrology from these investigations since the initial permit application. Some of the broader investigations of the geology in support of the conceptual model are highlighted in the section titled BROADER STUDIES AND EVALUATION complements material presented in the Renewal Application. Following that section, some of the specific findings (from drilling programs since 1999) that further refine knowledge of upper Salado and Rustler geology are considered, especially as they relate to the Culebra conceptual model. That section is titled WIPP GEOLOGY AND RECENT ADVANCES, and it is organized from oldest to youngest. Because drilling and other field programs have advanced our understanding of formations above the Rustler in some useful ways, there a section called USEFUL ANCILLARY OBSERVATIONS; the focus is on data and evaluation that extends our understanding of the geohydrology of rock units above the Rustler. A final section is titled SUMMARY, and in it I identify more succinctly useful geologic information for investigations of the last eleven years. Most of the hydrologic investigations and implications are examined in more detail in testimony provided by Mr.Richard L. Beauheim.

BASIC GEOLOGIC SETTING FOR THE WIPP

The regional to local geology and geologic setting for WIPP have been described in the original Permit Application and the Renewal Application (AR 090937). The relevant local stratigraphy and features that are frequently used in the following sections are reviewed briefly here, with some figures and maps for reference to allow reading this document generally independent of the Renewal Application.

The WIPP facility is located in the northern part of the Delaware Basin (Figure 1), a major depositional feature that accumulated thousands of feet of mainly marine sediments. The connection of the basin to the ocean was restricted during late stages, and the solutes in the water became concentrated enough to deposit the evaporite beds of the Castile, Salado, and Rustler Formations (Figure 2). Water/brine depth varied during this period, ranging from thousands of feet to complete desiccation (Holt and Powers, 1990; Hovorka et al., 2007; Powers and Holt, 1990). Non-marine siliciclastic beds of the Dewey Lake Formation (Dewey Lake) followed Rustler at about the end of Permian Period ~250 million years ago. The Salado, and especially the Rustler and overlying Dewey Lake (Figure 2), were being deposited across the previous margins of the basin with fewer effects at the margin; this illustrated that the basin had ceased to subside to any significant degree by this time. The Dewey Lake is overlain by Triassic Dockum Group beds of fluvial origin. Since near the end of Permian time, southeastern New Mexico has been above sea level with the exception of an apparently brief (and likely shallow) inundation near the middle of the Cretaceous Period, ~100 million years ago (Bachman, 1980; Lang, 1947; Kues and Lucas, 1993). There are no known sediments in the area around WIPP ranging in age between mid-Cretaceous and ~13 million years ago (mid-Miocene Epoch). By mid-Miocene, the basin was tilted slightly eastward as uplift occurred to the west along the Guadalupe Mountains. Erosion stripped overlying formations in the western part of the basin, and soluble evaporites there were being dissolved. Headward erosion and solution by the Pecos River extended to the north, and the Mio-Pleistocene Gatuña was deposited across erosion surfaces and in valleys related to the development of the Pecos River valley. By ~0.5 million years ago, many of the erosion surfaces, including the location at the WIPP facility, remain stable for a sufficient period of time that a calcareous soil (pedogenic calcrete) developed what has been called the Mescalero caliche. The calcrete has been modified by exposure locally since formation, and along active areas of erosion and solution has been deformed, tilted, or removed. The Berino soil is a red, mainly sandy siltstone that formed over areas of the Mescalero beginning ~300,000 years ago. In the last few tens of thousands of years, large areas of southeastern New Mexico have been blanketed with sand dunes that are mainly stabilized by vegetation.

Along with regional relationships, this indicates the area was above sea level and subject to erosion. The timing of erosion and thickness of overburden removed since Triassic time has been estimated (Powers and Holt, 1995; Holt et al., 2005) for the WIPP site. This reconstruction, based on geologic history of the basin, helps understand how the overburden on the Culebra has varied with time.

The Renewal Application reviews data available about large-scale tectonic processes, including igneous activity and faulting. These data show that the region is tectonically stable, with no indication of significant activity during the relevant operating and monitoring period for WIPP. This stability is part of the reason for locating the WIPP facility in southeastern New Mexico, and more than thirty-five years of investigations is consistent with this decision.

Non-tectonic processes are active in the area, as reviewed by the Renewal Application. Chief among those is solution of evaporite rocks at the surface and near-surface, resulting in features such as the well-known Nash Draw to the west of the WIPP site. Before a repository site was selected in southeastern New Mexico for investigation, these non-tectonic processes were recognized. They have been a part of investigations for the WIPP project, at some level, since then. The principal concern about dissolution is the effect it could have on the hydrogeology of relevant units and isolation of TRU mixed waste at the WIPP facility. The Renewal Application describes some of the history of the study of dissolution. This history starts with an initial general expectation that dissolution had an effect on the hydrogeology, especially of the Rustler. The subsequent 26 years of detailed sedimentologic and stratigraphic evaluation of the rocks have provided thorough knowledge of the rocks and their history. Some of the details of this long evaluation of the rocks are expanded upon in this testimony to show the broad-based, but in-depth, knowledge of the Rustler, in particular. This knowledge shows the limits of the effects of dissolution and karst on Rustler hydraulic properties at the WIPP site and provides the basis for the current conceptual model of Culebra hydrology.

BROADER STUDIES AND EVALUATION

In the late 1990s, Robert Holt recognized that Culebra transmissivity (T) values, while highly variable across the WIPP site area, separated into two relatively distinct fields when plotted with respect to depth below ground level (see Powers et al., 2003 for an example of the early plotted data). The T values in each field also varied with depth in a similar fashion. The most apparent or probable factors contributing to these variations were considered to be 1) change in overburden (depth) affecting fracture aperture, 2) dissolution of upper Salado halite (affecting T values in the vicinity of Nash Draw), 3) the presence of halite above and below the Culebra, indicating possible cements that limit porosity, and 4) variability in gypsum filling porosity in the Culebra.

To evaluate the relationships between these geological factors and Culebra T values, a series of geological investigations were undertaken to provide area-wide data regarding Rustler geology and Salado dissolution.

To best provide estimates of overburden to the Culebra, a map of the elevation of the Culebra was created using data points from WIPP, potash exploration, and oil and gas drillholes (Figure 3) (Powers, 2002a, 2002b, 2003a; Powers et al., 2003). Geologic units in this setting have great continuity, and the resulting maps also are good representations of the surface of the unit. By subtracting the elevation at any point in such a map from the elevation at ground level, the overburden thickness can be estimated with confidence at any desired point across the map area.

To evaluate the extent of dissolution of the upper Salado, a map was created of the thickness of an interval encompassing the upper Salado and lower Rustler. Across industry sources, the two most commonly recorded or interpretable units were the Culebra and the Vaca Triste Sandstone Member (Vaca Triste) of the Salado (Figure 2). In the vicinity of the WIPP site this interval is generally greater than 600 ft (~180 m) east of Livingston Ridge (the eastern margin of Nash Draw) and decreases sharply at Livingston Ridge to ~500 ft (<~150 m) west of Livingston Ridge (Figure 4). A cross-section (Figure 5) based on geophysical logs from oil-field drillholes and a map of elevation of the uppermost salt of the Salado illustrates this sharp feature (e.g., figure 3 of Powers, et al., 2006a).

Halite margins in the Rustler were also re-evaluated by examining potash drillhole logs and geophysical logs of oil and gas wells across the WIPP site area (e.g., Powers, 2002a, 2002b, 2007; figure 9 of Powers et al., 2003). These margins are extended well beyond the WIPP site boundaries (Figure 6). While the boundaries near the site are similar to those drawn much earlier (e.g., Snyder, 1985), the data points are far more numerous than in earlier evaluations both locally and regionally due to intensive exploration and development drilling in more recent years. These data provide more sharply defined margins and opportunities to investigate the effects of halite on Culebra T values as well as the differences between early explanations of the distribution of halite due to dissolution (e.g., Powers et al., 1978; Snyder, 1985) and later explanations attributing the distribution of halite in the Rustler principally to depositional processes (Holt and Powers, 1984, 1986, 1988, 1990, 1999; Lorenz, 2006; Powers and Holt, 2000, 2008; Powers et al., 2003, 2006b). Sedimentologic features have been observed and documented for these rocks, leaving little justification for dissolution of Rustler halite beds as an explanation (Lorenz, 2006). Holt and Powers (1988), while providing the first comprehensive examination of the data and the first comprehensive interpretation of the distribution of halite as a depositional feature, nonetheless also explained the likelihood of limited dissolution of Tamarisk Member (Tamarisk) halite along the current margin in the southern part of the WIPP site. Mercer et al. (1998) reported modest brecciation of overlying sulfate beds as corroborating evidence, and Powers (2003) and later discussions include this relatively small area as having undergone some dissolution after deposition of overlying units.

The final factor contributing to variations of Culebra T values across the WIPP site and surrounding areas is the presence of gypsum filling porosity in the unit. Beauheim and Holt (1990) presented an initial evaluation based on more limited data. This factor is not discussed further here.

WIPP GEOLOGY AND RECENT ADDITIONAL INFORMATION

Since 1999, a number of new holes have been drilled at and around the WIPP site (Figure 7) that provide geologic data related to the conceptual model as well as to general understanding of the geological history of the upper Salado, Rustler, and overlying formations. Powers et al. (2006b) described several of the advances in understanding Rustler geology which are summarized here. The presentation is ordered by stratigraphic unit, beginning with the upper Salado, to preserve the general order of events.

Upper Salado Formation

The upper Salado and contact with the Rustler has been drilled, logged, and cored at several of the wells completed since 1999. The Salado at the WIPP site shows no evidence of dissolution since the Salado was deposited. As indicated in the Hydrology Program Plan (Sandia National Laboratories, 2003), several wells were located to test hydraulic properties of the Culebra where Salado was significantly reduced along Nash Draw by dissolution of the upper halite (SNL-16, SNL-19), near the upper Salado dissolution margin (SNL-1, SNL-2, SNL-12, SNL-13, SNL-17, SNL-18), or in an area mapped as a possible re-entrant of the dissolution margin (SNL-3, SNL-9). Cores were obtained across or near the Salado-Rustler contact in SNL-2, SNL-3, SNL-9, SNL-12, and SNL-16 (near the contact). Although planned, the contact was not drilled in SNL-13, SNL-17, and SNL-18 due to drillhole stability concerns at each location.

The two wells (SNL-3 and SNL-9; Figure 8) located in possible re-entrants on the Salado dissolution margin west and north of WIPP both showed normal stratigraphic sequences across the contact. At SNL-3, the contact (Figure 9a) is marked by laminar gypsum (Powers and Richardson, 2004), as found in the shafts and in some other cores. The overlying sediments show bedding and bioturbation undisturbed by brecciation that would indicate significant post-depositional dissolution. At SNL-9, the contact (Figure 9b) with uppermost Salado halite is a sharp surface overlain by a thin interval (~2.5 ft) of mudstone clasts and some distorted bedding (Powers and Richardson, 2003). It is possible that some post-depositional (most likely before the sediments became well indurated) dissolution of uppermost Salado halite occurred at SNL-9. The sharp contact, however, is similar to planation that occurs when fresher water floods a halite pan surface. As with SNL-3, there is no evidence of brecciation or rotation of blocks higher in the sequence that would signify grosser dissolution after the sediments were lithified. Although the possible re-entrants follow some thinning of the Culebra-Vaca Triste interval, there is no evidence in core that suggests any significant post-depositional dissolution.

SNL-2 was drilled about ¼ mile east of the dissolution margin mapped along Livingston Ridge (Powers and Richardson, 2003a). The core across the Salado-Rustler contact again showed normal stratigraphic relationships, preserved fine bedding and probable bioturbation in the lower Rustler, and halite fracture fillings and halite cements higher in the Rustler.

SNL-12 was drilled in an area where geophysical log interpretations left some uncertainty about upper Salado dissolution. The laminated sulfate at the boundary is not fractured and fine bedding is preserved undisturbed (Powers and Richardson, 2004a) (Figure 10).

In contrast, SNL-17 (Powers, 2009d) and SNL-18 (Powers, 2010b) show dramatic evidence of the effects of dissolution along the sharp margin as mapped by Powers (2002a, 2002b, 2003) and Powers et al. (2003, 2006b) (Figures 4, 7). In neither location was it possible, due to hole instability, to drill to or core the Salado-Rustler contact.

Until three WIPP shafts were mapped in detail through the Salado-Rustler contact (Holt and Powers, 1984, 1986, 1988), this contact was widely considered to be a location of post-depositional dissolution of upper Salado, at least in a thickening wedge from about the center of the WIPP site to the west (e.g., Powers, et al., 1978). The shaft mapping, however, showed in detail the undeformed sedimentary structures (bedding, channeling, bioturbation) of the basal Rustler, as well as fossil debris (Figure 11). While it is certain that the uppermost Salado halite would have undergone some dissolution during Permian time as the fresher marine water invaded the basin, this differs from the concept that dissolution occurred after these rocks had formed. Holt and Powers (1988) concluded that this was a normal progression from desiccating-upward halite pan deposits of the Salado to the basal shallow marine sediments of the Rustler as the sea transgressed.

Post-depositional dissolution has removed, and presumably is still removing, upper Salado halite along a sharply-defined margin west of the WIPP site (Powers, 2003; Powers et al., 2003, 2006b). Within Nash Draw, as described initially by Lee (1925), this process continues through solution and erosion.

Los Medaños Member

The Los Medaños Member (Los Medaños) was well exposed in WIPP shafts (Holt and Powers, 1984, 1986, 1990), leading to a detailed description and formal naming of the member (Powers and Holt, 1999). (Early project documents referred to this stratigraphic interval as the “unnamed lower member” of the Rustler Formation.) These exposures revealed well preserved depositional features, including small channels and invertebrate fossil fragments, at the base. Above the base, fine sandstones showed bedding, burrowing (bioturbation), and even a few fossil fragments replaced by halite. Higher in the sequence, thin halite beds preserved to the east formed in shallow saline pans. A regionally persistent sulfate bed (informally called A-1; Figure 2) is evidence of renewed transgression and flooding with less saline waters. Between A-1 and the base of the Culebra is a mudstone-halite interval (M-2/H-2) that shows the typical eastern facies deposited in a saline pan and western facies (including most of the WIPP site) deposited in saline mudflat to mudflat environments. The uppermost bed is a regionally persistent, distinctive gray claystone that is laminated to thinly bedded (Figure 12). This bed also displays some soft sediment deformation and adjustment to loading by continuing deposition in some cores and shafts (with a basal part of the Culebra variably brecciated).

