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EVALUATION OF KARST AT THE WIPP SITE

U. S. ENVIRONMENTAL PROTECTION AGENCY

Office of Radiation and Indoor Air

Center for the Waste Isolation Pilot Plant

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ACRONYM LIST

CARD	Citizens for Alternatives to Radioactive Dumping
CCA	Compliance Certification Application
CEM	Crosswell electromagnetic
CRA	Compliance Recertification Application
DC	Direct current
DOE	U.S. Department of Energy
DRZ	Disturbed rock zone
EM	Electromagnetic
EPA	U.S. Environmental Protection Agency
F	Frequency
LWA	Land Withdrawal Area
MT	Magnetotellurics
PA	Performance Assessment
SI	System International units
SNL	Sandia National Laboratories
SPDV	Site and Preliminary Design Validation
TDEM	Time Domain Electromagnetic Induction
TDS	Total dissolved solids
TEA	Trinity Engineering Associates
TRU	Transuranic
V	Velocity
W	Wavelength
WIPP	Waste Isolation Pilot Plant

EXECUTIVE SUMMARY

The Waste Isolation Pilot Plant (WIPP) is an underground facility for the permanent disposal of transuranic (TRU) defense-related waste, located at a remote site in southeastern New Mexico. The U.S. Department of Energy (DOE) operates the WIPP repository, with oversight by the U.S. Environmental Protection Agency (the Agency or EPA). A possible mechanism for release of radionuclides from the repository is the flow of contaminated brine up an intrusion borehole and into groundwater in an overlying formation. Modeling studies conducted by DOE and reviewed by the EPA have indicated that the Culebra member of the Rustler Formation is the most likely pathway for transport of radionuclides through groundwater under such a release scenario, although the potential effects of transport through the Magenta member of the Rustler Formation have also been included in performance assessment (PA) calculations.

EPA has previously addressed the issue of karst at WIPP, first during the 1991 WIPP Test Phase No Migration Variance determination, and second, during EPA's 1998 initial certification decision for WIPP. In both instances, EPA determined that karst will not impact the containment capabilities of WIPP. In EPA's 1998 certification decision, EPA reviewed existing information to understand the issue of karst around the WIPP site. As a result of that review, EPA concluded that, although it is possible that dissolution has occurred in the vicinity of the WIPP site sometime in the past (e.g., Nash Draw was formed ~500,000 years ago), dissolution is not an ongoing, pervasive process at the WIPP site.

Following the 1998 certification decision, several groups challenged EPA's decision in the United States Court of Appeals for the District of Columbia Circuit (No. 98-1322). One of the issues in this lawsuit was EPA's conclusions regarding karst at the WIPP site. The petitioners argued that EPA denied and ignored evidence of karst features at WIPP, and failed to address public comments regarding karst. On June 28, 1999, the U.S. Court of Appeals upheld all aspects of EPA's 1998 certification decision, including EPA's conclusion that karst is not a feature that will likely impact the containment capabilities of the WIPP.

During EPA's recertification process, commenters again raised questions regarding the potential formation of karst in the Culebra or Magenta and whether preferential groundwater pathways could exist or develop that could affect groundwater transport of radionuclides from the repository. Some comments proposed using a proprietary magnetotellurics (MT) technology, called Z-SCAN, to search for karst at the WIPP site.

Although the Agency addressed many of the same comments in the Response to Comments document (EPA 1998b), including general karst at WIPP, karst at WIPP-14 and other wells, and the relevance of Nash Draw, this report provides additional discussion on a number of topics discussed previously by EPA and responds to some new interpretations of the old information.

For the WIPP recertification evaluation, the Agency has re-evaluated the available evidence related to whether karst exists or could form at the WIPP site and provide preferential groundwater transport pathways for the release of radionuclides. This evaluation consisted of:

- A renewed review of the data available at the time of the CCA

- An examination of magnetotellurics, and other geophysical methods capabilities to detect karst in the Magenta or Culebra units at the WIPP site (Section 4.0)
- Development of a conceptual model of groundwater flow in the Magenta and Culebra units at the WIPP site (Section 5.0)
- Comparison of the conceptual model to the conceptual models of Snow 1998, and Hill 1999 (Section 6.0)

After careful review of the available information, EPA concludes that dissolution may have occurred in the immediate vicinity of WIPP-33. There is, however, no evidence, that dissolution is pervasive, wide spread, or has led to connected groundwater pathways, such as "underground rivers" as noted by the stakeholders. From the perspective of performance assessment, this lack of interconnection between localized dissolution features will render any effects on travel times insignificant. If, in fact, point recharge is occurring, the effects have already been taken into account in hydraulic gradients measured in the Culebra and used in the WIPP performance assessment calculations.

The data indicate to EPA that Nash Draw and the WIPP site are almost two separate hydrologic systems under the current climate, have been that way for some time, and are expected to remain relatively independent into the future. Precipitation events at the WIPP do not significantly recharge the underlying units and lack of runoff does not indicate karst below. Any significant recharge to geologic units at the WIPP site appears to be the result of distal processes and/or from infiltration that takes thousands of years to reach the Rustler Formation. Precipitation events in Nash Draw may result in noticeable effects in Nash Draw, but provide little information about the WIPP site itself or the ability of WIPP to contain radionuclides.

Our review reaffirms our original certification decision that karst processes are not active at the WIPP site, and that karst processes will not affect containment of radionuclides at the WIPP site now or during the regulatory time period for 10,000 years.

1.0 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is an underground facility designed for the permanent disposal of transuranic (TRU) defense-related waste, located at a remote site in southeastern New Mexico. The U.S. Department of Energy (DOE) operates the WIPP repository and the U.S. Environmental Protection Agency (the Agency or EPA) reviews information related to WIPP and certifies that WIPP complies with federal regulations. DOE submitted the Compliance Certification Application (CCA) to the Agency in 1996. The Agency reviewed the CCA and supplemental information provided by DOE and certified that DOE had met federal regulatory requirements for disposal in May 1998, and DOE began accepting waste at WIPP in March 1999.

The WIPP Land Withdrawal Act (WIPP LWA), requires DOE to submit a Compliance Recertification Application (CRA) every 5 years after the initial receipt of waste at WIPP. The first CRA was submitted to the Agency in March 2004 (DOE 2004). The CCA and the CRA are required to include a current description of natural and engineered features at the WIPP site that may affect the performance of the disposal system, including the hydrogeology of the disposal system (40 CFR 194.14(a)). Information regarding the presence and characteristics of potential transport pathways, including solution features, is required to be included in the CRA. In the CRA, DOE is required to provide updated information to the Agency to allow for a determination of whether the WIPP site remains in compliance, including any new hydrologic or hydrogeologic information (40 CFR 194.15(a)).

Releases of radionuclides to the accessible environment must be limited by the WIPP disposal system for 10,000 years (40 CFR 191.13). Releases of radionuclides from the undisturbed repository to the accessible environment are not predicted to be significant during this time period (DOE 2004, Section 6.0.2.2; Leigh et al. 2005, Section 4.2). However, human activities that disturb the underground repository could cause radionuclide releases during the repository performance period under some conditions. DOE therefore carried out performance assessment (PA) modeling to determine the likelihood of significant releases of radionuclides caused by human activities.

One of the possible mechanisms for release of radionuclides from the repository is the flow of contaminated brine up an intrusion borehole and into an overlying formation. Because the Culebra is the most transmissive unit above the repository, it is the most likely pathway for subsurface transport of radionuclides if they are released from the repository (DOE 2004, Section 6.0.2.3.5). However, flow up the borehole is allowed to enter into the Magenta member of the Rustler Formation and into other overlying units. These additional units are parameterized toward the low end of the permeability ranges in order to maximize flow into the Culebra and potential releases (DOE 2004, Section 6.4.6).

DOE did not account for the possible effects of karst on transport in the Magenta or Culebra, because DOE found no evidence that karst exists at the WIPP repository. In their CCA decision, the Agency acknowledged that karst terrain is present in areas near the WIPP site boundary (EPA 1997). However, after examining the available data and public comments, the Agency concluded that karst features are not pervasive over the disposal system and are not associated with any identified preferential groundwater flow paths or anomalies in the Magenta or Culebra members of the Rustler Formation above the WIPP site. Since the CCA, questions have been raised related to the hydrology of the Rustler Formation, in particular the Culebra and Magenta. Snow 1998 and Hill 1999 evaluated the site and stated that there may be indirect evidence of karst dissolution features in and above the Culebra at the WIPP site and that these karst features could lead to unacceptable releases of radionuclides. In addition, some comments proposed to the Agency that a proprietary, Z-SCAN magnetotelluric remote sensing technique be employed to find karst at WIPP (CARD 2004).

The Agency evaluated evidence regarding the possible existence of karst over the WIPP disposal system. This evaluation included a review of data obtained prior to the CCA (Section 2.0) and of karst processes (Section 3.0). The proposed use of Z-SCAN for detecting karst at the WIPP site was reviewed, and other potential methods for detecting karst were also evaluated (Section 4.0). A conceptual model of hydrologic processes at the site was developed (Section 5.0), and other WIPP site conceptual models were reviewed (Section 6.0). After reviewing the available information, the Agency concluded that dissolution may have occurred in the immediate vicinity of WIPP-33. There is no evidence, however, that dissolution is pervasive or has led to connected groundwater pathways (e.g., “underground rivers”). From the perspective of performance assessment, this lack of interconnection between localized dissolution features will render any effects on travel times insignificant. If, in fact, point recharge is occurring, the effects have already been taken into account in hydraulic gradients measured in the Culebra and used in the WIPP PA and modification to transmissivitiy values as a result of assumed mining at WIPP.