Holt and Powers (1988) and Powers and Holt (2000) described the basic relationships of the mudstone-halite (M-#/H-#) intervals within the Rustler (Figure 13). Based on evidence from cores, shafts, and geophysical logs, these intervals record the differences in environments that existed across the area of WIPP (Figure 14). Generally to the east, shallow halite pans (shallow brine lakes) produced intervals with thin halite beds, muddy halite beds, halitic mudstones, and mudstones. Halite in the muddy or mudstone intervals ranged from displacive (pushes aside the soft sediment as the crystal grows) to incorporative (includes soft sediment as the crystal grows) to planed or corroded (eroded or dissolved as fresher water floods the pan). Like all pans, these had margins, and these margins shrank during periods of desiccation and expanded with increased brine availability. Near the margin of standing water, the sediments on the flats would be saturated as well with brine, producing displacive and incorporative halite growth. Farther from the margin, the flats would be higher in elevation and subject to fresher water inflow and recharge from upland areas. With sufficient exposure, soil features can begin to form in these mudflat areas. The mudflats are highly susceptible to shrinkage due to desiccation and/or thermal contractions. The apertures of such fractures more distal to the brine filled with fibrous gypsum where sulfate dissolved in the pore water was dominant. Nearer the brine pan, NaCl brines filled these synsedimentary fractures with fibrous halite (Figure 15). Where gradients were sufficient, channels could develop on the mudflat, as found in one shaft and also at drillhole WIPP-19 (Holt and Powers, 1988; Powers and Holt, 2000). Upland mudflats in these units also show color and vertical lithologic differences related to distinct episodes of halite pan development that can be documented in geophysical logs and, to a lesser extent, cores. Recognizing these relationships is essential to understanding the features of the mudstone-halite facies and correctly interpreting single features pulled out of context.

Powers and Holt (2008) detailed the continued abuse of an illustration (Chaturvedi and Channel, 1985) purporting to be evidence of an open fracture in the lower mudstone-halite (M-1/H-1) exposed in the Waste Shaft (formerly known as the Ventilation Shaft). Detailed mapping of the Ventilation Shaft after being enlarged for use as the Waste Shaft shows this interval includes fractures filled with fibrous halite – not open fractures. The halite in the fractures in the shaft, as originally drilled, was dissolved by fresh water seeping down the shaft walls from the Culebra in the months between drilling and photographing. These fractures and filling are consistent with the model of formation in the halite pan to mudflat environments as proposed by Holt and Powers (1988) and Powers and Holt (2000).

A second suggestion commonly heard regarding the subunits of the Los Medaños is that the geologic record of the drilling of WIPP-14 (Sandia National Laboratories and D'Appolonia Consulting Engineers, 1982) is evidence of a filled cavern. The report of lithology based on cuttings refers to "mud" from an interval (836.2-917.6 ft) in the upper Los Medaños that includes the informal anhydrite unit (A-1) and upper mudstone-halite (M-2/H-2). In the basic data report, the interpretation was reported as "…dissolution residues bounding the interbeds of dolomite." The lithologic description of "mud" has been represented as evidence of karst or cave fillings at this depth. Nevertheless, the geophysical logs of the drillhole show clearly that A-1 is present through this interval (Figure 16). The cuttings of reddish-brown "mud" reported is consistent with the bulk of M-2 throughout the area, as shown in multiple reports. There is no evidence of cavern development, filled or unfilled, at WIPP-14 in this interval or elsewhere. Lorenz (2006, p. 250) concludes "Proponents of karst at this location have misinterpreted annotations in the lithologic log and have ignored critical complementary evidence such as the geophysical logs. The stratigraphic section penetrated by the drillhole has not been disrupted or displaced by karst-related dissolution features."

Powers et al. (2006b) explained the significance of the persistent gray layer at the top of the Los Medaños to understanding the depositional environments preceding Culebra deposition. It is deposited across underlying mudstone and halite facies and is not a residue developed by later dissolution. The more local soft sediment deformation and limited brecciation of basal Culebra is most likely due to some early removal of halite (possibly displacive, as found in SNL-15) by fresher transgressing waters that produced the Culebra. This gray clay was cored in most SNL-series wells, with excellent examples from SNL-2, SNL-6 (Powers, 2010a), SNL-10 (Powers, 2009b), and SNL-15 (Powers and Richardson, 2008c). These display undisturbed fine laminae and a sharp contact with the overlying Culebra (Figure 12).

All of the SNL-series wells penetrated the upper Los Medaños and core was recovered from the upper interval. The subunits and lithologies are consistent with earlier descriptions and facies interpretations (e.g., Holt and Powers, 1988). One difference is that the limits of halite in the lower part of the member (M-1/H-1, below A-1) are better defined because of observations made while drilling these holes (e.g., halite cement in SNL-2; Powers and Richardson, 2003) and gleaned from records of potash drilling (Powers, 2002a, 2007). Halite has been preserved even close to the Salado dissolution line at SNL-2. The form of halite (cement rather than as purer beds) is very consistent with the depositional model.

Culebra Dolomite Member

The Culebra interval was cored at each of the SNL-series locations, and recovery was variable, as past experience has shown, in response to the degree to which porosity is filled. As described in Powers et al. (2006b), porosity showed some filling by halite in SNL-6 and SNL-15 (Figure 17), both of which are located east of all Rustler halite margins. Sulfate pore fill also was dominated by anhydrite rather than gypsum, consistent with the greater stability of anhydrite in a very saline environment. Both of these features were predicted (Beauheim and Holt, 1990; Holt, 1997) based on depositional models of the Rustler and Culebra.

The more recent cores have also been included in a more detailed analysis of gypsum in the Culebra and its effect on hydraulic parameters. Halite-filled porosity not only indicates that porosity is virtually filled but that unsaturated (with respect to halite) water is not moving through the Culebra in this area.

Tamarisk Member

In its simplest form, the Tamarisk (Figure 2) consists of a lower sulfate (A-2), middle mudstone/halite (M-3/H-3), and upper anhydrite (A-3) (Holt and Powers, 1988). The dominant feature in previous study has been the M-3/H-3 relationships (e.g., Holt and Powers, 1988; Powers and Holt, 2000) that are interpreted as representing a halite pan to mudflat environment, as previously described.

The lower sulfate bed, A-2, is well represented by cores from the newer wells across the WIPP site area. Near the middle of the bed, a thin siltstone or claystone is persistent, and unpublished regional studies of geophysical logs reveal that it is regionally present and thicker elsewhere. In some wells, the siltstone is higher in the unit, possibly because erosion has removed some of the upper A-2. The upper surface of A-2 has been eroded across bedding in some cores.

One significant refinement from the SNL-series wells comes from those locations on or near the margin of H-3 (Figure 7). This margin previously was interpreted as having been affected by dissolution within a narrow tract in the southeastern part of the WIPP site. SNL-8 was located northeast of the WIPP site where mapping from oil and gas well logs suggested the margin might also have undergone some dissolution (Powers, 2003, 2009a). Core from M-3 at SNL-8 showed an upper claystone that is bedded to laminated and includes angular gypsum clasts (Powers, 2009a). The basal part of A-3 is fractured to create some breccia (Figure 18). In view of the modest brecciation of the basal A-3, the tract of M-3/H-3 indicating some H-3 dissolution is considered to extend farther north along the margin than was demonstrable with previous data.

A dramatic feature of the Tamarisk is local erosion of A-2 on the mudflat area during deposition of the mudflat sediments. A channel erodes through A-2 at the WIPP Exhaust Shaft (Holt and Powers, 1986; Powers and Holt, 2000). A shallow channel deposit in M-3 was mapped in the Air Intake Shaft (Holt and Powers, 1990), and the upper surface of A-2 was partially eroded under the channel (Figure 19). Core from WIPP 19 through this interval shows no A-2 overlying the Culebra. Instead a graded conglomerate is present. On the basis of only the core data from WIPP 19, Ferrall and Gibbons (1980) suggested this was a dissolution residue, formed as a cave filling. Given the current information and depositional model of the Rustler, including the mudstone-halite units, the shapes and features of the channeling are consistent with a depositional model and not with cave formation or karst.

Angular to rounded clasts of gypsum are encountered in upper M-3 in a number of boreholes. The finding of an angular clast in the upper M-3 of drillhole WIPP 13 was interpreted by Holt and Powers (1988) as a possible indicator of dissolution of H-3 in an isolated pocket separated from the remaining halite facies tract. The mapping of WIPP shafts, regional correlation with the mainly halitic facies, and widespread encountering of clasts where the overlying A-3 is not brecciated indicates an alternate explanation that is simpler and much more consistent with all data.

The Waste, Exhaust, and Air Intake Shafts were mapped in detail and reveal that upper M-3 includes a thin anhydrite or gypsum and clay bed that is variably distorted by soft deformation of the underlying mudstones. This thin sulfate bed is clearly separate from the overlying A-3, and it was deposited by a freshening event that diluted and raised the saline pan water level high enough to transgress onto the mudflat area, depositing the thin anhydrite. There are thin sulfate beds observable in log traces and during drilling (e.g., SNL-6; Powers, 2009). The sulfate clast in WIPP 13 has not been correlated specifically with these; it may be a very thin, unresolvable (by geophysical logs) unit in the main part of the depositional basin. Nevertheless, after being deposited as a thin (1 ft or less) bed, it subsequently was deformed within the more plastic claystones and mudstones during loading. It may locally be more broken, forming clasts such as those encountered routinely during drilling and coring. Small, angular to rounded clasts, graded by size by transport in some cores, are common in M-3. These more angular clasts are the remnants of a continuous bed disrupted by soft sediment deformation and not the result of downdropping of a brecciated overlying bed (A-3) following dissolution.

Coring at SNL-18 (Powers, 2010b) and SNL-17 (Powers, 2009d) along the upper Salado dissolution margin and at SNL-16 (Powers, 2009c) and SNL-19 (Powers, 2009e) in Nash Draw showed extensive alteration of A-3. The unit is variably thinned, fractured to brecciated, deformed, and is porous. The effects of dissolution propagate upward through the stratigraphic section to a height similar to, or greater than, the thickness of removed halite (see also Holt and Powers, 1988). This finding is also an appropriate factor to apply to other parts of the formation where it has been suspected or proposed that halite has been dissolved.

In contrast, H-3 at SNL-6 (Powers, 2010a; Powers et al., 2006b) shows a lower argillaceous halite that is equivalent to much of the mudstone (M-3) facies to the west and southwest. The upper halite beds thin to the west and the included anhydrite beds are believed to converge to the west and south with the base of A-3 along the halite depositional margin.

Magenta Dolomite Member

Cores of the Magenta (Figure 20) across the site show basal high amplitude wavy bedding or stromatolitic forms that grade into flatter wavy and lenticular bedding through much of the member. Cores from the western area show more development of nodular gypsum in one or more beds near the top of the member. Cores and resistivity logs indicate that porosity is relatively higher through about one-third to one-half the member. Away from Nash Draw and Livingston Ridge, fractures in the Magenta were uncommon and mostly filled with fibrous gypsum.

The biggest difference with previous drilling and coring was to find halite in the Magenta in SNL-6 cores. It fills limited fracture porosity. The setting is similar to the Culebra at SNL-6 and

SNL-15 in that halite is present in overlying and underlying members. The Magenta was not cored at SNL-15, and cuttings were powdery from drilling with air. Cuttings were not diagnostic of halite in the Magenta at SNL-15, although it seems likely to be present there as well.

SNL-16, in Nash Draw, is very near outcrops of the Magenta, and the Magenta presents a very reduced thickness due to erosion. At SNL-17, along the upper Salado dissolution margin, the Magenta was not cored, and cuttings through the interval were mainly granular gypsum. At SNL-18, also along the upper Salado dissolution margin, the Magenta recovered from core was at near-vertical dip and apparently represents only at fraction of the normal thickness of 25-30 ft. The Magenta is well-preserved in Nash Draw at SNL-19 with a normal thickness and sedimentary features. Some erosional planes within the middle of the member at SNL-19 are more prominent than in cores from wells to the east. Near the top of the Magenta at SNL-19, some fractures show reddish brown silt that is most like from the Dewey Lake.

WIPP-33 was drilled and partially cored in 1979 about 1/2 mile west of the WIPP site boundary. The purpose of drilling was principally to determine whether a collapse chimney had caused a surface resistivity anomaly. Several cavities were observed in the upper Rustler (Magenta and Forty-niner) by drops in the drillstring as well as subsequent caliper logs and a video log. Bachman (1981) mapped old gypsite (fine gypsum) spring deposits along the margin of Nash Draw west of WIPP 33. He proposed that the spring deposits were the result of infiltration in the vicinity of WIPP 33 and circulation through upper Rustler to Nash Draw, with seepage producing the gypsite. Fossils and U-series dates indicate these deposits are old (>20,000 years), and the gypsite deposits are not active. This indicates that, if such a system existed, it is not active today.

Forty-niner Member

The Forty-niner, like the Tamarisk, consists of a lower sulfate (A-4), middle mudstone-halite (M-4/H-4), and upper sulfate (A-5). Most of the attention is focused on the H-4 margin and explanations for the distribution of halite, just as in lower mudstone-halite units. In shaft mapping (e.g., Holt and Powers, 1984), M-4 displayed undisturbed sedimentary structures that were striking in view of the general proposition that these mudstone units were the residue after dissolving significant halite (Figure 21). The evidence was in conflict with the dogma. These observations started the detailed sedimentological investigations of the Rustler that had not previously been conducted.

Powers et al. (2006b) compare some of the findings from newer wells with previous mapping results. Of most interest was the core of the lower part of M-4/H-4 at SNL-6 (Powers, 2010a). There the halite and siltstone are in stratigraphic positions similar to the reddish-brown lower half of M-4 at the shafts. The halite at SNL-6 represents the halite pan for this lower part of the mudstone-halite unit. The upper part of the unit at SNL-6 shows bedding, cross-bedding, and erosion that suggests it is a high-energy mudflat tract farther from a halite pan not cored but represented in well logs to the southeast of SNL-6.

The upper sulfate (A-5) appears reduced in thickness in Nash Draw and along Livingston Ridge in some SNL-series wells.

USEFUL ANCILLARY OBSERVATIONS

Both drilling programs and some supplemental mapping activities produced information that is useful to understanding some of the Rustler as well as overlying units. Here a few selected examples are summarized.

Dewey Lake Formation

The Dewey Lake was present at most well locations except SNL-16. It was only sampled through cuttings and geophysical logs. As previously noted (Powers, 1997), sulfate cements and fibrous gypsum tend to be found stratigraphically higher to the east and lower to the west toward Nash Draw. Relatively fresh water was encountered in Dewey Lake above the sulfate cement zone in SNL-14 (Powers and Richardson, 2008b) and SNL-12 (Powers and Richardson, 2004a). At SNL-13, near the southwest corner of WIPP, the Dewey Lake is relatively thin and lacks sulfate cements (Powers and Richardson, 2008a). There water was observed by downhole camera seeping into the lower 53 ft of the formation.

Water of natural origin has been found in drillholes and wells in the Dewey Lake in the southern part of the WIPP site. Brine of anthropogenic origin has been found at the WIPP facilities and immediate surroundings. The brine there was primarily found in the Santa Rosa Formation (Santa Rosa) and the very top of Dewey Lake (Powers, 1997). Deeper drilling within the facility boundary returned dry Dewey Lake cuttings.

Later drilling of C-2737 showed water in the upper Dewey Lake south of the site facilities (Powers, 2002c). As a consequence, another well (C-2811) was drilled nearby to monitor this zone (Powers and Stensrud, 2003).

To understand the distribution of water in the Dewey Lake, Powers (1997, 2003b) developed a conceptual model. The natural water in the southern part of the WIPP site is found on top of the sulfate-cemented zone in the Dewey Lake. The newer wells at SNL-12, SNL-13, and SNL-14 show this same relationship. This differs from C-2737 and C-2811, where the anthropogenic water was encountered about 100 ft above the cemented zone. There is occasionally some confusion of the anthropogenic highly saline waters at the top of Dewey Lake and the natural groundwater to the south that rests on the sulfate-cemented zone.

Santa Rosa Formation

The Santa Rosa or Dockum Group was encountered in SNL-6, SNL-8, and SNL-15, the easternmost new wells. Water was produced in SNL-6 (Powers, 2010a) and SNL-8 (Powers, 2009a) from the formation, and some field evidence of quality and water levels was obtained.

Gatuña Formation

The Gatuña was drilled in many of the SNL-series wells. As in previous experience, the formation thins to the east in the upland areas and thickens toward Nash Draw. Relatively thick (65 ft) Gatuña was drilled at SNL-3, along the trend of a likely pre-Gatuña paleovalley that includes the location of WIPP 14. There the Gatuña is nearly 100 ft thick. SNL-5 is to the west of SNL-3, and it encountered 29 ft of Gatuña. SNL-5 may indicate that the main paleovalley trend is north of SNL-5, leading to areas along Livingston Ridge where Bachman (1985) mapped Gatuña gravel channels.

Pre-Gatuña topography continues to be of interest because of the possible indications that overburden was thinned by erosion and then buried by Gatuña and sand dunes.

Recharge in Southeastern Arm of Nash Draw

Lee (1925) reported on karst features in Nash Draw, but he did not provide a map of locations or description of many features. Vine (1963) clearly described disrupted strata of upper Salado and higher units in Nash Draw and attributed the disruption to dissolution, mainly of upper Salado. Vine mapped some of the individual karst features found in the draw. Bachman (1981) revised the geological map in greater detail and noted additional features.

The southeastern arm of Nash Draw was more intensively examined to define drainage basins and solution and collapse features as basic information that can help define recharge to Nash Draw and Culebra Dolomite (Powers, 2006a, 2006b). Previous work in other parts of Nash Draw was also incorporated to provide a broader view (Powers et al., 2006a). While these studies documented a larger number of individual features (caverns, sinkholes), captured drainage, and coalescing features, the main finding was that some of the internally drained basins have larger than expected area that can focus more of the runoff. Areas with more focused runoff appear to have more open and developed karst features. Probable evidence of flooding in one recharge point after a late 2004 major rainfall was observed in the largest basin. In addition, springs flowing year-round from upper Rustler sulfates indicate the system has some storage capacity. Nonetheless, the spring data as well as some reports from drilling in parts of southeastern Nash Draw suggest that the Culebra remains confined in that area and that much of the local infiltration is running through porosity in the upper sulfate bed of the Tamarisk and somewhat in the Magenta.

Hillesheim et al. (2006) analyzed high-frequency pressure data from WIPP monitor wells and suggested that short-term pressure increases are associated with rainfall events. The connection may not be in southeastern Nash Draw but elsewhere. Pressure in a closed (confined) system can be transmitted considerable distance and does not indicate direct recharge at a monitor well.

SUMMARY POINTS

The SNL-series wells tested several aspects of the Culebra geohydrological conceptual model, resulting in good confirmation and some modification.

The geological analysis showed strong effects of upper Salado dissolution on the overlying Rustler beds, including the Culebra. The margin of upper Salado dissolution is rather sharp for such a geological process, and Livingston Ridge directly overlies the margin. There is very limited to no observable dissolution of upper Salado beyond a few hundred yards east of the margin. Hypothesized re-entrants eastward from the dissolution margin at Livingston Ridge were directly tested with two drillholes. The drillholes revealed no evidence of significant dissolution at those locations.

The presence of halite in Rustler has a strong influence on hydraulic properties of the Culebra, as shown especially by monitor wells at SNL-6 and SNL-15, where halite occurs in members above and below the Culebra. Core evidence and interpretation of a large number of geophysical logs improved definition of the halite margins. Both SNL-6 and SNL-15 cores of the Culebra showed halite within the member.

Field evidence from Nash Draw, especially the southeastern arm, provides evidence of focused runoff from large internally-drained basins. Numerous karst features in Rustler sulfate beds and Magenta Dolomite in these locations provide points of infiltration. Nevertheless, local springs provide discharge points and data from previous drilling suggest that the Culebra remains confined beyond the margin of upper Salado dissolution in Nash Draw.

The geological model of Rustler deposition provided by Holt and Powers (1988) and Powers and Holt (2000) continues to be confirmed and strengthened by these investigations, while details emerge to refine some aspects. Claims of karst features in WIPP shafts or WIPP-14, for example, are not supported either directly in those locations or by the depositional model. Cavernous porosity in upper Rustler at WIPP-33 was interpreted by Bachman (1981) as related to a possible spring system, no longer active, that deposited gypsum along western Nash Draw. It is not along the pathway of fluid flow in the Culebra.

4. Conclusions

Investigations since 1999 of the geology and geohydrology of the WIPP site continue to support the conclusion that the site is appropriate for disposal of TRU mixed waste. The site has a long history of general geological stability, and that stability is supported by continued investigations. Field work to establish additional hydrology test and monitor wells has helped to refine our understanding of the processes by which these formations were deposited and subsequently altered. The main difference in geological understanding from early years is a sedimentological basis for the distribution of halite in the Rustler. The main difference in understanding and modeling the hydrology of the Culebra is a well-established relationship between hydraulic parameters and geologic factors.

These developments provide confidence of the appropriateness of WIPP for continued use as a disposal site for TRU mixed waste. The rock system is well characterized for understanding potential pathways that are being monitored. Thick evaporites protect the waste, and they are clear evidence of the lack of circulating water through the rock system to the disposal horizon. WIPP is located in an area of general, long-term geological stability, and surface processes are not a threat to deep disposal at the site.

It is my professional opinion that the geologic characteristics of the WIPP site and surrounding area will prevent releases to the ground water or subsurface environment, and thus are protective of human health and the environment in accordance with 40 CFR Part 264, Subpart X.

REFERENCES

Bachman, G.O., 1980, Regional geology and Cenozoic history of Pecos region, southeastern New Mexico: Open-file Report 80-1099, US Geological Survey, Denver, CO.

Bachman, G.O., 1981, Geology of Nash Draw, Eddy County, NM: Open-file Report 81-31, US Geological Survey, Denver, CO.

Bachman, G.O., 1985, Assessment of near-surface dissolution at and near the Waste Isolation Pilot Plant (WIPP), southeastern New Mexico: SAND84-7178, Sandia National Laboratories, Albuquerque, NM.

Beauheim, R.L., and Holt, R.M., 1990, Hdrogeology of the WIPP site, *in* Powers, D.W., Holt, R.M., Beauheim, R.L., and Rempe, N., eds., 1990, Geological and Hydrological Studies of Evaporites in the Northern Delaware Basin for the Waste Isolation Pilot Plant (WIPP): Guidebook 14, Geological Society of America (Dallas Geological Society), p. 131-179.

Beauheim, R.L., and Powers, D.W., 2004, Integration of geologic information in the WIPP safety case, in Geological Disposal: Building Confidence Using Multiple Lines of Evidence: Proceedings, First AMIGO Workshop, Yverdon-les-Bains, Switzerland, 3-5 June 2003, OECD Nuclear Energy Agency, Issy-les-Moulineaux, France (ISBN:9264015922), p. 145-149.

Beauheim, R.L., McKenna, S.A., Powers, D.W., and Holt, R.M., 2007, Geoscientific data collection and integration for the Waste Isolation Pilot Plant: Linkage of Geoscientific Arguments and Evidence in Supporting the Safety Case, Second AMIGO Workshop Proceedings, Toronto, Canada, 20-22 September 2005, OECD NEA, p. 125-132 (ISBN 978-92-64-01966-9).

Ferrall, C.C., and Gibbons, J.F., 1980, Core study of Rustler Formation over the WIPP site: SAND79-7110, Sandia National Laboratories, Albuquerque, NM.

Hillesheim, M.B., Beauheim, R.L., and Richardson, R.G., 2006, Overview of the WIPP groundwater monitoring programs with inferences about karst in the WIPP vicinity, *in* Caves & Karst of Southeastern New Mexico, L. Land and others, eds., NM Geological Society Fifty-seventh Annual Field Conference Guidebook, p. 277-286.

Holt, R.M., 1997, Conceptual model for transport processes in the Culera Dolomite Member, Rustler Formation: SAND97-0194, Sandia National Laboratories, Albuquerque, NM, 160 p.

Holt, R.M., Beauheim, R.L., and Powers, D.W., 2005, Predicting fractured zones in the Culebra Dolomite, *in* Faybishenko, B, Witherspoon, P.A., and Gale, J., eds., Dynamics of Fluids and Transport in Fractured Rock: AGU Geophysical Monograph Series, v. 162, p. 103-116.

Holt, R.M., and Powers, D.W., 1986, Geotechnical activities in the exhaust shaft, Waste Isolation Pilot Plant: DOE-WIPP 86-008, Department of Energy, Carlsbad, NM 88221.

Holt, R.M., and Powers, D.W., 1988, Facies variability and post-depositional alteration within the Rustler Formation in the vicinity of the Waste Isolation Pilot Plant, southeastern New Mexico: WIPP-DOE-88-004, Department of Energy, Carlsbad, NM, 88221.

Holt, R.M., and Powers, D.W., 1990, Geotechnical activities in the air intake shaft (AIS): DOE/WIPP 90-051, U.S. Department of Energy, Carlsbad, NM.

Holt, R.M., and Yarbrough, L., 2002, Analysis report, Task 2 of AP-088, Estimating Base Transmissivity Fields: Report to Sandia National Laboratories, ERMS 523889.

Hovorka, S.D., Holt, R.M., and Powers, D.W., 2007, Depth indicators in Permian Basin evaporites, *in* Schreiber, B.C., Lugli, S., and Babel, M., eds., Evaporites Through Space and Time: Geological Society of London, Special Publications 285, p. 301-330.

Kues, B.S., and Lucas, S.G., 1993, Stratigraphy, paleontology and correlation of lower Cretaceous exposures in southeastern New Mexico, in Love, D.W., et al., eds., Carlsbad Region, New Mexico and West Texas: 44th NMGS Fall Field Conference Guidebook, New Mexico Geological Society, Socorro, NM, p. 245-260.

Lang, W.B., 1947, Occurrence of Comanche rocks in Black River valley, New Mexico: American Association of Petroleum Geologists Bulletin, v. 31, p. 1472-1478.

Lee, W.T., 1925, Erosion by solution and fill, *in* Contributions to the Geology of the United States, 1923-24: US Geological Survey Bulletin 760-C, p. 107-121.

Mercer, J.W., Cole, D.L., and Holt, R.M., 1998, Basic data report for drillholes on the H-19 hydropad (Waste Isolation Pilot Plant – WIPP): SAND98-0071, Sandia National Laboratories, Albuquerque, NM.

Powers, D.W., 1997, Geology of piezometer holes to investigate shallow water sources under the Waste Isolation Pilot Plant, *in* Duke Engineering and Services, 1997, Exhaust Shaft: Phase 2 Hydraulic Assessment Data Report involving Drilling, Installation, Water-quality Sampling, and Testing of Piezometers 1-12: DOE/WIPP 97-2278, US Department of Energy, Carlsbad, NM.

Powers, D.W., 2002a, Analysis report Task 1 of AP-088, Construction of geologic contour maps: report to Sandia National Laboratories, April 17, 2002 (ERMS # 522085)

Powers, D.W., 2002b, Addendum to Analysis report Task 1 of AP-088, Construction of geologic contour maps: report to Sandia National Laboratories, July 23, 2002

Powers, D.W., 2002c, Basic data report for drillhole C-2737 (Waste Isolation Pilot Plant – WIPP): DOE/WIPP 01-3210, US Department of Energy, Carlsbad, NM.