2.0 COMPLIANCE CERTIFICATION APPLICATION DATA AND INTERPRETATION

DOE summarized information related to the potential formation of karst at the WIPP site that was available at the time of the CCA (DOE 1996, Section 2.1.6.2 and Appendix DEF). DOE recognized that karst could be important because of its potential effects on the hydrogeology of units overlying the repository. The geomorphology of the region surrounding the WIPP site was recognized to be influenced by karst processes, particularly in karst areas of Nash Draw (DOE 1996, Appendix DEF). Bachman 1981 summarized information related to the development of karst in the region.

A 1980 gravity survey at the site identified a number of gravity anomalies that Barrows et al. 1983 interpreted as possible evidence of karst at the WIPP site. A 0.6 milligal negative anomaly with a double half-width of 900 ft was observed. Barrows interpreted and proposed that this anomaly was due to density alterations in the vicinity of karst channels. In their evaluation of the Barrows interpretation, the Environmental Evaluation Group (EEG) concluded that "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 interpretations offered by Barrows and co-workers and to provide alternative interpretations, if feasible." EEG also made the observation that "the gravity interpretations are inherently ambiguous" (Chaturvedi and Channell 1985). However, the interpretation of karst did not account for other potential causes of the gravity anomalies, and a well drilled at the site of one low-gravity anomaly (WIPP-14) revealed normal stratigraphy through the zones proposed to be affected by karst (DOE 1996, Section 2.1.6.2.1).

A study carried out by LeGrand and reported by Chaturvedi and Channel 1985 concluded that near-surface karst features had developed in Nash Draw, but that there were no significant karst features in areas east of Nash Draw, including the WIPP site. Bachman 1985 re-examined the evidence related to karst in the vicinity of WIPP. In that study, although evidence of halite and gypsum dissolution were found at WIPP-33 west of the WIPP site, no evidence was found of significant karst (e.g., "underground rivers" as claimed by stakeholders) development at the WIPP site. From the available evidence, DOE 1996 therefore concluded that karst development in units above the repository that could affect repository performance would not occur over the regulatory time frame.

The Agency reviewed the information related to the existence of karst as presented by DOE in the CCA (EPA 1997 and 1998b) and also reviewed comments by stakeholders regarding karst at the WIPP site (EPA 1998a). The Agency acknowledged that karst terrain is present in the vicinity of the WIPP site and that dissolution-related features may occur in the immediate WIPP area, for example, at WIPP-33. However, the Agency concluded that these dissolution features are not associated with preferential groundwater flow paths, and cited the results of groundwater tracer tests as evidence (EPA 1997).

The Agency also reviewed information related to the possible development of karst at WIPP during the 10,000 year regulatory period (EPA 1997 and 1998b). The Agency observed that the Mescalero Caliche is relatively pervasive over the WIPP site. Because caliche only develops in arid areas with relatively little recharge, the presence of the Mescalero Caliche indicates that there has been an arid climate and very low recharge conditions over a long period of time at the WIPP site. The presence of the caliche, combined with DOE's future precipitation assumptions, led the Agency to conclude that the development of karst features has not been pervasive and will not impact the containment capabilities of the WIPP during the 10,000 year regulatory period (EPA 1997, 1998a, 1998b).

The Agency addressed many additional comments in the Response to Comments document (EPA 1998b), including most of the general topics discussed in this document, such as general karst at WIPP, karst at WIPP-14 and other wells, and the relevance of Nash Draw. This report provides additional discussion on a number of topics discussed previously by EPA and responds to some new interpretations of the old information. EPA finds that the evidence for the lack of pervasive karst at WIPP is even stronger today than at the time of EPA's 1998 certification decision. In fact EPA finds many of the arguments for karst put forward by the stakeholders to be unsupported by data and often inconsistent.

3.0 DESCRIPTION OF KARST PROCESSES

In regions of carbonate rocks and evaporites, weathering and erosion produce unique landforms called karst or karst topography. Karstification (the processes of producing karst) and karst are defined by Jennings 1971 as "terrain (and associated processes) with distinctive characteristics of relief and drainage arising primarily from a higher degree of rock solubility in natural water than is found elsewhere."

This definition of karst stresses that distinctive landforms and other surface characteristics develop on highly soluble rocks, and that a unique type of drainage pattern results from karst processes. Because most rocks are soluble to some extent, karst will develop only on those rocks that are particularly susceptible to dissolution. The dissolution process can create and enlarge cavities within the rocks, leading to the progressive integration of voids beneath the surface. These interconnected voids allow for large amounts of water to be funneled into an underground drainage system, disrupting the pattern of surface flow. The physical surface and groundwater hydrologic system coexist with the chemical dissolution processes; as each part of the physical and chemical process progresses, pronounced groundwater circulation increases and the surface streams become a poorly developed surface network. At maturity, a karst surface terrain is literally "a bleak and waterless place" (Monroe 1969) characterized by irregular topography containing many closed depressions and interrupted streams.

In the region around WIPP, Nash Draw is a feature that is derived by erosion and dissolution processes that have removed the evaporite beds (Bachman, 1985). Nash Draw contains caves and collapse sinks that are indicative of karst processes (Figure 3-1). In addition, aerial photography of Nash Draw shows diverted drainage and vanishing streams. In contrast, locations around the WIPP site show no similar types of features (Figure 3-2).

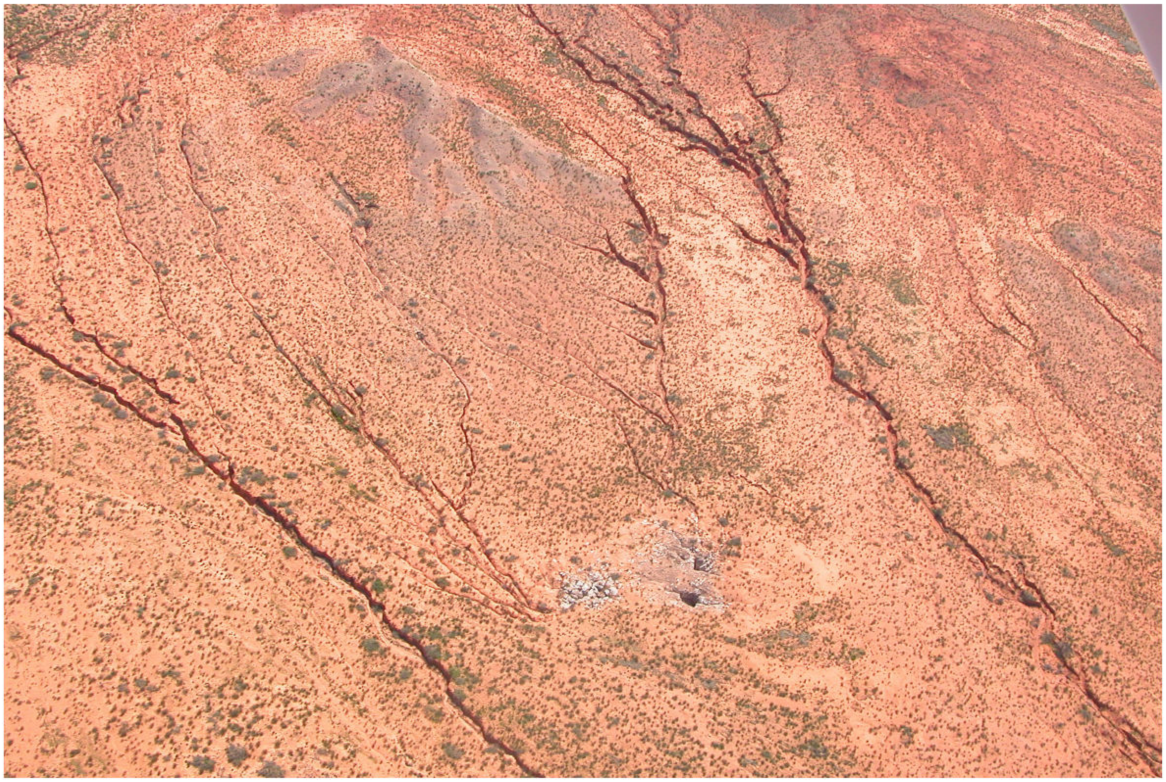

Figure 3-1. Low-Angle Aerial Photograph of Nash Draw

Note: Diverted drainage, vanishing streams, and the open sinkholes that capture them, in the Forty-niner Member of the Rustler Formation exposed in Nash Draw (Lorenz 2005).

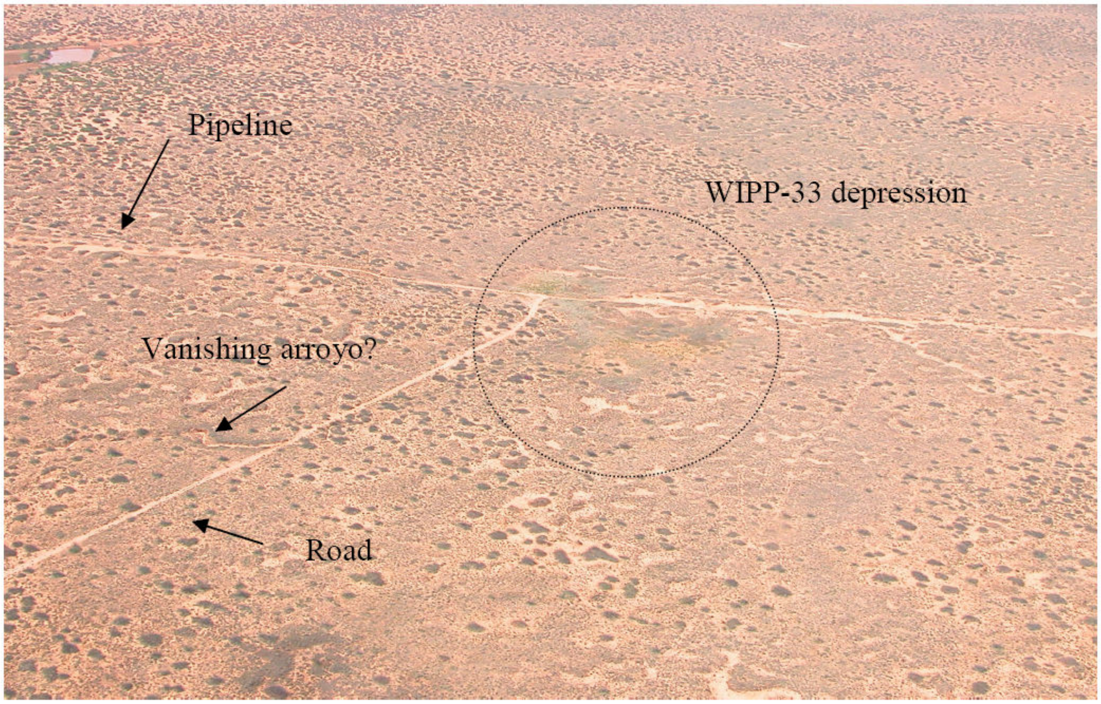

Figure 3-2. Low-Angle Aerial Photograph of the Area in the Vicinity of Drillhole WIPP-33

(Source: Lorenz 2005)

Note: Drillhole WIPP-33 is located at the junction of the east-west road and the pipeline. Note the absence of well-defined drainages entering the area, as compared to Figure 3-1.

4.0 METHODS FOR DETECTING KARST AT THE WIPP SITE

Stakeholders have proposed that geophysical methods be used to search for karst at the WIPP site. Gravity surveys, magnetic surveys, and Time Domain Electromagnetics Induction (TDEM) methods are unlikely to be useful for detecting karst in the Magenta or Culebra because these tools would not provide adequate resolution for karst definition. Seismic reflection methods cannot be used to search for or resolve karst in the Magenta or Culebra at WIPP, because the size of the karst voids would be much smaller than the limits of resolution. Subsurface geophysical methods, such as crosswell seismic studies or Crosswell Electromagnetics (CEM) similarly lack the required resolution for detecting karst voids in the Magenta or Culebra at the WIPP site. Magnetotelluric methods for detecting karst at WIPP have also been considered and found to be unsuitable for this purpose because of a lack of the necessary resolution at the depths of the Magenta and Culebra.

A variety of geophysical techniques have been used in the past as part of the site characterization activities at the WIPP site. Stakeholders proposed the detection of karst features in the Rustler Formation (i.e., Magenta and Culebra) by using the Z-SCAN magnetotelluric interpretation technology to detect large-scale karst voids above the WIPP site (CARD 2004). EPA evaluated the potential use of magnetotellurics to map the possible presence of karst features in the Magenta and/or Culebra members of the Rustler formation. The EPA also examined other potential geophysical methods that might be used to detect large-scale karst features in the Magenta or Culebra units were also assessed, including the use of gravity surveys, magnetic surveys, Time Domain Electromagnetics Induction, seismic reflection techniques, subsurface reflection seismic techniques, and subsurface electromagnetic techniques.

Geophysical methods can be used to detect anomalies, or changes, in rock formations. These anomalies help identify variations in characteristics of the rocks. However, geophysical techniques can be ambiguous and open to interpretation. Thus, it is often difficult to get agreement in interpretation of field data by different observers and to reach a conclusive correlation between the field data and in situ geological characteristics of the rock formation.

Geophysical techniques require a sharp and noticeable contrast in physical properties between the host rock and the target to distinguish the recorded signals clearly. The contrast in rock properties for various geophysical methods are related to changes in electrical conductivity (which is the inverse of rock resistivity), rock density, elasticity, and magnetism depending on the geophysical technique used. Conclusive and reliable detection of a target feature, such as a karst void or mineral ore body, is dependent on the position, orientation, dimension of the target and its surroundings. These techniques, if applicable in a given geological situation, can be used for detection of subsurface features. The Rustler Formation at the WIPP, which is the expected host rock for any potential karst in the vicinity, is composed of halite, anhydrite/gypsum, dolomite, and siltstone. Geophysical properties of these rocks are non-uniform and vary both in vertical and horizontal directions at the WIPP.

Geophysical survey methods using electrical (resistivity), acoustical, gravitational (density), or magnetic properties can be used to detect subsurface features. Structures or features in the subsurface can be identified by mapping, analyzing, and modeling geophysical survey data. The depth of investigation (how deep a geophysical tool can measure) and the resolution (how well a tool can measure a subsurface feature or see details of a feature) can depend on a number of factors, including the types of rocks and minerals present, the power of the recording equipment, and the variations of rock properties or contrast.

In an ideal situation, the target of the investigation would be homogeneous within a sharply contrasting rock medium. A sharp contrast in physical properties between the host rocks and the target helps to separate the recorded signals and improve the consistency of interpretations. It is also desirable that masking layers in the overburden, above the target zone, be absent. For the present analysis, the geophysical methods should be capable of detecting brine-filled voids (karst) a few feet in cross-section within the Culebra and Magenta members of the Rustler Formation at a depth of 700 to 1,000 ft from the surface. The Rustler Formation is lithologically complex. Thus, the physical properties in the Rustler Formation vary significantly, both laterally and vertically, which could complicate interpretation of geophysical data.

4.1 Magnetotelluric Methods

Stakeholders have proposed that the Z-SCAN magnetotelluric method (MT) be used to attempt to detect karst features in the Magenta and Culebra members of the Rustler Formation. The MT method is a passive surface geophysical technique in which the earth's natural electromagnetic field is measured to investigate the electrical resistivity structure or changes of the subsurface. The basic theory of this method was first proposed by Caginard in 1953. Dobrin 1960, in explaining the technique, stated that "the magnetic fields induced by the alterations in earth currents would be measured simultaneously with the voltage fluctuations between electrodes at the surface. The ratio between the amplitudes of these alternating voltages and then associated magnetic fields would be plotted as a function of frequency. Caginard's theory could be applied to this plot so that the resistivity would be deduced as a function of depth."

Stakeholders have suggested that the size of the karst features likely to affect groundwater flow in the Culebra or Magenta above the WIPP site would be on the order of 3 ft in height and several feet in width, and would be found at depths ranging from approximately 590 ft to 700 ft. Determining the presence of features of this size and at these depths is a difficult geophysical problem. Electrical or electromagnetic (EM) techniques could be used to discern changes in resistivity associated with the presence of karst voids. Because the karst voids are expected to be filled with brine and are present in a fairly resistive host rock, the objective would be to map a conductive target within a resistive background. An ideal geoelectrical environment would be required to confirm detection of karst features using the MT method.

MT requires both magnetic and electrical field components. The main difficulty associated with this process is recording the magnetic field, because this requires prolonged recording instrument setup time using complex equipment. Apart from the longer setup time, the magnetic signals require more time to record than the telluric recordings. To mitigate these difficulties, Hermance and Thayer 1975 proposed a modification that involves making field- and base-station measurements simultaneously.

In addition to complexities associated with field measurements, other problems hinder achievement of a uniform and reliable interpretation of a geological target. A non-uniform geological structure, much like the variation in the Rustler, can distort the electrical current flow and create anomalies in the field measurements (Telford et al. 1995). One-dimensional, uniform, and isotropic and horizontal layers are generally easier to interpret. It is more difficult to interpret two- and three-dimensional features, such as tabular geometries, faults, and veins. “Apart from features with pronounced symmetry like the sphere and ellipsoid, no entirely successful interpretation procedures have been developed to date” (Telford et al. 1995).

Variation in geoelectrical properties of the rock formations in the upper part of the overburden (Upper Ochoan, Dockum and recent formations) can cause “static shift.” These are vertical displacements of the apparent resistivity sounding curves, between adjacent sites or between two curves at one site. This shift is caused by the electrical field generated from boundary charges on surficial inhomogeneities, severely distorting the recorded data and misleading interpretations of the data, making it difficult to locat the target zone. Closely spaced sampling can reduce or eliminate the effect of static shift (Vozoff 1991). However, extremely dense sampling, in addition to increase in operational cost may also create logistical and interpretational difficulties.