Powers, D.W., 2003a, Addendum 2 to Analysis report Task 1 of AP-088, Construction of geologic contour maps: report to Sandia National Laboratories, January 13, 2003 (ERMS # 522085)

Powers, D.W., 2003b, TEST PLAN, TP 02-05 Geohydrological Conceptual Model for the Dewey Lake Formation in the Vicinity of the Waste Isolation Pilot Plant (WIPP): Sandia National Laboratories.

Powers, D.W., 2006a, Analysis Report, Task 1B of AP-114, Identify possible area of recharge to the Culebra west and south of WIPP: report to Sandia National Laboratories, April 1, 2006 (ERMS # 543094)

Powers, D.W., 2006b, Analysis Report, Task 1D of AP-114, Collect current and historic information on water levels and specific gravity in potash tailings ponds within the Culebra modeling domain: report to Sandia National Laboratories, March 31, 2006 (ERMS #543124)

Powers, D.W., 2007, Analysis Report for Task 1A of AP-114: Refinement of Rustler halite margins within the Culebra modeling domain: report to Sandia National Laboratories, October 5, 2007.

Powers, D.W., 2010a, Basic data report for drillhole SNL-6 & -6A (C-3151) (Waste Isolation Pilot Plant): DOE/WIPP 07-3323, US Department of Energy, Carlsbad, NM.

Powers, D.W., 2009a, Basic data report for drillhole SNL-8 (C-3150) (Waste Isolation Pilot Plant): DOE/WIPP 05-3324, US Department of Energy, Carlsbad, NM.

Powers, D.W., 2009b, Basic data report for drillhole SNL-10 (C-3221) (Waste Isolation Pilot Plant): DOE/WIPP 07-3363, US Department of Energy, Carlsbad, NM.

Powers, D.W., 2009c, Basic data report for drillhole SNL-16 (C-3220) (Waste Isolation Pilot Plant): DOE/WIPP 07-3364, US Department of Energy, Carlsbad, NM.

Powers, D.W., 2009d, Basic data report for drillhole SNL-17 & -17A (C-3222) (Waste Isolation Pilot Plant): DOE/WIPP 07-3365, US Department of Energy, Carlsbad, NM.

Powers, D.W., 2009e, Basic data report for drillhole SNL-19 (C-3234) (Waste Isolation Pilot Plant): DOE/WIPP 07-3367, US Department of Energy, Carlsbad, NM.

Powers, D.W., 2010b, Basic data report for drillhole SNL-18 (C-3233) (Waste Isolation Pilot Plant): DOE/WIPP 07-3366, US Department of Energy, Carlsbad, NM.

Powers, D.W., and Holt, R.M., 1990, Sedimentology of the Rustler Formation near the Waste Isolation Pilot Plant (WIPP) site, *in* Powers, D.W., Holt, R.M., Beauheim, R.L., and Rempe, N., eds., 1990, Geological and Hydrological Studies of Evaporites in the Northern Delaware Basin for the Waste Isolation Pilot Plant (WIPP): Guidebook 14, Geological Society of America (Dallas Geological Society), p. 79-106.

Powers, D.W., and Holt, R.M., 1995, Regional geological processes affecting Rustler hydrogeology: IT Corporation report prepared for Westinghouse Electric Corporation, 209 p.

Powers, D.W., and Holt, R.M., 1999, The Los Medaños Member of the Permian Rustler Formation: *New Mexico Geology*, v. 21, no. 4, p. 97-103.

Powers, D.W., and Holt, R.M., 2000, The salt that wasn't there: mudflat facies equivalents to halite of the Permian Rustler Formation, southeastern New Mexico: *Journal of Sedimentary Research*, v. 70, no. 1, p. 29-36.

Powers, D.W., and Holt, R.M., 2008, Lessons from early site investigations at the Waste Isolation Pilot Plant, *in* Rempe, N.T., ed., Deep Geologic Repositories: Geological Society of America Reviews in Engineering Geology, v. XIX, p. 83-97, doi: 10.1130/2008.4019(09), March.

Powers, D.W., and Richardson, R.G., 2003a, Basic data report for drillhole SNL-2 (C-2948) (Waste Isolation Pilot Plant): DOE/WIPP 03-3290, US Department of Energy, Carlsbad, NM.

Powers, D.W., and Richardson, R.G., 2003b, Basic data report for drillhole SNL-9 (C-2950) (Waste Isolation Pilot Plant): DOE/WIPP 03-3291, US Department of Energy, Carlsbad, NM.

Powers, D.W., and Richardson, R.G., 2004a, Basic data report for drillhole SNL-12 (C-2954) (Waste Isolation Pilot Plant): DOE/WIPP 03-3295, US Department of Energy, Carlsbad, NM.

Powers, D.W., and Richardson, R.G., 2004b, Basic data report for drillhole SNL-3 (C-2949) (Waste Isolation Pilot Plant): DOE/WIPP 03-3294, US Department of Energy, Carlsbad, NM.

Powers, D.W., and Richardson, R.G., 2004c, Basic data report for drillhole SNL-1 (C-2953) (Waste Isolation Pilot Plant): DOE/WIPP 04-3301, US Department of Energy, Carlsbad, NM.

Powers, D.W., and Richardson, R.G., 2004d, Basic data report for drillhole SNL-5 (C-3002) (Waste Isolation Pilot Plant): DOE/WIPP 04-3305, US Department of Energy, Carlsbad, NM.

Powers, D.W., and Richardson, R.G., 2008a, Basic data report for drillhole SNL-13 (C-3139) (Waste Isolation Pilot Plant): DOE/WIPP 05-3319, US Department of Energy, Carlsbad, NM.

Powers, D.W., and Richardson, R.G., 2008b, Basic data report for drillhole SNL-14 (C-3140) (Waste Isolation Pilot Plant): DOE/WIPP 05-3320, US Department of Energy, Carlsbad, NM.

Powers, D.W., and Richardson, R.G., 2008c, Basic data report for drillhole SNL-15 (C-3152) (Waste Isolation Pilot Plant): DOE/WIPP 05-3325, US Department of Energy, Carlsbad, NM.

Powers, D.W., and Stensrud, W.A., 2003, Basic data report for drillhole C-2811 (Waste Isolation Pilot Plant – WIPP): DOE/WIPP 02-3223, US Department of Energy, Carlsbad, NM.

Powers, D.W., Lambert, S.J., Shaffer, S-E., Hill, L.R., and Weart, W.D., eds., 1978, Geological characterization report, Waste Isolation Pilot Plant (WIPP) site, southeastern New Mexico: SAND78-1596, v. I & II, about 1500 p., Sandia National Laboratories, Albuquerque, NM 87185.

Powers, D.W., Holt, R.M., Beauheim, R.L., and McKenna, S.A., 2003, Geological factors related to the transmissivity of the Culebra Dolomite Member, Permian Rustler Formation, Delaware Basin, Southeastern New Mexico, *in* Johnson, K.S., and Neal, J.T., eds., Evaporite karst and engineering/environmental problems in the United States: Oklahoma Geological Survey Circular 109, p. 211-218.

Powers, D.W., Beauheim, R.L., Holt, R.M., and Hughes, D.L., 2006a, Evaporite karst features and processes at Nash Draw, Eddy County, New Mexico, *in* Caves & Karst of Southeastern New Mexico, L. Land and others, eds., NM Geological Society Fifty-seventh Annual Field Conference Guidebook, p. 253-266.

Powers, D.W., Holt, R.M., Beauheim, R.L., and Richardson, R.G., 2006b, Advances in depositional models of the Permian Rustler Formation, southeastern New Mexico, *in* Caves & Karst of Southeastern New Mexico, L. Land and others, eds., NM Geological Society Fifty-seventh Annual Field Conference Guidebook, p. 267-276.

Sandia National Laboratories, 2003, Program plan, WIPP integrated Groundwater Hydrology Program, FY03-09, Revision 0. March 14, 2003: Sandia National Laboratories ERMS 526671.

Sandia National Laboratories and D'Appolonia Consulting Engineers, 1982, Basic data report for drillhole WIPP 14 (Waste Isolation Pilot Plant – WIP)): SAND82-1783, Sandia National Laboratories, Albuquerque, NM.

Vine, J.D., 1963, Surface geology of the Nash Draw quadrangle, Eddy County, New Mexico: Bulletin 1141-B, US Geological Survey, 46 p.

FIGURES

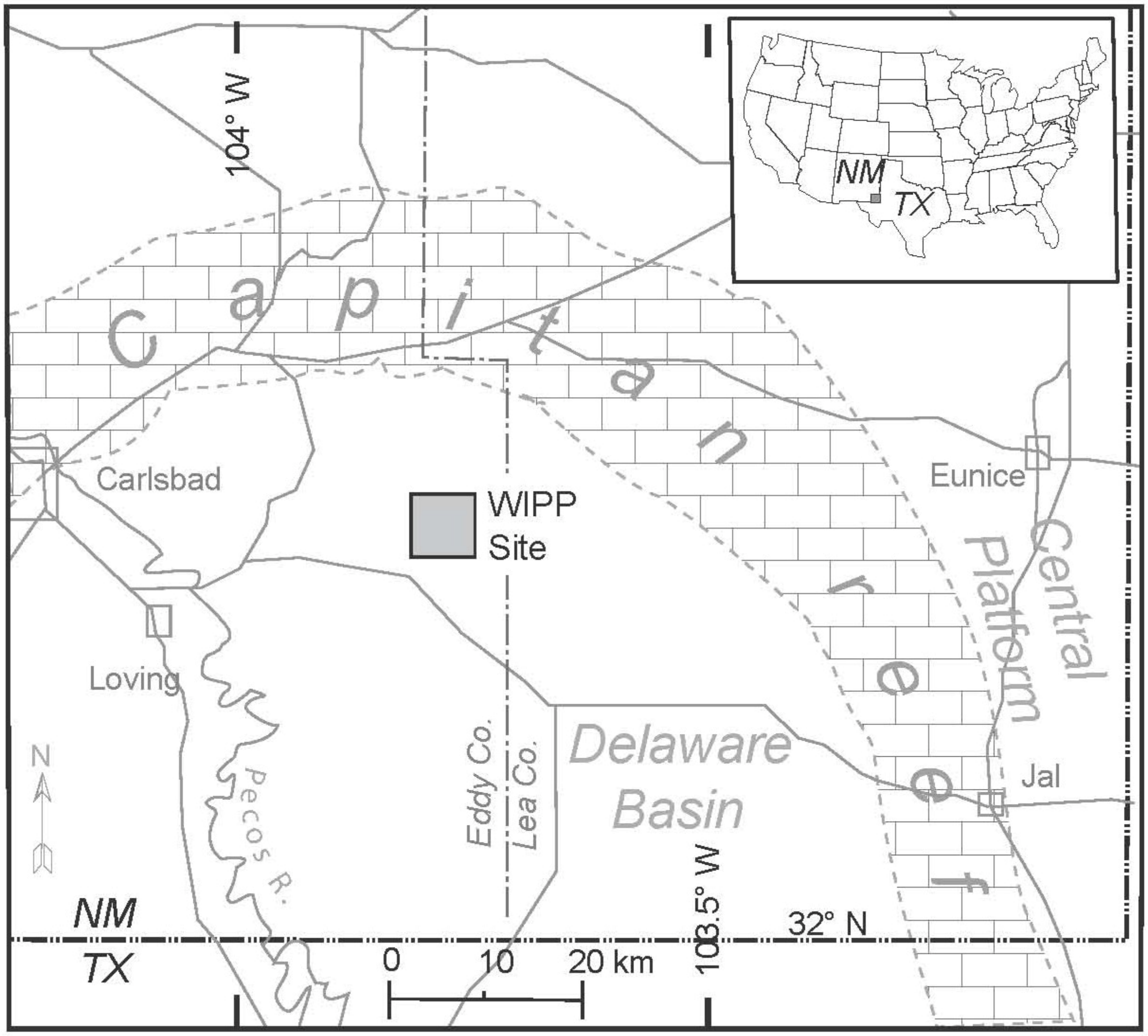

Figure 1. General Location Map of theWIPP facility.

The site is located in the northern Delaware Basin, a major basin that accumulated tens of thousands of feet of sediment beginning ~500 million years ago. The Central Basin Platform to the east separated the Delaware Basin from the Midland Basin. The Capitan reef grew around the margin of the Delaware Basin and eventually cut off circulation to the ocean to the south. Late Permian evaporite formations (~250 million years old), the units used at the WIPP facility for disposal, were deposited in this closed basin and across the reef into the surrounding shelf areas. Modified from Powers (2010b).