Identification of very large karst features can be well-suited to electromagnetic geophysical methods. Geophysical methods, however, measure the contrasts in rock properties and this, to a large extent, depends upon geology, porosity, permeability, and fluid characteristics and contents in the pores of the rocks (see paragraph below). Although targets with larger dimensions will provide more prominent and detectable signals than smaller targets, the most critical factor is the contrast in properties. It is not very clear what degree of contrast we can expect between dolomite and features created by dissolution. Due to the specific characteristics of the WIPP site, detection of the features at the size and depths of interest is beyond the resolution of any known electromagnetic geophysical tools. This is both because the feature (karst void) is too small to be mapped, or “seen” at Magenta and Culebra depths and that the contrast between rock and karst properties is not significant at the relevant depths. The following modeling studies and analyses were carried out to support this conclusion.

4.1.1 Resolution of Magnetotellurics

Magnetotellurics (MT) is a geophysical technique that measures naturally occurring changes in the earth’s electric and magnetic fields. It does so by recording orthogonal components of the electric and magnetic fields at a surface location over time. These data are processed to obtain values of apparent resistivity as a function of frequency. The different frequencies of electromagnetic waves penetrate the earth and provide information at various depths. Further analysis of the data results in estimates of true subsurface resistivity as a function of depth from the surface.

The MT method has inherently lower resolution than seismic methods and is typically used where seismic methods are not cost efficient. In general, MT methods are primarily used as reconnaissance tools prior to deployment of more expensive seismic exploration. Xiao (2004), stated in the conclusion of his study related to “ Magnetotelluric Exploration in the Rocky Mountain Foothills, Alberta” that “while MT cannot image detailed structure in the same detail as seismic reflection, it can image the structural style and work as a reconnaissance tool in exploration”.

The resolution power of MT depends on the depth to the target, the thickness and resistivity of the target, and the overall resistivity of the host, particularly above the target. Longer wavelengths with lower frequencies penetrate deeper; consequently, the resolution power of MT decreases with depth because longer wavelengths have less ability to map thinner features. A higher-resistivity background, host rock, allows waves to penetrate deeper, longer wavelengths, longer waves, can "see" deeper features as the resistivity of the rocks is increased, but with lower resolution.

MT resolution also depends on the quality of the data. State-of-the-art MT data acquisition and processing can be used to achieve high-quality data, but the associated error is still usually a percent or more and noise (i.e., environmental and anthropogenic) can decrease the quality of the data. Most of the noise found in MT data comes from anthropogenic (man-made) sources, such as power lines and pipelines. These sources create artificial electromagnetic fields that can be much stronger than the naturally occurring MT signal of interest. It is not always possible to avoid noise at all recording stations and at all times. Other sources of noise can also interfere and degrade the recorded signal, as was pointed out by Telford et al. 1995, which states, "The coil is a critical component in MT work. Generally it is necessary to install it in a shallow trench, because very slight motions create noise voltages, particularly troublesome in wooded areas."

4.1.2 Resistivity Characterization of Karst

Resistivity to an electric or magnetic field is a property that can be measured for any material, and is a measure of that material's opposition to the flow of electrical current. The inverse of resistivity is conductivity. The resistivity of rocks varies over orders of magnitudes (over powers of ten). Measurement of resistivity from the earth's surface can provide estimates of the subsurface rock types at various depths. Inferences can also be made about other properties of these rocks, such as porosity and pore fluid. For example, resistivity can provide information to determine if rock pores are filled with water (normally conductive) versus oil or gas (normally very resistive).

A karst feature is a void created in rock. The size of karst can vary tremendously, but for this evaluation, the size is assumed to be on the order of a few feet and the karst is assumed to be filled with brine. These properties were selected based on assertions made by Stakeholders (CARD 2004). For any geophysical tool to work, a mappable (recordable) contrast in rock properties must exist. For this review of possible magnetotelluric applications, a resistivity contrast must be present between the host rock and the target (the brine-filled karst). The other factors used in determining the geophysical resolution of a target are its size and depth from the surface.

Resistivity of the geologic formations mainly depends upon their fluid content, porosity, fracturing, temperature, and inclusions of conductive components (Keller 1989). Brine in pore spaces and fracture openings and inclusion of conductive clay minerals can lower the rock resistivities. In a discussion of resistivity variations in rock units, Xiao 2004 states that, "The electrical resistivity of rocks depends on the density of charge carriers and the geometry of current pathways. High porosity, high salinity pore fluid, high saturation of fluid, or partial melting of rock will give a high quantity of charge carriers. Good interconnection between pores can give a high density of electric current pathways." (For additional information on electrical properties of rocks and minerals see Telford et al.1990.)

Sandia National Laboratories (SNL) provided electrical logs for wells WIPP B-25 and WIPP-13 located on the WIPP site (Figure 4-1). A review of the electrical logs for these wells showed that the resistivity of the Culebra member averages 6 to 8 ohm-meters[1] over a thickness interval of 21 to 23 ft. The overlying units (including the Magenta) are generally more resistive (Table 4-1), which would enhance the ability of MT to map the Culebra. Mapping the Magenta member is likely to be more difficult, since the resistivity contrast between it and overlying units is not as great.

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[1] The electrical resistivity of any material is defined as the resistance, in ohms, between opposite faces of a unit cube of that material. If the resistance of a conducting cylinder having a length l, and cross-sectional area S is R, the resistivity is expressed by the formula $\rho = RS/l$. The unit of resistivity in the metric system is the ohm-centimeter. For practical purposes, to accommodate long distances, as is in the well-logging, this is converted into ohm-meter. One ohm-meter = 100 ohm-centimeters ($1\Omega m = 100\ \Omega cm$).

Table 4-1. Average Resistivities for Formations and Members in WIPP Area, Estimated from Electrical Logs for Wells WIPP B-25 and WIPP-13

Formation	Member	WIPP B-25			WIPP-13		
		Depths (feet)	Thickness (feet)	Average Resistivity (ohm-meters)	Depths (feet)	Thickness (feet)	Average Resistivity (ohm-meters)
Overburden		0-20	20	na	0-35	35	Na
Santa Rosa		20-46	26	25			
Dewey Lake		46-180	134	25			
Dewey Lake		180-420	240	150	35-450	415	20
Dewey Lake		420-525	105	25	450-515	65	12
Rustler		525-586	61	1000	515-565	50	1000
Rustler	Magenta	586-612	26	25	565-585	20	15
Rustler		612-698	86	1000	585-704	119	1000
Rustler	Culebra	698-721	23	8	704-725	21	6
Rustler		721-730	9	4	725-735	10	10
Rustler		730-770	40	100	735-765	30	100
Rustler		770-800	30	20	765-800	35	25
Rustler		800-840	40	4	800-845	45	4
Salado		840-901	61	500	845-1020	175	1000

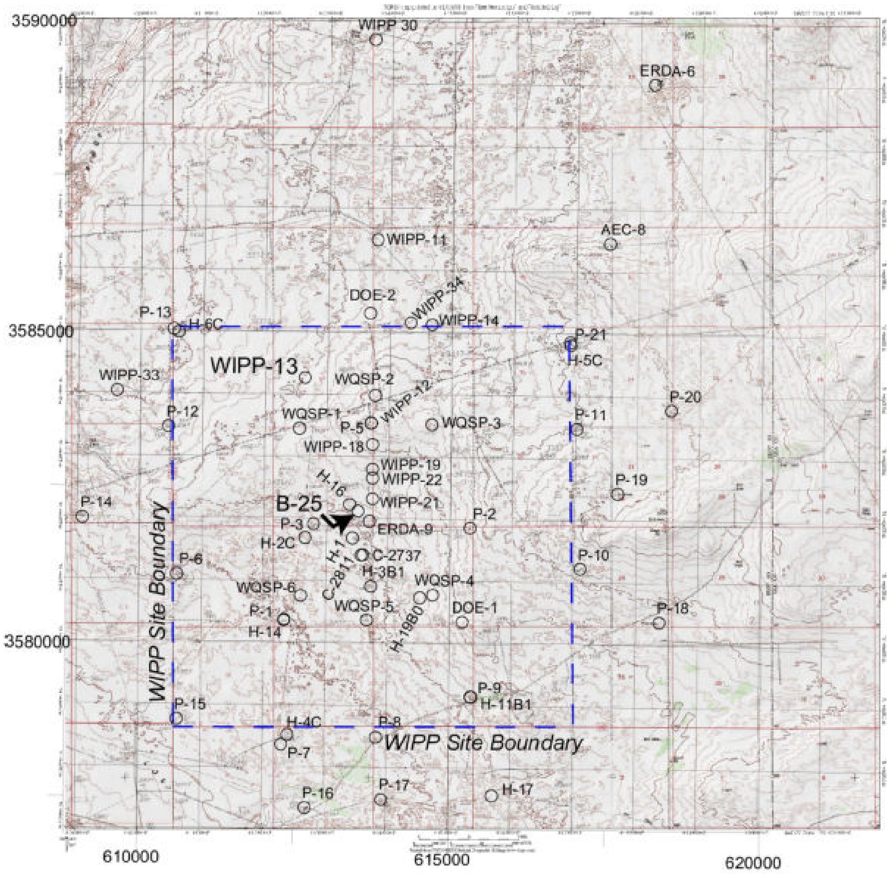


Figure 4-1. Locations of Wells WIPP-13 and B-25

Water resistivity varies with the type and amount of dissolved solids. For example, the resistivity of seawater is typically 0.3 ohm-meters (ohm-m), but more dilute waters will have higher resistivity. The Culebra and Magenta groundwater compositions have relatively high total dissolved solids (TDS) (DOE 2004), and would therefore be expected to have relatively low electrical resistivity. Therefore, if there is a sufficient contrast in resistivity between a brine-filled karst and the surrounding rock, then it may be possible to detect karst. If, however, the resistivity of the brine filling the karst is relatively high, such as 300-400 ohm-m, then there would be little to no contrast between the Culebra/Magenta host rock and brine; in such a situation, mapping resistivity contrast would be of no use. Thus, to determine if a large-scale, brine-filled karst void could be mapped as a resolvable target, a lower resistivity for brine (i.e., 0.5 to 1 ohm-meters) has been assumed in the following calculations.

If a 3-ft-high, water-filled void was present within the Culebra (average 22-ft section), it would reduce the average resistivity of the member section. Assuming the resistivity of water is between 0.5 and 1.0 ohm-meters, and the 3-ft section is about 14% of the total thickness, introducing water into the section would lower the resistivity from 8 ohm-meters to about 7 ohm-meters. This is an indiscernible resistivity change, especially because the two electrical logs examined show that the resistivity of the Culebra varies between 6 and 8 ohm-meters. Therefore, MT mapping could not discerned if the resistivity variations were intrinsic to the Culebra, or if they were caused by brine-filled voids.

It is for these reasons that the primary application of MT is in the petroleum and mineral exploration where it is used to detect large lithologic changes. Typically, MT is effective where targets are very thick and exhibit strong resistivity contrasts with their surrounding host rock. Resistivity changes identify the interfaces between regions of different resistivity (current flows across the boundaries of different resistivities, which causes electric charges to build up on the interfaces (Xiao 2004). It is also true that resistivity structure and geological structure do not coincide perfectly, and this typically can create problems for identification of structures with smaller dimensions. In general, the difference between detectable low- and high-resistive zones are substantial—10-fold or more.

4.1.3 Models of the WIPP Site

In order to determine the limits of resolution for MT, modeling was performed using a commercial geophysical workstation (WinGLink) assuming noise free ideal conditions at WIPP. Several models (Figure 4-2) were developed to determine the maximum, or best, resolution possible for a section representative of the WIPP site. In other words, these calculations were designed to answer the question, “What is the smallest brine-filled void that could be resolved by MT at the depths of interest?” The “target” in this case is a conductive body within the Culebra, which could be interpreted as water-filled karst. Additional unrealistic simulations were run to generally test the concept by answering the question, “How conductive would an object have to be in order to be mapped at these depths by MT from the surface?”

Figure 4-2 shows a generalized resistivity section for WIPP. The different colors represent different resistivity values and are shown for a flat-lying section. All units extend laterally to the right and left of the section shown, and in and out of the page. The model was constructed from the resistivity and depth values shown in Table 4-1. This table lists geologic formations and members, with their depths and average resistivities derived from electrical logs recorded in the two WIPP wells (B-25 and WIPP-13). The resistivity for water was assumed to be 1 ohm-meter, although there are circumstances where it can be lower or higher, depending on the solids dissolved in the water.

The first modeled change was to introduce a section of the Culebra that has a resistivity of 5 ohm-meter compared to the baseline model value for the Culebra of 8 ohm-meter. This model simulates a section of Culebra where 1.0 ohm-m water has replaced 40% of the Culebra, either in pores or in a single zone within the 20-ft Culebra.

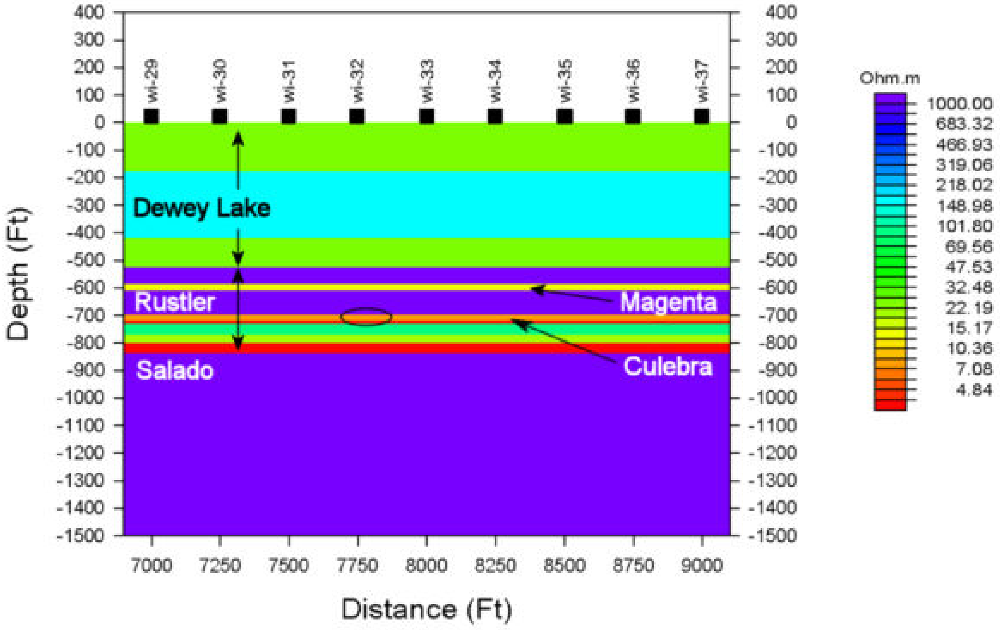


Figure 4-2. Generalized Resistivity Model for WIPP Area

No vertical exaggeration. Depths and resistivities are estimated from electrical logs. The region of the Culebra varied in the model exercises is shown by oval. Resulting data are shown in Figure 4-3.

Figure 4-3(a) shows the comparison between the data for an 8 ohm-meter Culebra and a 5 ohm-meter Culebra. Shown are the amplitude and phase data calculated for the 5 ohm-m section (solid line) compared to the amplitude and phase data calculated for an 8 ohm-m Culebra (dots). There is no discernible difference, or departure, between the data sets. Therefore, a feature of this size (approximately 8 ft for a single zone within the Culebra) cannot be mapped by MT.

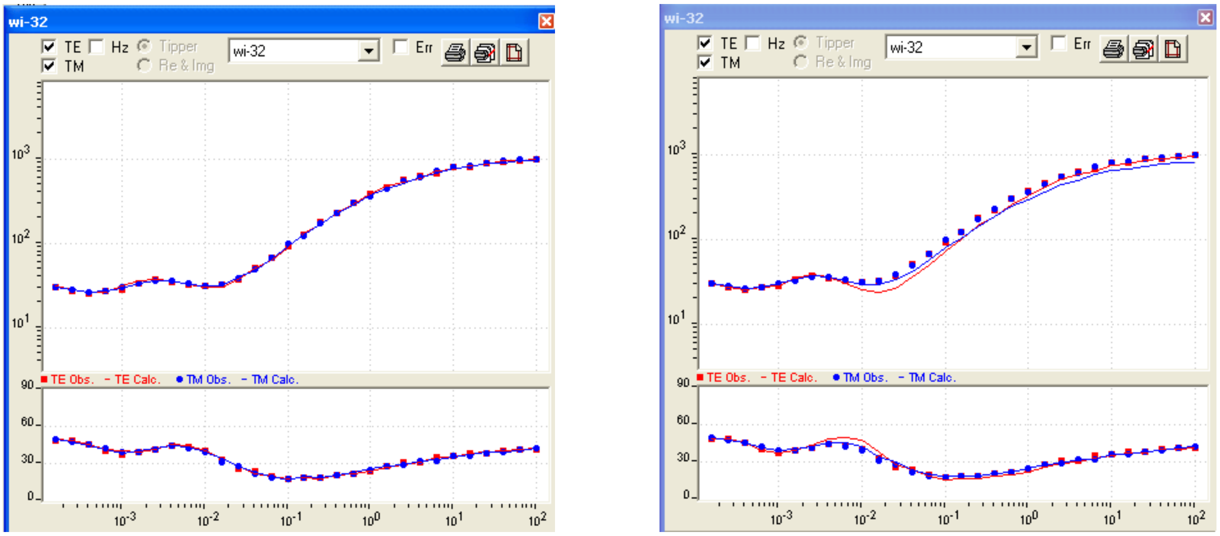
The 8 ohm-m section is shown by the blue dots. The results for modeling variations in resisitivity are shown by the solid red and blue lines—these are the two 'modes' of MT data that are calculated. The red line (TE mode) is the one most sensitive to vertical resistivity changes and hence, most important in this study. These are typical MT data responses for a station, showing apparent resistivity amplitude on the top and phase on the bottom of each station plot. The x scale is log frequency, where the shallower data (higher frequencies) are on the left. The y-scales are log-apparent resistivity (top of plots P and phase in degrees bottom of plots).

These models primarily illustrate resistivity in an ideal and undisturbed (affected by influence of other units) condition. Also, only the interpretational aspect of the MT method has been examined. The potential uncertainties in the data and complexities due to non-uniform rock properties should also be considered. The WIPP site has several layers of rocks (eight separate units above the Culebra and six above the Magenta) and each has influence on the apparent resistivity. Also, it is very likely that the horizontal inhomogeneity at the WIPP site will interfere and obstruct obtaining a confirmed and uniform interpretation. The noise, static shift, and 2- or 3-dimensional analysis of a minute structure in a complex geoelectrical environment is not a convincing method for karst detection. Also, MT has a lower inherent resolution than the seismic method (Xiao 2004).