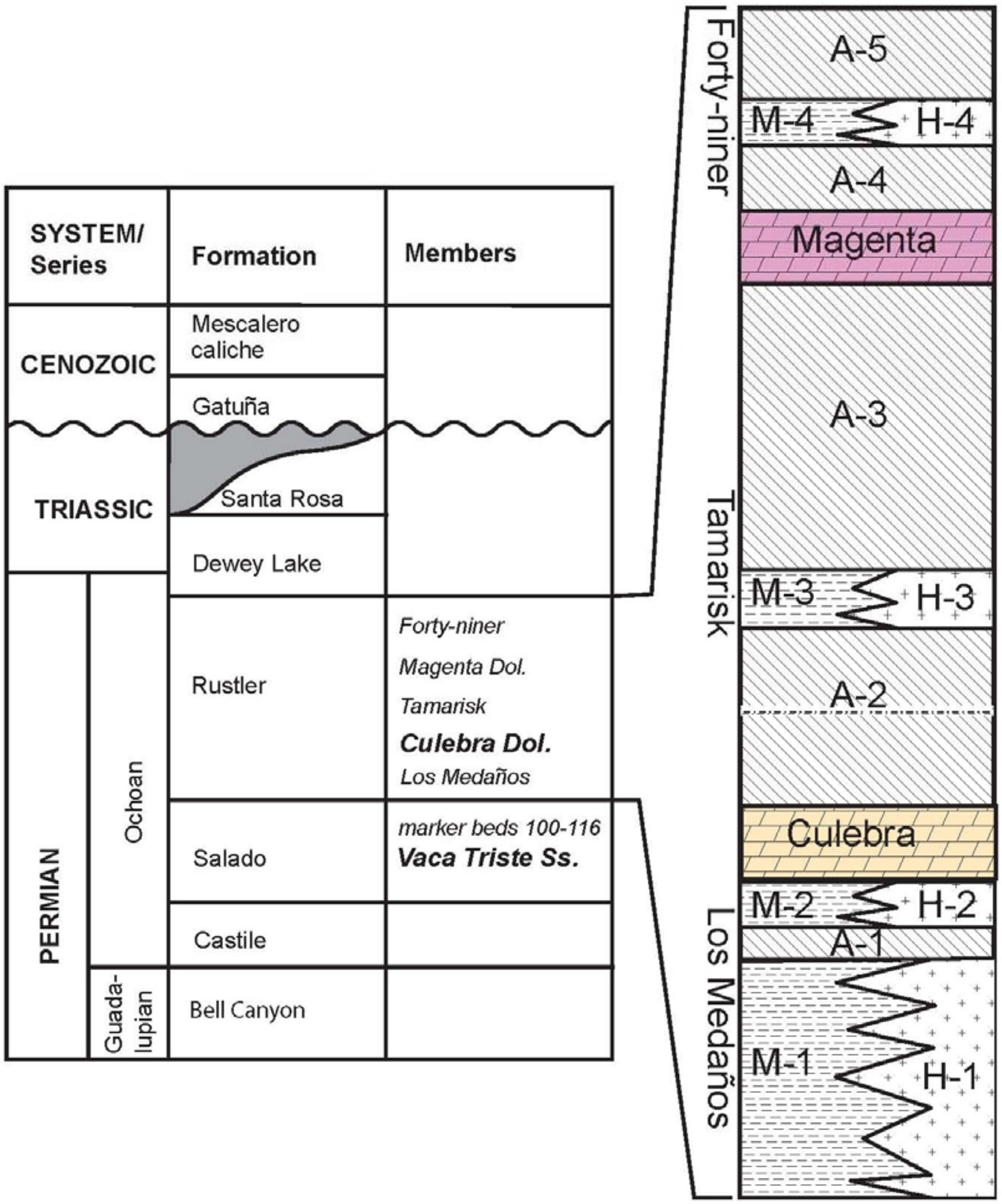

Figure 2. Principal Stratigraphic Units at WIPP.

The WIPP site disposal horizon is located within the Salado, while the Rustler includes the Culebra , the most significant hydrologic unit overlying the Salado. Along with the five formally named members of the Rustler, informal names have been given to signify anhydrite (A-#) or the facies relationships between mudstone to halite (M-#/H-#) units. The broader relationships and significance of these units is explained in the text. Modified after Holt and Powers (1988).

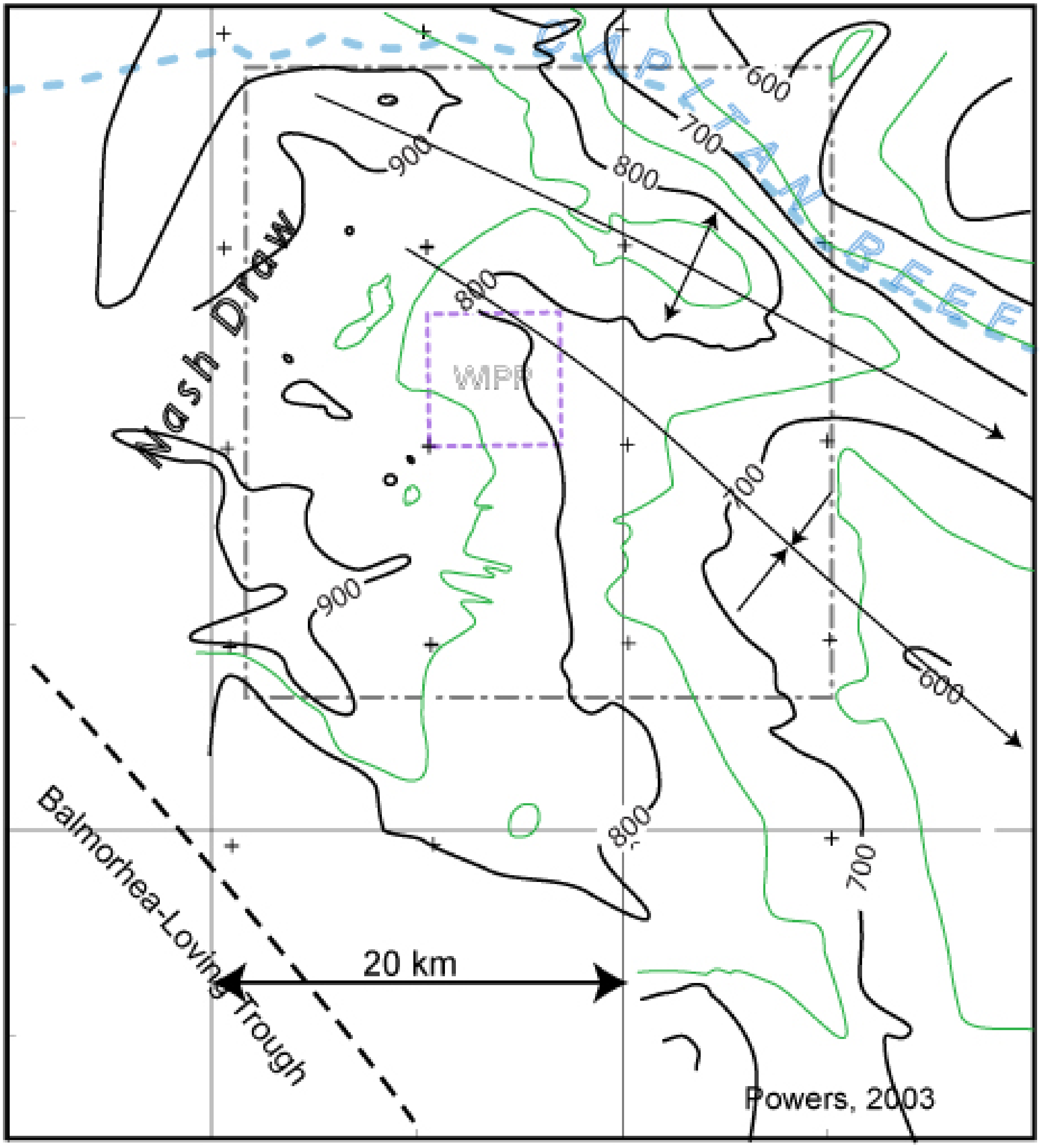

Figure 3. Elevation (meters above mean sea level) of the top of Culebra. This simplified map (from Powers, 2003) shows general eastward slope (dip), a northwest-southeast trending high to the northeast of WIPP, and another similar high southwest of WIPP. The area along the southwest corner of the map is affected by dissolution. This map is used with digital surface elevation data to estimate the depth to Culebra (overburden) over a large area with good confidence. Overburden thickness is a key parameter in predicting Culebra hydraulic properties between test wells.

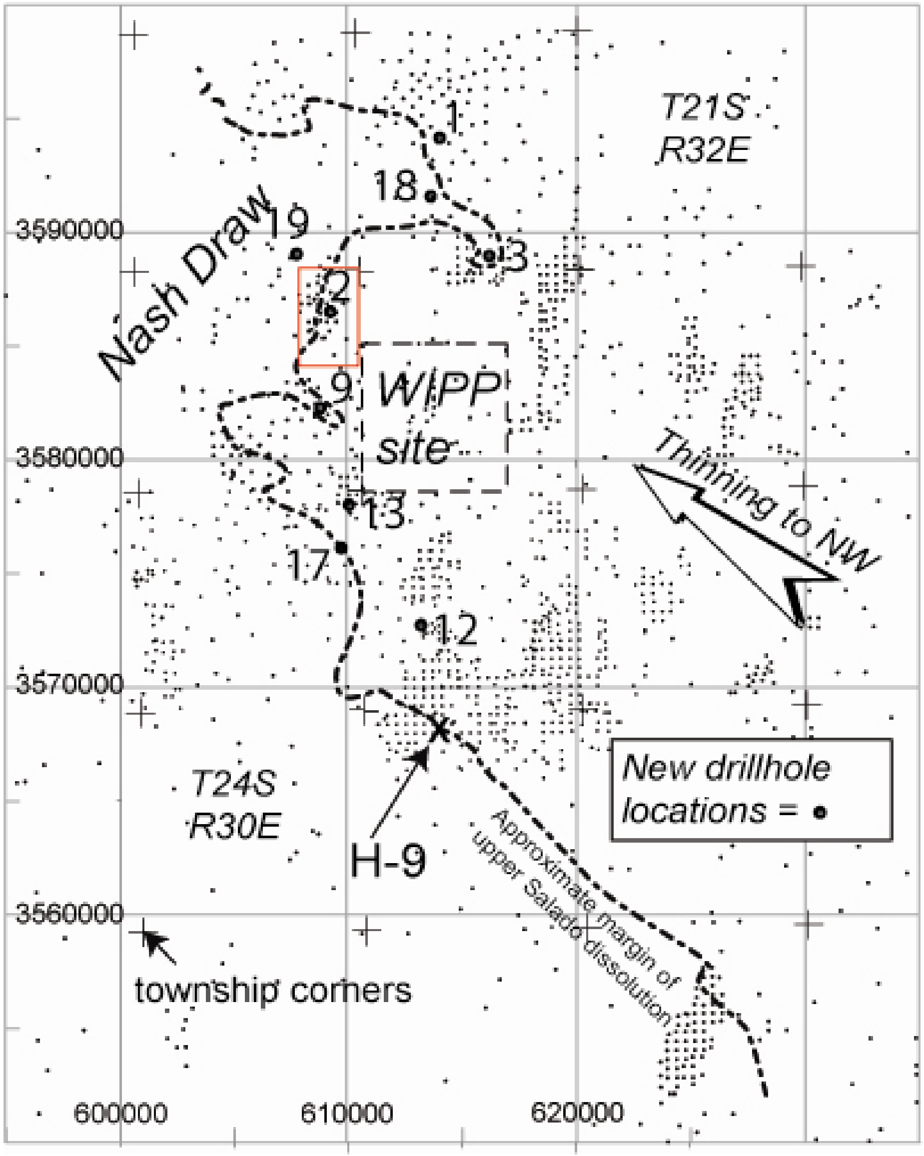

Figure 4. Margin of Upper Salado Dissolution. The dashed line represents the approximate eastern extent of dissolution of upper Salado halite. Small dots represent data points from geophysical or geological logs of drillholes where the thickness between the Vaca Triste and the Culebra could be reliably determined. The margin is sharply defined, in contrast to a broader thickening to the east due to depositional trends. It is the cause of the development of the Livingston Ridge escarpment and underlies it. Larger dots with numbers represent locations of SNL-series wells near the margin. The red rectangle marks the approximate outline of the map in Figure 5. Gridlines are spaced 10 kilometers (~6 miles) apart. Modified from Powers (2003) and Powers et al. (2003).

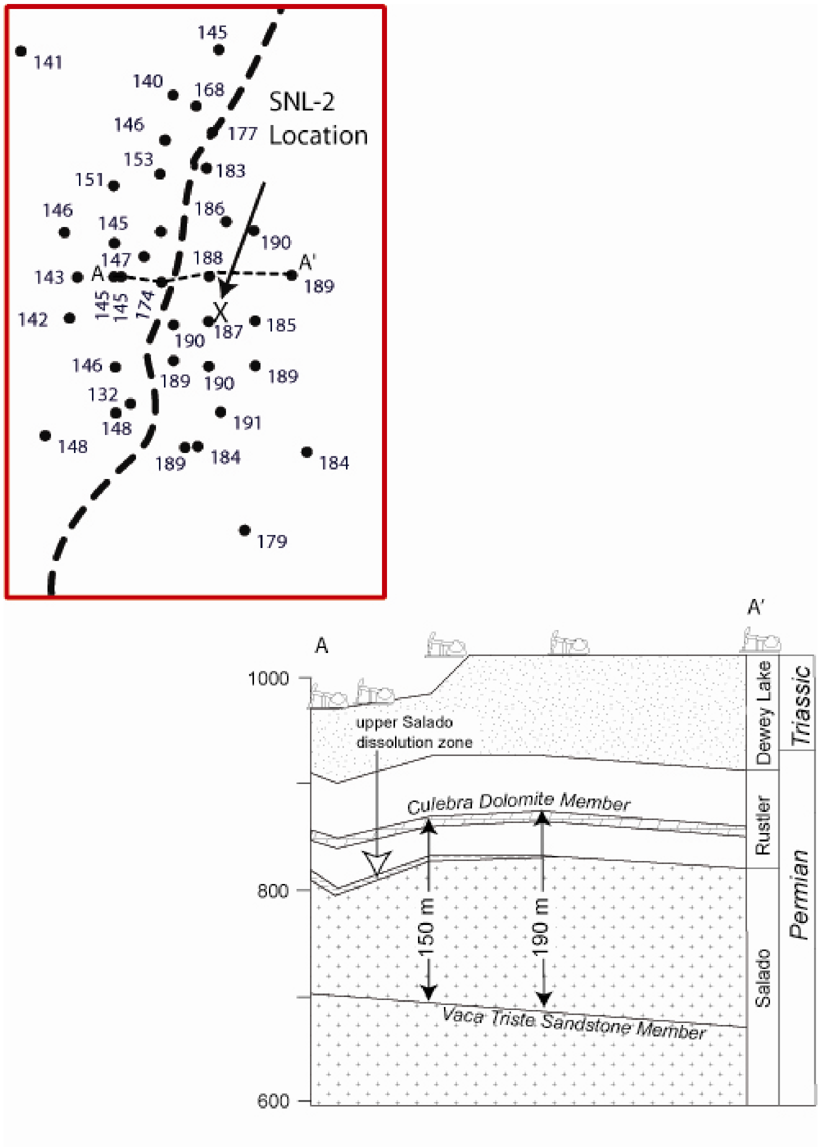

Figure 5. Detailed Map and Cross-Section of Vaca Triste-Culebra Thickness Change Along Dissolution Margin. The values alongside drillhole locations are thickness in meters. The sharp change underlies Livingston Ridge and is the cause of it. SNL-2 was drilled along the margin after it was defined by industry drillhole data. The Salado-Rustler contact shows no signs of post-depositional dissolution at SNL-2, and halite is present in the lower Rustler (Powers and Richardson, 2003a). The cross-section A-A' is ~1200 meters or ~0.75 mile long. Modified from Powers et al. (2003).