The next models were run to test the limits of MT and answer the question, “How low would the resistivity of the Culebra have to be in order to be detectable by MT?” The second model assumed that the entire 20-ft section of Culebra was replaced by a void space containing only water (an unrealistic scenario). Comparison of the results of this model to the baseline model is illustrated in Figure 4-3(b). There is a noticeable departure in amplitude and phase between the model data and those for the normal section Culebra with no water-filled karst features. However, this difference probably would not be discernable at the WIPP site, given real-world data containing noise (i.e., environmental and anthropogenic). Even if this departure was detectable at the WIPP site, replacement of the entire thickness of the Culebra by water is beyond the limits of what could be expected from karst formation at WIPP.

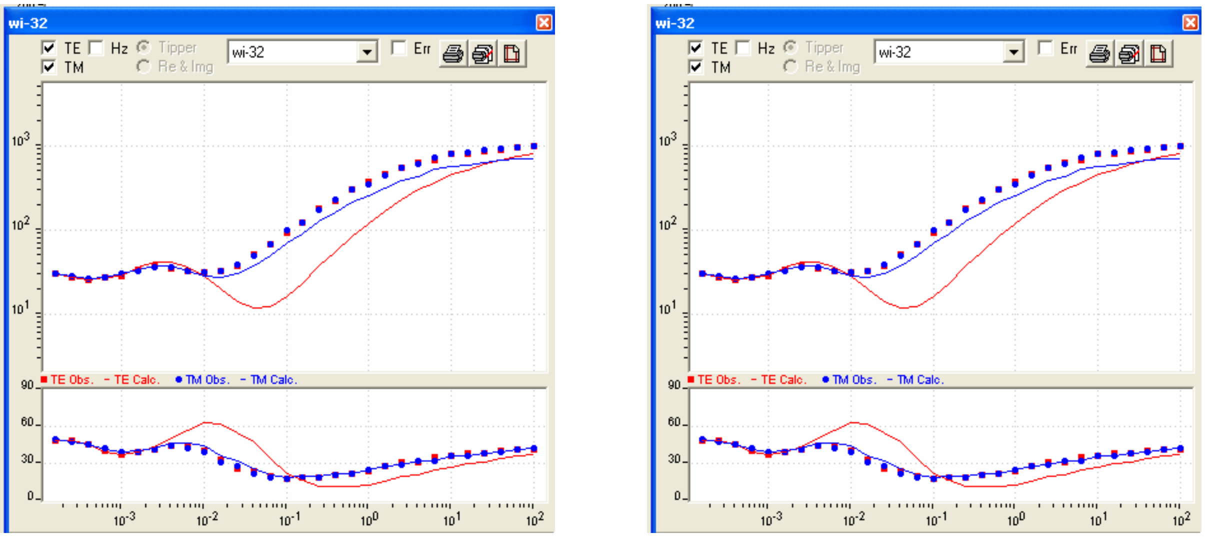
The third and fourth models (Figures 4-3(c) and (d)) reduced the resistivity even further. The resolution can be improved if the target is more conductive, for instance, if the target was a mineralized zone (such as nickel ore). The resistivity of the Culebra was unrealistically lowered to 0.1 ohm-meter (Figure 4-3(c)) and 0.01 ohm-meter (Figure 4-3(d)). Although this is not a plausible scenario for the WIPP site, it does show the limit for MT. There is a noticeable departure between the model and background data (both amplitude and phase) indicating that MT could detect a 20-ft section of 0.1 ohm-meter at the given depth. These calculations illustrate circumstances, not present at WIPP, in which features could be detected by MT methods at the depths relevant to this study.

The models demonstrate the limits of MT resolution at depths of 700 ft in a stratigraphic-resistivity section similar to the WIPP area. Although these models were calculated for a section within the Culebra, similar results are obtained when modeling the Magenta. Even though the Magenta is at a shallower depth, it is still a difficult target because of the same issues associated with the Culebra. At the very minimum, the entire Magenta section (20 ft average) would need to have a resistivity of 0.4 ohm-meters to be mapped by MT; this scenario is not physically realistic.



(a) Comparison of a 8 ohm-m Culebra vs.
5 ohm-m Culebra

(b) Comparison of a 8 ohm-m Culebra vs.
1 ohm-m Culebra



(c) Comparison of a 8 ohm-m Culebra vs.
0.1 ohm-m Culebra

(d) Comparison of a 8 ohm-m Culebra vs.
0.01 ohm-m Culebra

Figure 4-3. 1 MT Model Results Comparing a Background of Normal Culebra Section Resistivity (8 ohm-m) to Variation in Resistivity of the Culebra

4.1.4 Evaluation of the Stakeholder Proposal

Stakeholders proposed using Z-SCAN to map possible karst features. Z-SCAN is a surface mapping tool developed by Digital Magnetotelluric Technologies (DMT), based in Oklahoma. The Agency was unable to find published information related to Z-SCAN in professional journals or evidence that it has been subjected to scientific peer review.

In their proposal, the Stakeholders suggest acquiring Z-SCAN data at several of the WIPP boreholes in order to map possible solution cavities at depths of up to 1000 ft (328 meters). DMT claims (per their website, http://www.dmttechnologies.com/home.html) to have "vertical subsurface sampling as small as 0.8 ft at 5,000-ft depths with depth accuracies of +/- 25 ft in most areas." However, the scientific basis of this claim was not provided on the website.

The inherent accuracy of the MT tool, in a noise-free environment and simple stratigraphy, is typically assumed to be 2% to 3% of depth. The tool's ability to resolve layer thickness decreases with depth, because the wavelengths increase as depth increases. The MT signal is very weak when compared to artificial, or man-made, electromagnetic energy. In fact, the magnetic portion of the MT signal varies from about 0.1 to 10 nanoteslas at frequencies between 100 Hertz and 0.01 Hertz (the frequency ranges used to investigate depths up to 10,000 ft), compared to power-line magnetic signals on the order of 3000 nanoteslas. These types of man-made fields are between 100 and 10,000 times greater than natural fields. See Figures 4-4 through 4-6 for comparison of power line and natural magnetic field strengths.

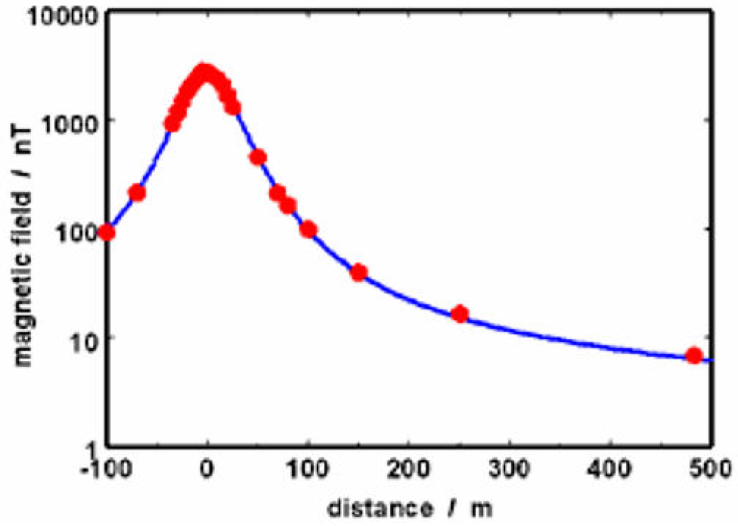


Figure 4-4. Typical Maximum Magnetic Fields from Different Voltage Power Lines, and Distance from Line

Note that scale is in microteslas; one microtesla = 1000 nanotesla
(Source: www.emfs.info/Source_transmission.asp)

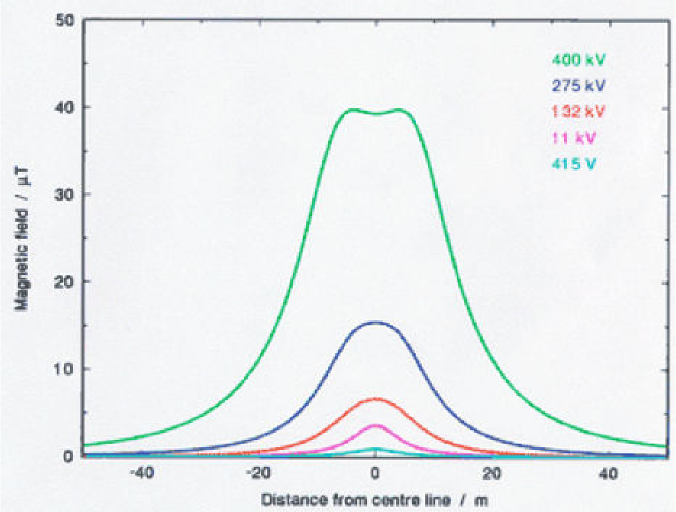


Figure 4-5. Magnetic Field Calculated by Distance from a 400 kV Power Line

(Source: www.emfs.info/Source_transmission.asp)

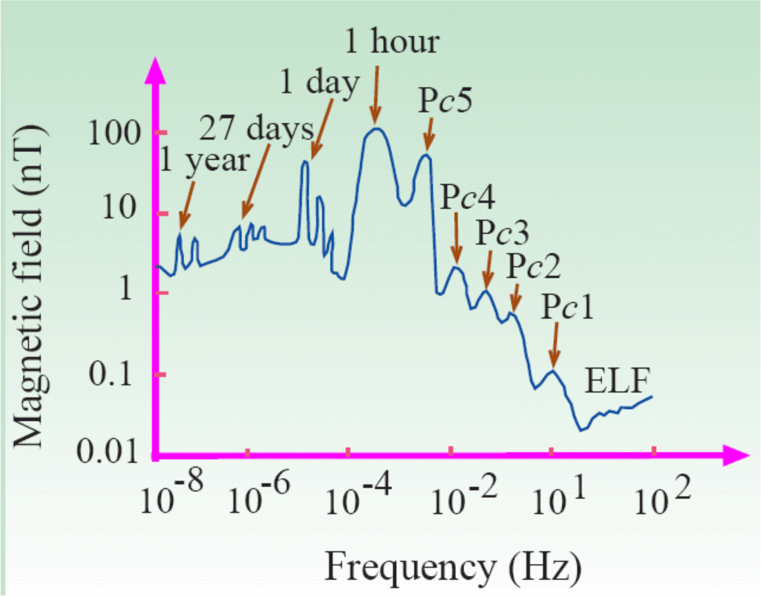


Figure 4-6. Typical Magnetic Spectra from MT Signal

The measurements required for the WIPP site would use frequencies toward the higher end (right side) of the graph. (Source: Caglar and Eryildiz 2000. *Ast. Soc. Pacific Conf. Series* Vol. 205, pp. 2-8-215)

Information available to the Agency, as summarized in the previous analysis, indicated that MT methods would not be useful for locating karst at WIPP. Consequently, the Agency required additional information regarding the technical feasibility of using the Z-SCAN magnetotelluric method for finding karst features in the Culebra and Magenta at the WIPP site.

EPA attempted to obtain additional information pertaining to the feasibility and costs of using Z-SCAN MT technology to locate karst at WIPP. EPA provided a list of questions regarding the Z-SCAN MT to Digital Magnetotellurics Technologies (DMT), however, no response was received.

An examination of the references listed on the DMT website and a search of the literature did not reveal any technical publications that would provide information supporting the use of the Z-SCAN technology for detecting karst at WIPP. The Agency therefore was unsuccessful in obtaining additional information to support the Stakeholders' contention that the Z-SCAN technology could be used to detect karst at WIPP. In the absence of information that demonstrates that the Z-SCAN method would perform as the Stakeholders claim, the Agency does not support the use of this technology to search for karst at WIPP.

4.1.5 Conclusions Regarding Use of Magnetotellurics

Magnetotellurics cannot be used to resolve karst features, if present, in the Culebra or Magenta members of the Rustler Formation because:

- Even if the karst voids encompassed the entire thickness of the Culebra, the voids would still be too small to be detected at the depths for these formations in the WIPP area, given the resistivities of the units and formations above them. Modeling using site data indicates that the characteristics of the Culebra and Magenta are such that voids (several feet in diameter) would be indistinguishable from the host rocks;

- Data error or noise would further limit the ability of MT methods to resolve features of this size; and

- Even if MT could map resistivity changes that could be interpreted as brine-filled karst, the resistivity of the features would not be significantly different from changes caused by lithology or increased porosity. There would not be a definitive interpretation of karst that could not be explained by other natural features in the subsurface, because the karst features are too small and have too low of a contrast to be defined uniquely.

MT is primarily used as a reconnaissance tool to delineate the target area for more applicable (detail-oriented) seismic surveys.

In summary, the Z-SCAN technology, both acquisition and interpretation, does not appear to be a proven (with unique interpretation) or cost-effective method for investigating karst at relatively shallow depths within and above the Culebra.

4.2 OTHER GEOPHYSICAL METHODS

A number of geophysical methods have been employed at WIPP in the past (DOE 2004, Appendix MON Attachment A). For example, a geophysical survey using Time Domain Electromagnetics Induction (TDEM) methods detected a conductor interpreted to be the

WIPP-12 Castile brine reservoir and also indicated that similar brine occurrences may be present within the Castile under a portion of the waste disposal panels (DOE 2004, Chapter 2). A microgravity survey of a portion of the site during 1980 indicated the presence of localized low-gravity anomalies around the WIPP site (DOE 2004, Chapter 2). Barrows et al. 1983 interpreted these results as possible evidence of karst, but drilling during 1981 at a low-gravity anomaly revealed normal stratigraphy throughout the zones proposed to be affected by karst.

In the following sections, potential geophysical survey methods are evaluated and their ability to detect karst in the Magenta or Culebra members of the Rustler Formation at the WIPP site is considered. The evaluated surface techniques include gravity surveys, magnetic surveys, TDEM, and seismic methods. Subsurface (crosswell) geophysical methods are also considered.

4.2.1 Gravity Surveys

Gravity surveys measure the vertical and lateral variations in the earth's gravitational pull that are caused by subsurface changes in rock density. Gravity measurements (usually expressed in milligals) are normally obtained as "point" measurements on a grid established over the site. It requires precise survey information to locate the exact and accurate positions of the gridlines. It is relatively more expensive and requires several corrections to detect the changes in the gravity data. By comparing the changes in data values from one point to the next, maps are produced and interpreted as showing subsurface rock characteristics.

Gravity surveys are widely used to detect buried structures and for reconnaissance work. The gravity method has poor resolution compared to most other geophysical methods because of its coarse data spacing and inherent resolution. In addition, the causes of gravity anomalies can be difficult to interpret, as previously observed at the WIPP site (Section 4.2). Therefore, additional gravity survey measurements are unlikely to provide useful information relative to karst at the WIPP site.

4.2.1.1 Resolution of Gravity Surveys

The gravity geophysical tool does not have the resolution to distinguish small features in the subsurface. This tool is usually used to gain an understanding of large objects. A gravity survey may 'see' an anomaly, but not be able to discern details about it. As noted in the CRA (DOE 2004, Appendix MON, Attachment A Section MON-A-6.3.3), a gravity survey may detect an anomaly, but drilling or other geophysical tools may be needed to evaluate it in detail as has been done historically at WIPP.

4.2.1.2 Past Gravity Survey Activity at WIPP

Sandia National Laboratories conducted a gravity survey during 1981 and 1982 to detect and acquire information on the "Disturbed Zone" of the Castile Formation that was originally revealed by seismic measurements. A negative gravity anomaly (at WIPP-33) was indicated by the regional survey. An additional gravity survey revealed a 0.6 milligal negative anomaly with a double half-width of 900 ft. Barrows et al. 1983 interpreted and proposed that this anomaly was due to density alternations in the vicinity of karst channels. However, it has generally been observed that "gravity interpretations are inherently ambiguous" (Chaturvedi and Channell 1985). Nevertheless, a negative gravity anomaly exists in the vicinity of WIPP-13, WIPP-14, and WIPP-33, and its origin can be interpreted in many different ways. Drilling at WIPP-14 revealed that no karst structures existed. On the other hand, Bachman 1985 identified karst at WIPP-33, in an area northwest of the WIPP site boundary (DOE 2004).

4.2.2 Magnetic Surveys

Magnetic surveys measure the magnetic anomalies in rocks. The local changes (anomalies) in the main magnetic field (if present) are due to the magnetic mineral content in the rock formations. In order for magnetic surveys to be useful, there must be a magnetic contrast between the units being mapped. Magnetic susceptibility is an important variable in the magnetic survey, similar to the role of density in gravity surveys and its interpretation. Magnetic susceptibility of a rock formation primarily depends upon the amount of ferrous and other magnetic materials (magnetite, titano-magnetite, pyrrhotite) present in the rock. Large-scale anomalies are typically related to the susceptibility of rock formations. Magnetic surveys are conducted from the air, land, and sea. Airborne magnetic surveys are mainly used in petroleum exploration to establish a rough estimate of the depth and topography of the basement igneous rocks (Telford et al. 1995). Measurements are normally recorded with the use of magnetometers, measuring various orientations of the earth's naturally occurring magnetic field strength (a reasonably static field). These are normally "point" measurements (like gravity) where only one measurement is recorded at each location. In describing the difficulties associated with interpretation, Telford et al. 1995 state that "Because of the erratic and complex character of magnetic maps, interpretation is often only qualitative. Indeed, interpretation is something of a fine art."

4.2.2.1 Resolution of Magnetic Surveys

Resolution of magnetic surveys is poor (in non-ferrous rocks) compared to most other geophysical methods. Sedimentary rocks have the lowest and igneous rocks have the highest magnetic susceptibility. The magnetic susceptibility of dolomite (the rock type in the Culebra and Magenta) is in the range of 0 to 0.9, with an average of 0.1 ($\times 10^3$ SI or System International units), compared to magnetite (at the highest range), which ranges from 1200 to 19,200 with an average of 6000×10^3 SI.