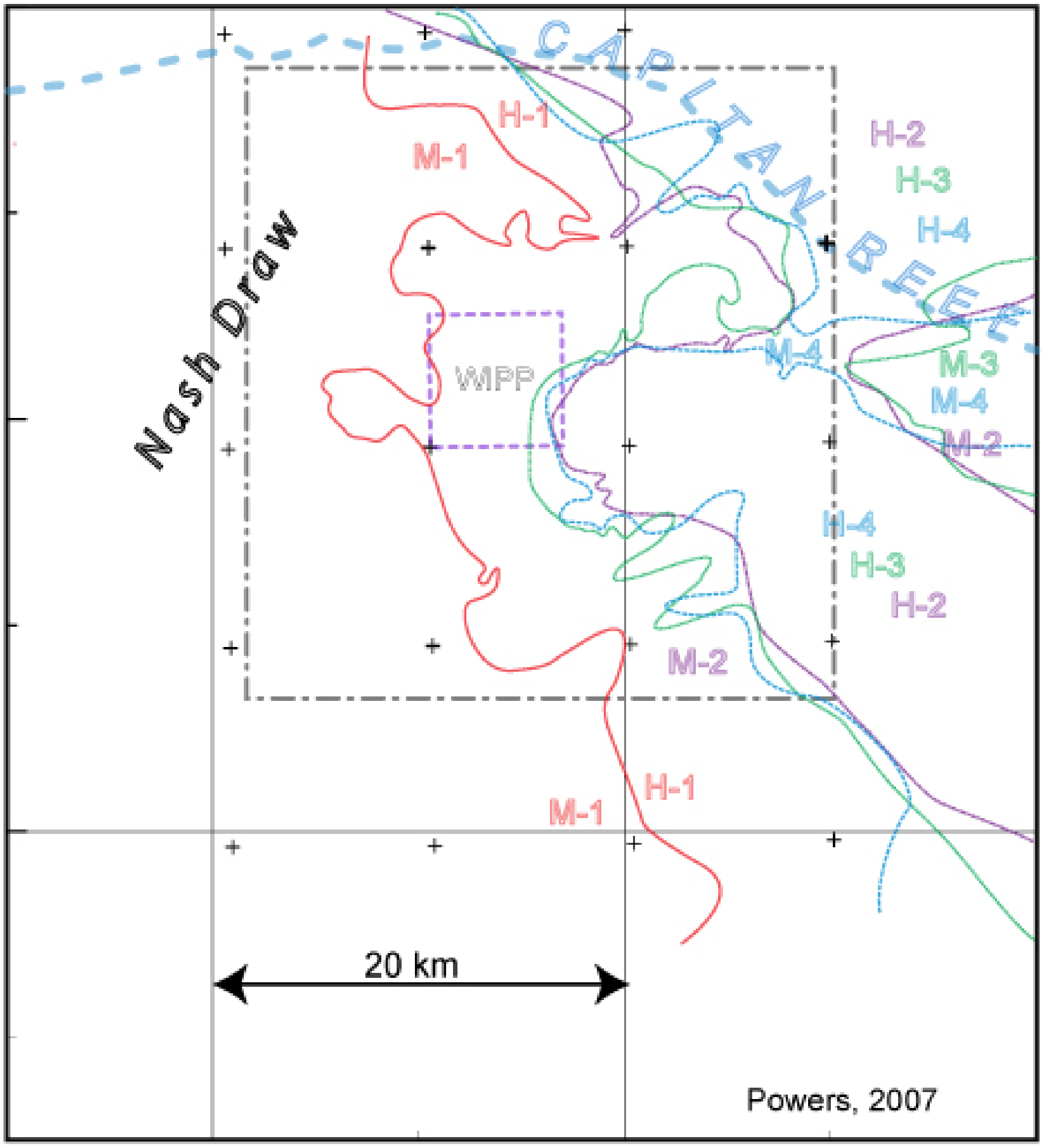

Figure 6. Composite of Rustler Halite Margins.

Halite margins are numbered as H-# (on side with halite) and M-# (on side without halite). The presence of halite, especially below and above the Culebra in the east, modifies the hydraulic character of the unit. See Figure 2 for informal stratigraphic unit designations and positions within the Rustler. Modified from Powers (2007).

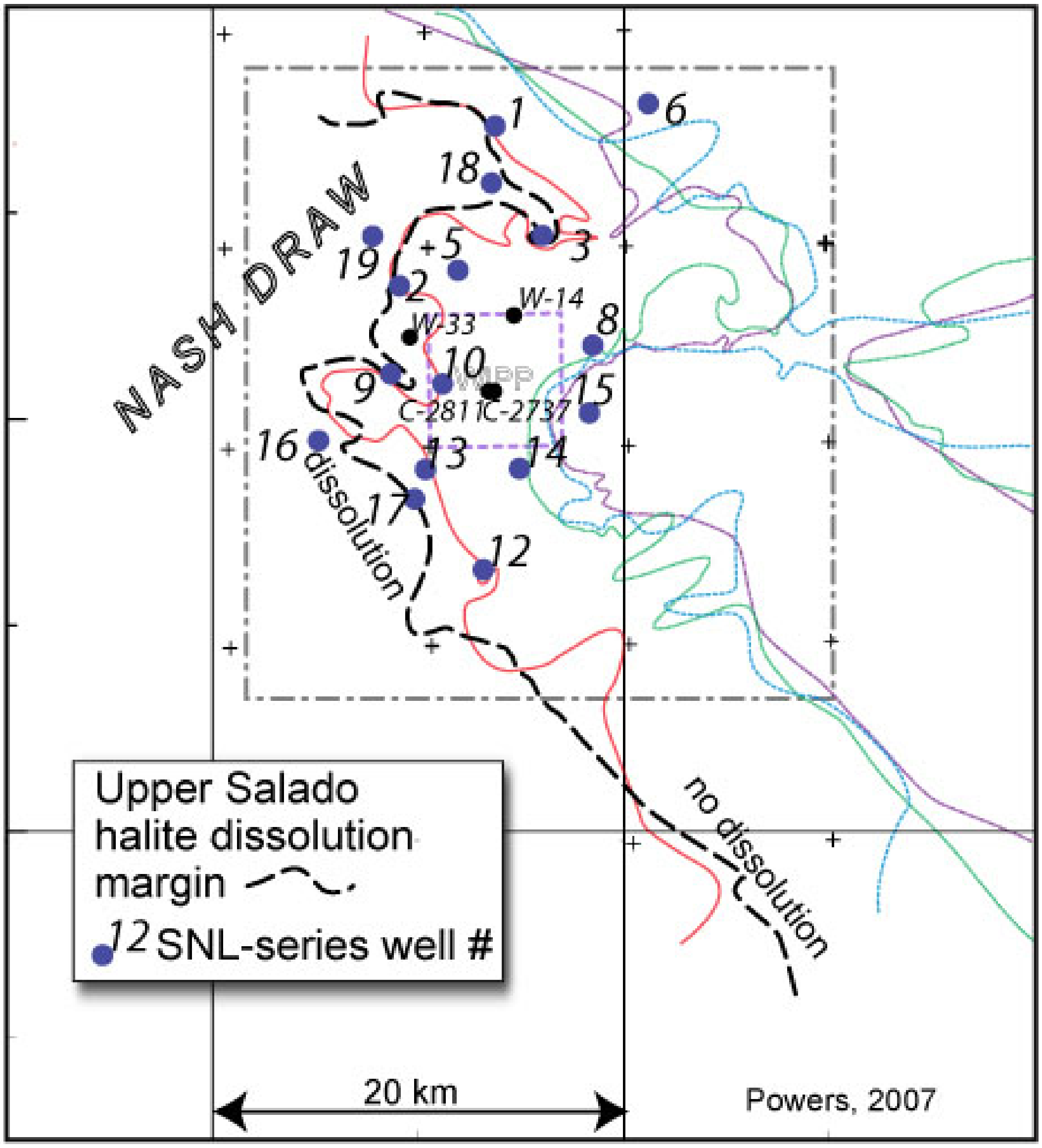

Figure 7. Location of SNL-series Wells and Selected Other Wells.

The locations have been plotted along with the upper Salado dissolution line (black dashes, see Figure 5) and each of the Rustler halite margins (see Figure 6). The "SNL" designator has been omitted for clarity. W-14 is WIPP 14, and W-33 is WIPP 33. Modified after Powers (2007).

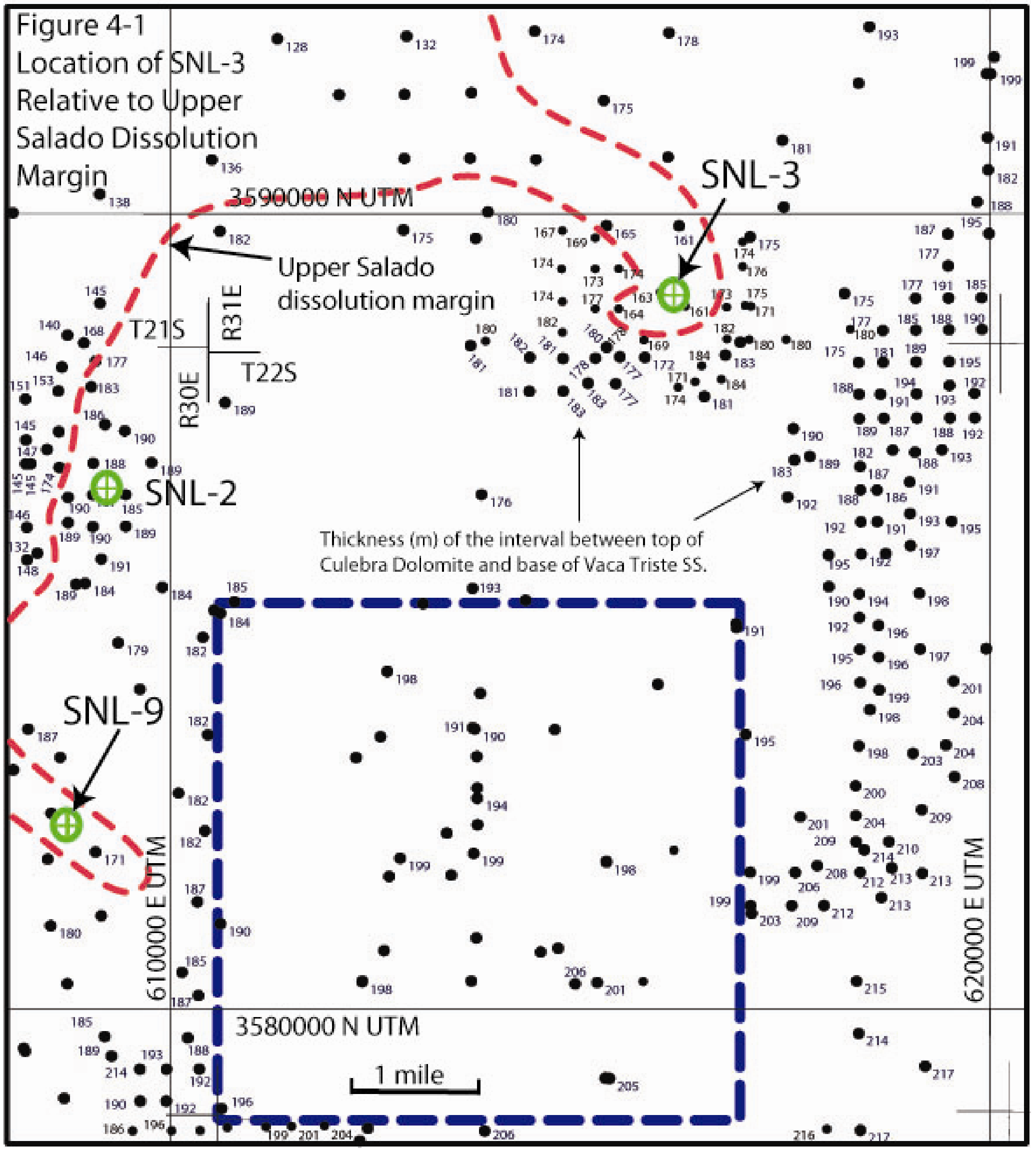

Figure 8. Location of SNL-3 and SNL-9 in Upper Salado Dissolution Margin "Re-entrants."

The two wells were located to test geology and hydrology properties in "re-entrants" to the dissolution margin defined partly on thickness of Vaca Triste to Culebra and partly on other factors. Figure 4-1 from Powers and Richardson (2004b), modified slightly to show location of SNL-9.

Figure 9. Core from Salado-Rustler Contact at SNL-3 and SNL-9.

These locations (Figure 8) were chosen to drill and test for upper Salado dissolution east of the margin along Livingston Ridge. The SNL-3 core (left) showed little or no disturbance or removal. While the SNL-9 core (right) above the contact shows minor disruption, the contact does not indicate much removal of upper Salado halite, if any. (Powers and Richardson, 2003b, 2004b)

Figure 10. Salado-Rustler Contact at SNL-12.

The thin-bedded or laminar sulfate that marks the top of the Salado is overlain by undisturbed, thin bedded sediments of the basal Rustler. There is no evidence of post-depositional dissolution along this contact. When SNL-12 was drilled and cored, the margin of upper Salado dissolution at this location was somewhat uncertain based solely on geophysical logs from oil and gas industry drilling. (see Powers and Richardson, 2004a)

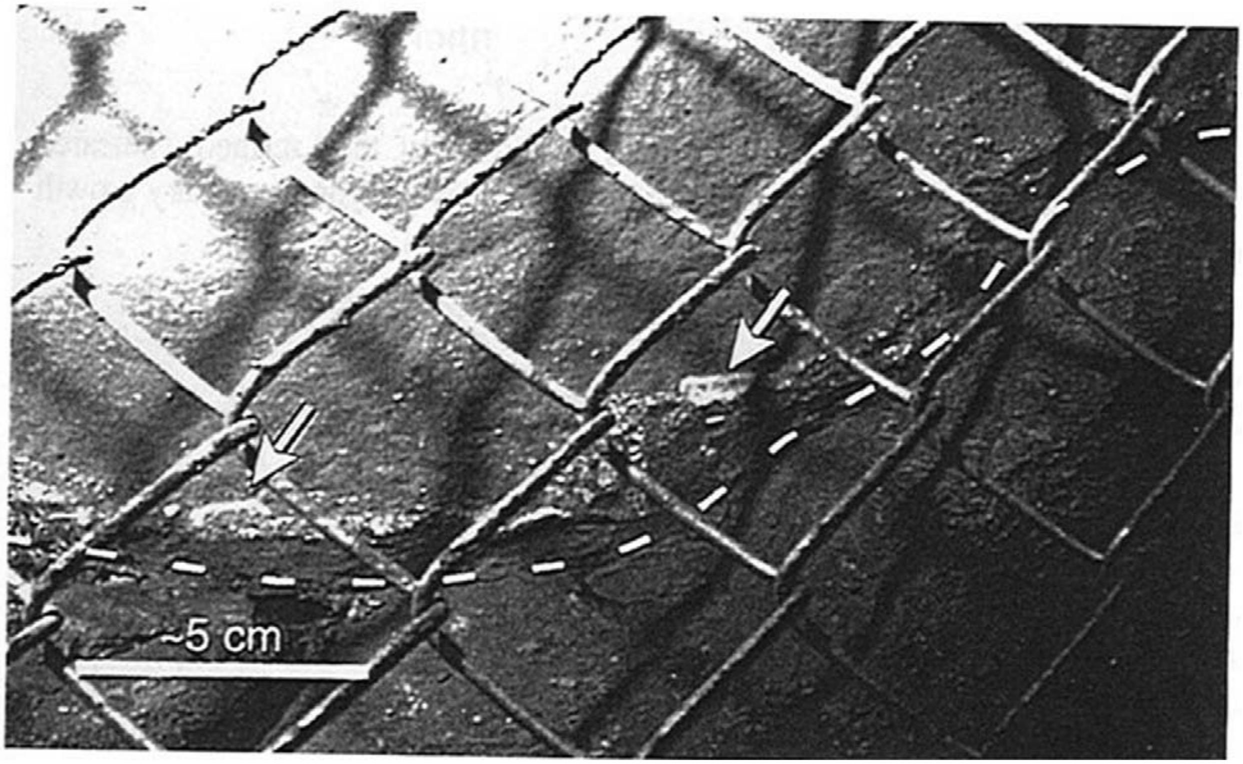

Figure 11. Channel Deposits with Fossil Clasts Near Base of Rustler in Waste Shaft.

Just above the undisturbed Salado-Rustler contact, these bedded deposits with fossil clasts (arrows) of unidentified bivalves show that the zone was deposited in a much lower salinity environment as marine water began to transgress across the giant salt pan than had formed the Salado. Despite early interpretations of a “dissolution wedge” at the contact across the site, the large-diameter (more than 20 ft) shafts revealed the true nature of the formation of these transitional rocks. (Holt and Powers, 1984; Powers and Holt, 2000)

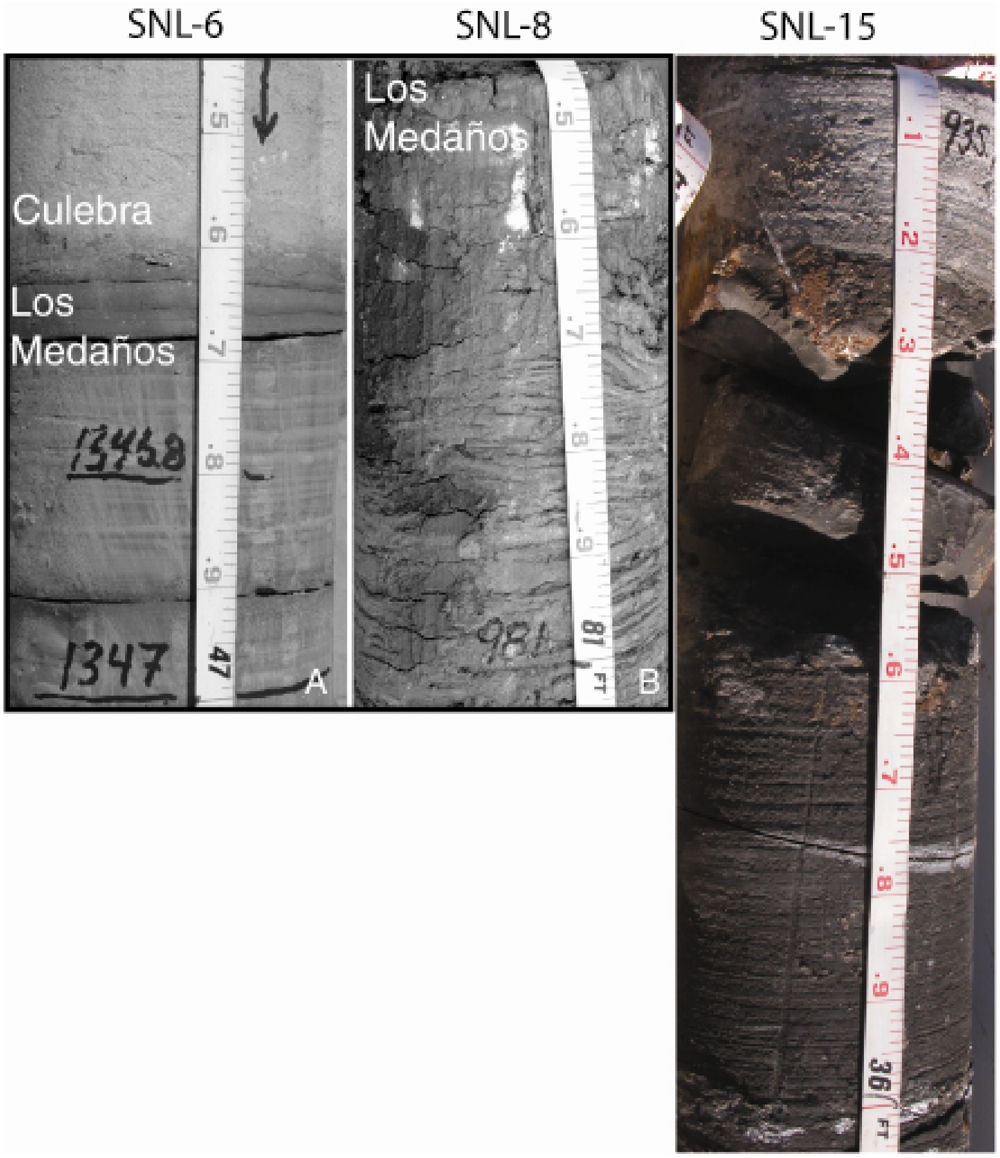

Figure 12. Gray Clay and Claystone Underlying Culebra at SNL-6, SNL-8, and SNL-15.

These three wells illustrate the very fine bedding and lamination of the clastic sediments across the basin as the transition occurred from a broad halite pan of M-2/H-2 into the near-normal shallow marine environment of the Culebra. The gray clay and underlying reddish-brown mudstones span the margins of H-2, showing continuity of the depositional relationships between the halite pan and mudflat tracts. Modified from Powers et al. (2006b).

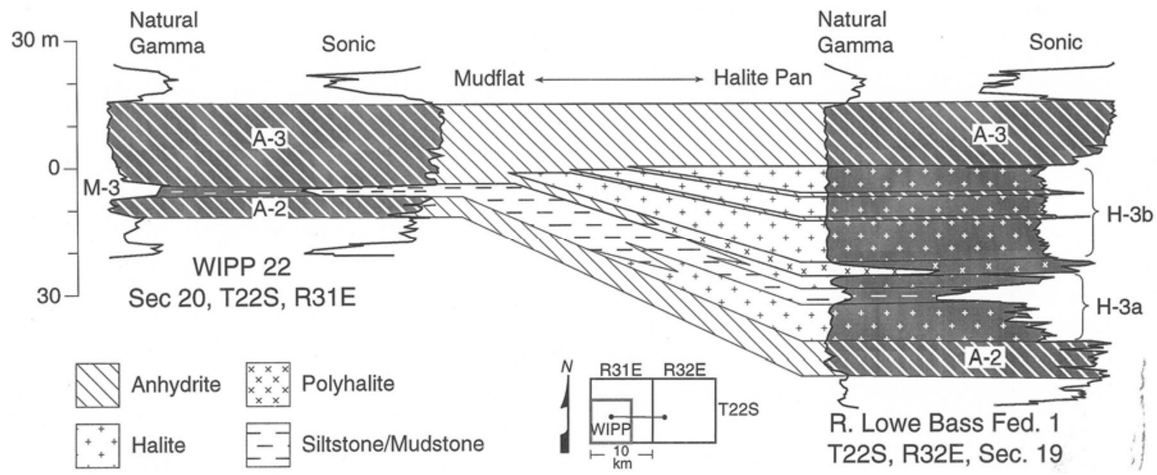

Figure 13. Halite Pan to Mudflat Facies Relationships from Geophysical Logs.

Along with the sedimentological evidence from shafts and cores across the WIPP site, abundant geophysical logs attest to the lateral relationships. M-3/H-3 is more striking than other units because of the greater lateral thickness and purity of the halite pan (H-3) deposits east of the WIPP site, as shown by R. Lowe Base Fed. 1 well in this example (Powers and Holt, 2000).

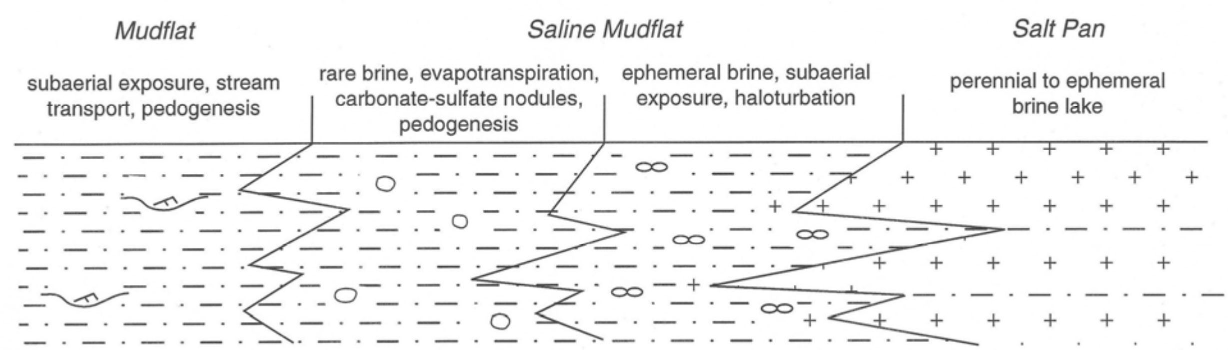

Figure 14. Lateral Depositional Environment Relationships and Rock Types (Facies).

The generalized “model” of halite pan deposits such as the M-#/H-# intervals shows lateral environments from high-salinity pan (right, east at the WIPP site) to the low-salinity exposed mudflat (left, west at the WIPP site) (Powers and Holt, 2000). Lateral environment changes always occur (the world is never just a beach, for example), and related lateral rock types are to be expected. These changes in the vicinity of the WIPP site are found in detailed sedimentological examination and analysis, and this did not occur during early investigations at the WIPP site.

Figure 15. Halite-filled Fracture from M-1/H-1 at SNL-2.

The lower halite pan deposits (H-1) extend farther west than other halite pan deposits of the Rustler near the WIPP site. Beyond the zone where halite is crystallizing from standing brine, the saline mudflat is affected by the brine at times by temporary enlargement of the brine pool or by evaporation from the exposed surface where brine or saline water has infiltrated laterally. During exposure, the mudflat may be affected by desiccation or thermal contraction to create separations or “fractures.” The aperture creates a lower fluid pressure zone and the brine migrates to the fracture, filling it with solutes, in this case halite. (see Powers and Richardson, 2003a)

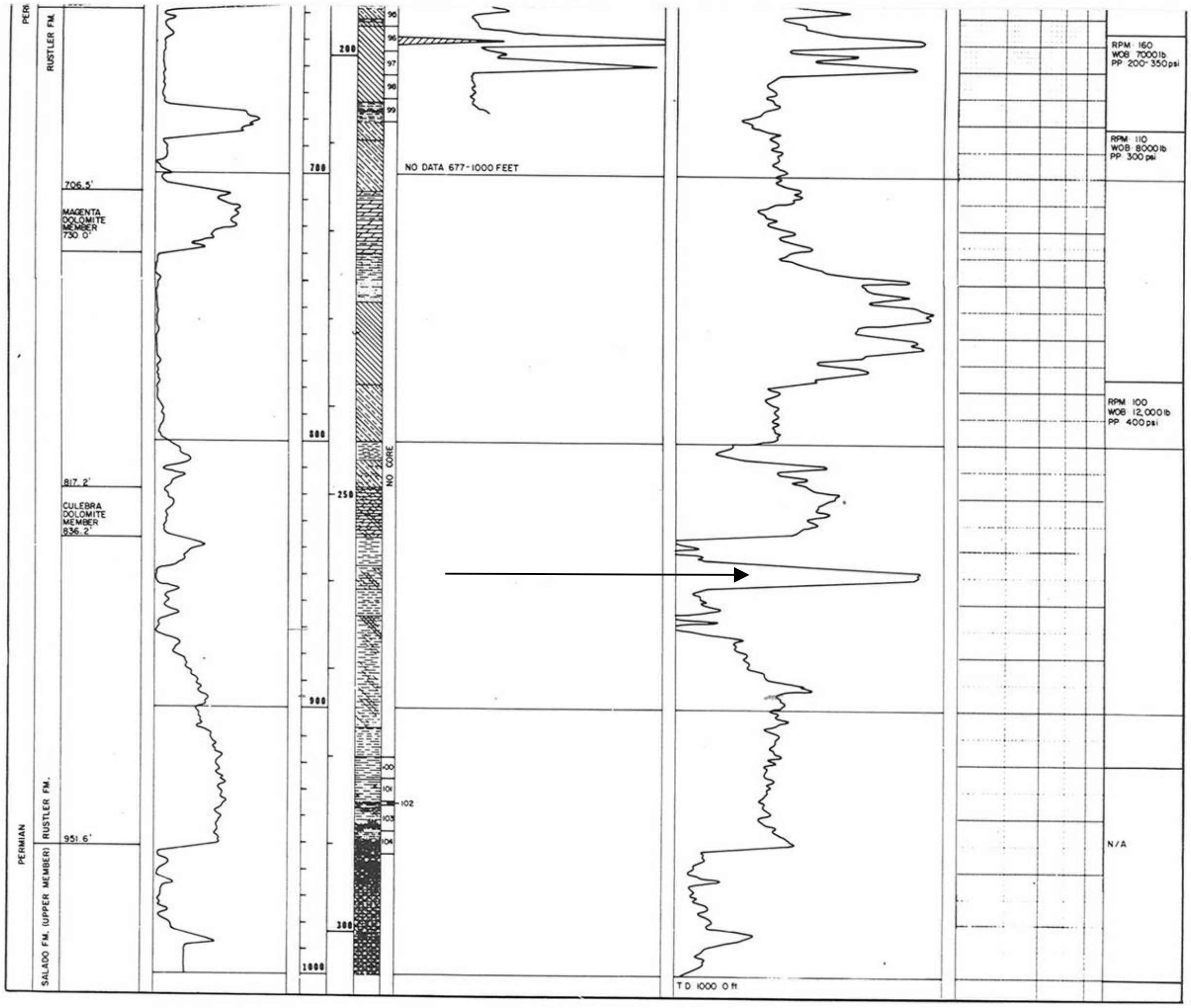

Figure 16 Geophysical Log of Rustler Formation at WIPP 14.

The geologic log of cuttings from WIPP 14 describes an interval below the Culebra as "mud" with color descriptors and other lithologies. It has been misinterpreted as evidence of cavern fill. A cuttings log represents an initial understanding of the geology encountered during drilling and is a valuable tool. Here it reflects the geology, but is somewhat limited by whatever factors occurred during drilling. The geophysical log of the well clearly shows the presence of A-1 (peak density at arrow) and other stratigraphic units of the interval, similar to other drillhole logs around WIPP 14. The stratigraphy is normal and not interrupted or destroyed by cave development. (Sandia National Laboratories and D'Appolonia Consulting Engineers, 1982; see also Lorenz, 2006)

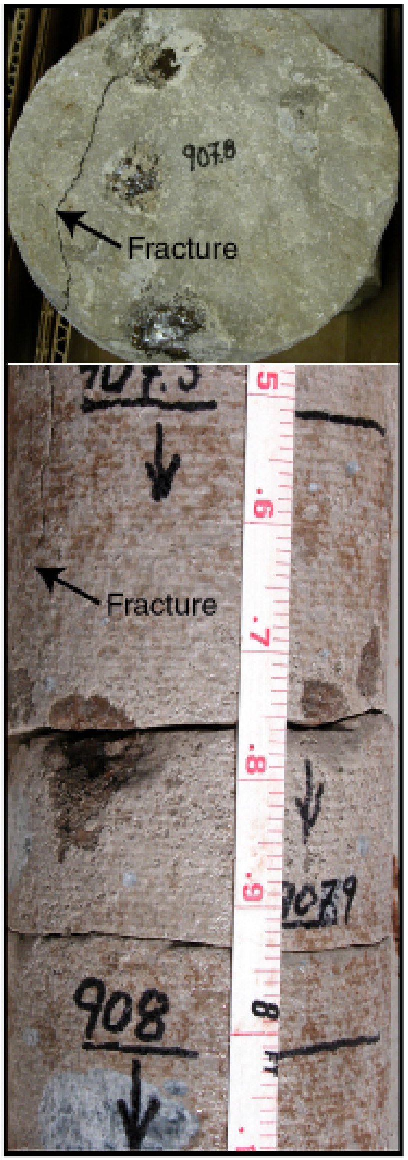

Figure 17. Halite-Filled Porosity in Culebra Dolomite at SNL-15.

The upper Los Medaños (H-2) and middle Tamarisk (H-3) halite beds are present at SNL-15, and porosity is filled with halite. Along the surface of the core (lower photo, arrow below 908), early (near time of deposition) vugs were created and filled by sulfate, which here is both anhydrite and some gypsum. Porosity is almost non-existent, brine seeps slowly into the well, and the fluid pressure is high because the salt beds transfer pressure of the rock column to the brine. The existence of such halite filling in the Culebra was predicted. (Powers et al, 2006b)

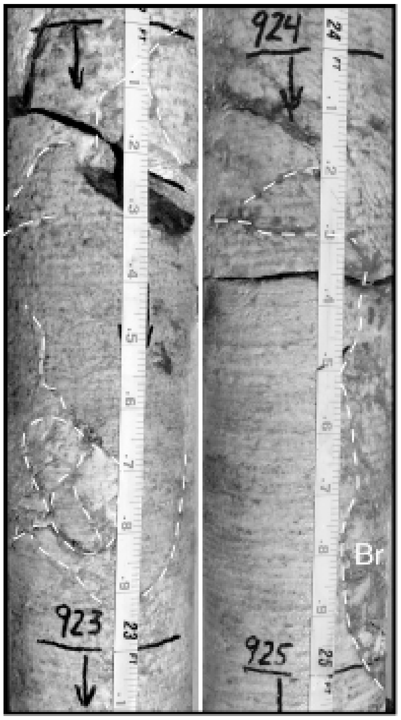

Figure 18. Fractured and Deformed Basal A-3 at SNL-8.

SNL-8 was drilled and cored near the margin of H-3 (see Figure 7) to test a zone near such a margin. The basal A-3 is disturbed and fractured; it is interpreted as indicating some post-depositional dissolution of H-3 in a narrow tract along the current margin. This tract is mainly in the southern part of WIPP and has been described in Holt and Powers (1988) and Beauheim and Holt (1990). (Powers et al., 2006b)

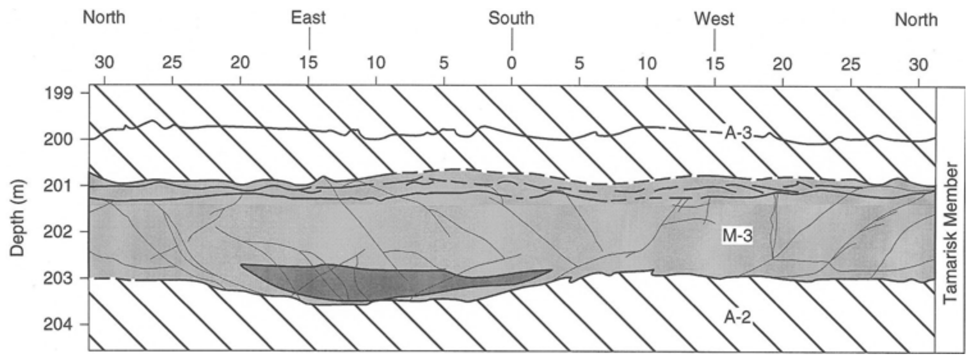

Figure 19. Map of M-3 (Tamarisk Member) at the WIPP Air Intake Shaft.

A-2, the anhydrite above the Culebra, has been removed by erosion at the Exhaust Shaft at the WIPP facility (Holt and Powers, 1986) and WIPP 19 (north of the WIPP site center) (Powers and Holt, 2000). The M-3 mudstones and conglomerates fill the channels. At the Air Intake Shaft, Holt and Powers (1990) found a lesser channel deposit that had eroded the surface of A-2 less than 2 ft. The map is a flat illustration of the 360 degree map around the large diameter (~20 ft) shaft, and the numbers at the top are the circumference in feet from a south line. (Holt and Powers, 1990)

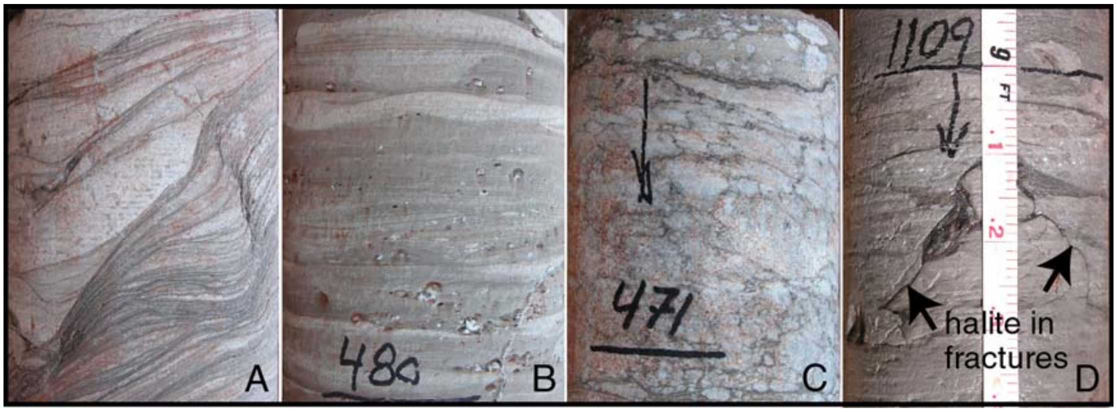

Figure 20. Sedimentological Features of Magenta Dolomite Member.

At the base of the Magenta, high-amplitude wavy bedding and hemisphoidal structures show that the sediment bottom hosted extensive algal growth (A, SNL-1). Lower amplitude wavy bedding and small cross-laminae are common in the middle of the Magenta, and even small gypsum clasts may be included (B, SNL-1). The upper Magenta across the site shows some increasing nodular gypsum to the west (C, SNL-1). Halite cements porosity in the Magenta where both H-3 and H-4 are present at SNL-6 (D). (Powers et al., 2006b)

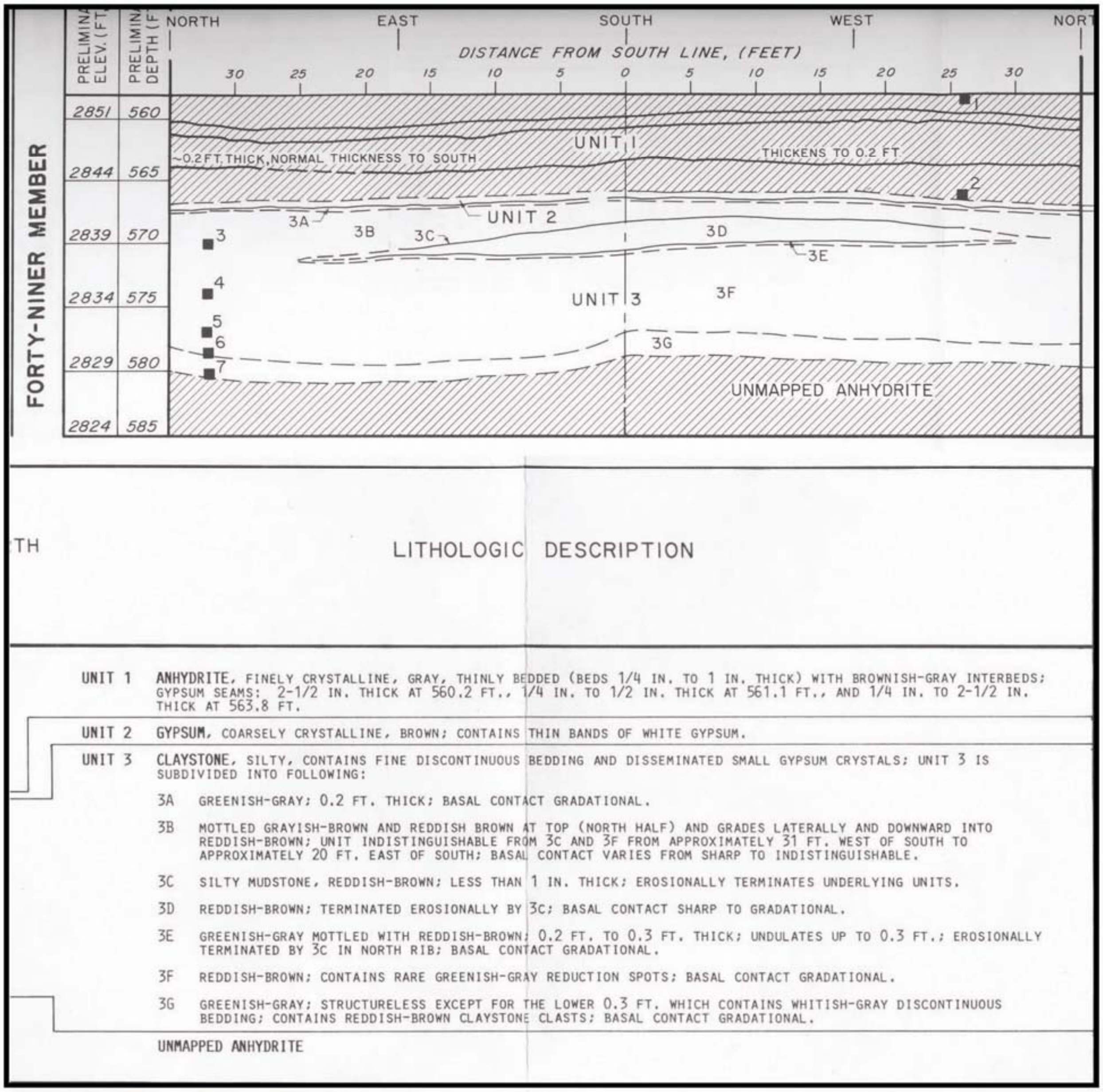

Figure 21. Map of M-4 at WIPP Waste Shaft.

In 1984, while mapping the Waste Shaft, Holt and Powers (1984) found well preserved sedimentary features in the uppermost mudstone unit of the Rustler. This contrasted with the common perception that these units were simply the residue after halite (known to be present to the east of the WIPP site) had been dissolved after the formation was deposited. This finding started the sedimentological study of the Rustler at the WIPP site that showed the evidence that halite in these beds is distributed mainly due to original depositional processes rather than by large-scale removal by dissolution at a later time. (Holt and Powers, 1984; Powers and Holt, 2008)