Magnetic anomalies are caused by igneous intrusion, flows, or sedimentary rocks with iron ores. Magnetite and other ferromagnetic minerals are the primary source of local magnetic anomalies. Magnetic survey results are interpreted from the magnetic contours and profiles. Magnetic anomalies may only show trends, and interpretations are often qualitative at best, and uniqueness in interpretation is seldom achieved. In general, this method provides relatively complex and erratic results. The Magenta and Culebra are typically low in iron content and therefore magnetic variations will not be easily detected. Magnetic anomalies in the Magenta or Culebra are not anticipated to be large and easily distinguishable at depths of 590 ft or greater. The local karst features in the Rustler are small and their presence does not increase the magnetite content in the rock. Therefore the magnetic susceptibility in the Culebra or Magenta will remain unchanged and will not provide any detectable magnetic trend for identification of karst. It is apparent that the magnetic survey is not a useful geophysical tool for detecting karst at WIPP.

4.2.2.2 Past Magnetic Survey Activity at WIPP

The potential application and scope of utilization for magnetic surveys in the WIPP environment is very limited. Airborne magnetic surveys were used to detect the location of igneous dikes at the early stages of site characterization. These surveys were conducted by the U.S. Geological Survey. Elliot 1976 also studied the aeromagnetic response and came to the conclusion that a series of dikes with near-vertical orientation are responsible for the magnetic anomaly seen in the collected data. Other geophysical tools were used to verify the conclusion. Magnetic methods were not independently used in any other situation at the WIPP site.

4.2.3 Time Domain Electromagnetics Induction (TDEM)

TDEM is a controlled-source geophysical method that measures subsurface resistivity changes. TDEM is similar to MT in that it measures electrical resistivity, but TDEM does not have the depth of penetration of MT. However, in many cases, the resolution of TDEM is slightly better than MT, especially when attempting to detect a conductive feature. The basic principle of this method is to create an alternating magnetic field by passing alternating current through a coil. This field is measured by using a sensitive electronic amplifier or potentiometer bridge. There are several ways these surveys can be conducted in the field.

TDEM data are recorded by laying out a large loop of wire (on the order of 100 meters per side) on the surface. A current is applied through the loop, which generates a magnetic field. This field penetrates the subsurface; the depth of penetration is dependent on the size of the loop, the amount of current sent through the loop, and the resistivity of the subsurface rocks. As the magnetic field transmits into the subsurface, it creates secondary magnetic and electric fields that can be recorded at the surface. TDEM systems measure the resultant magnetic and/or electric fields at the surface in various orthogonal directions as a function of time. The resulting data are a set of points that reflect resistivity changes at numerous depths in the subsurface.

Because TDEM is a controlled-source method, it is not subject to the same noise problems as MT. In areas of high cultural noise (such as power lines) this can be an advantage. TDEM is subject to natural noise sources (the MT signal) that can cause delays in recording; TDEM recording is typically paused during high natural signal events.

4.2.3.1 Resolution of TDEM Surveys

As is the case with other geophysical methods, minimum size of detection with TDEM is an important issue. In TDEM, depth, size, and resistivity are important considerations. It was estimated that (in general) TDEM techniques might miss detecting brine pockets less than 5 meters in thickness (DOE 1988).

It is widely believed among practicing geophysicists that TDEM methods generally detect layers with conductance values of about 1/3 or greater than the sum of conductance values from all above-lying strata, with conductance defined as the ratio of thickness to resistivity. In the TDEM survey at the WIPP site, conductance was estimated as the ratio of thickness to resistivity. Based on this rather simple calculation, it was determined that the brine with resistivity of 1 ohm-m would not be detectable. Therefore, it can be safely assumed that detection of karst (typically of smaller dimension and with less conductive fluid content) in the

WIPP environment would be very difficult, because any results would be uncertain in interpretation and precision.

4.2.3.2 Past TDEM Survey Activity at WIPP

Blackhawk Geosciences (a DOE contractor) conducted a TDEM survey in 1987 to detect and characterize the Castile brine pockets at the WIPP site. The main premise of this survey was that the brine-saturated rocks would be more conductive and geoelectrically more distinct than the more resistive Salado halite.

The Castile is located approximately 3,000 ft below the surface and is more than 1,000 ft thick. Electrical impulses from the surface were introduced into the subsurface and the resulting conductivity signals were processed to create apparent resistivity profiles. At WIPP, a north-south grid pattern was used to measure 38 points at the grid intersections. Thirty-six data points were used to create an interpreted geologic profile based on varying electrical properties (apparent resistivity profiles) of the rocks at depth. Because of the substantial depth of the target location and field logistics (the large transmitter loop size required to access this depth), the data density was modest, which probably reduced the capability of the method to detect the relatively small brine pockets. The geologic profiles were not uniform in interpretation and thickness, and the arrangement of conductive layers in the subsurface can definitely increase uncertainty in results. In addition, due to the sparse data points, only a one-dimensional approach to inversion of the data points was used. Thus a three-dimensional problem was forced into a one-dimensional solution, and this restricted the ability of the system to detect inclined or angularly oriented pockets. Detection of a karst void within the Magenta or Culebra units at WIPP would present similar problems as those encountered for the Castile.

Blackhawk Geosciences compared the TDEM results with the magnetotelluric results supplied by Bartel 1989. Bartel's work was related to characterization of the Culebra. TDEM results were also compared with the results obtained by Skokan et al. 1989 using a magnetic induction method, and the results were found to be in good agreement.

However, several questions were raised by reviewers regarding the accuracy of the depth estimate, minimum detectable size, and consistency in interpretations (EPA 1998c). It was estimated that the qualitative depth accuracy was on the order of 70 meters. The minimal size of the brine pocket or brine-saturated region that may be detected by this method is dependent upon the depth of occurrences, orientation, size, and conductivity (resistivity). It was decided that there were not enough measurements taken to accurately predict the size of Castile brine pockets or brine-saturated regions (EPA 1998c).

4.2.4 Seismic Reflection Techniques

Seismic reflection surveys measure subsurface changes in rock acoustic velocity and density. They are carried out by creating low frequency sound waves, on the order of 10 to 100 hertz, at or near the earth's surface via various means (explosive charges—such as dynamite, weight drops, or specialized vibration-creating equipment—known as vibroseis), and measuring the returns of the waves as they reflect off various subsurface rock interfaces and propagate back to the surface. These measurements are recorded as a function of time. Numerous points are recorded simultaneously. Compared to other geophysical techniques, seismic methods are relatively precise with greater resolution. However, seismic methods tend to be relatively expensive.

Propagation of sound waves in the subsurface is influenced by the elastic properties of the rocks, particularly density and acoustic (sound) velocity. Reflected sound waves are influenced by rock porosity, saturation, and temperature (Wilt 1995). Seismic reflection has the highest resolution of any surface-based geophysical technique, but is still on the order of tens of feet under normal field conditions at the depth of the Magenta or Culebra at WIPP. Reflections in the subsurface are possible every time the acoustic wave encounters a layer of differing rock velocity or density. Under ideal conditions, seismic data can map layers with thicknesses on the order of feet (if the target is very shallow) to tens of feet for a deeper target. However, ideal conditions are seldom achieved in the field and it is not always easy to determine the lithology or composition of the layers, even though their presence may be seen.

4.2.4.1 Resolution of Seismic Reflection Techniques

Seismic reflection acquisition systems typically achieve a frequency range of 10 to 100 hertz under ideal conditions. However, as the sound waves penetrate deeper strata, the frequency range decreases due to natural attenuation of the earth. To evaluate the resolving power of seismic reflection techniques, one must consider vertical and horizontal resolution, or the ability of the seismic sound wave to 'see' distinct features underground. Vertical resolution is defined by the Rayleigh Criterion, and the horizontal resolution is defined by the First Fresnel Zone. These two definitions set a limit of one-quarter of the wavelength of the seismic sound wave as the lower limit of resolution or object definition (Lorenzo 2003).

Seismic wavelength is defined as the velocity divided by frequency ($W = V/F$). Therefore, if the Culebra is assumed to have an average velocity of 15,000 ft/sec (obtained from DOE-2 Sonic Log, 15,625 ft/sec, estimated 15,000 ft/sec), and the average center seismic frequency is assumed to be 50 hertz, the wavelength would be 300 ft. Therefore, the vertical and horizontal resolution would be one-quarter of this wavelength, and equal to 62.5 ft. Even if a center frequency of 100 hertz is assumed at the depth of the Culebra, the resolution would be approximately 37.5 ft. Therefore, seismic reflection tools cannot be used to search for or resolve karst near WIPP, because the size of the karst will be much smaller than the limits of seismic resolution.

4.2.4.2 Past Reflection Seismic Activities at WIPP

DOE used several seismic techniques during WIPP site selection and characteristic activities. SNL conducted three seismic surveys from 1976 to 1978, totaling 79 miles of data (Hern et al.

1978; Griswold 1977; and DOE 1996, Appendix GCR). In 1976, DOE purchased 189 miles of 1950- to 1960-vintage seismic data acquired by Shell Oil Co. DOE also examined 709 miles of seismic data in the offices of Exxon and Amoco during this time period. In 1976, DOE attempted to acquire high-resolution seismic data; however, these data were not interpretable. Later in 1979, DOE recorded seismic data directly over the WIPP site. More details regarding past reflection seismic activities at WIPP are available in the CRA (DOE 2004 Appendix MON, Attachment A, Section MON-A-6.2.3)

Seismic reflection data was used at the WIPP site to identify the "Disturbed Zone" in the Castile. Information regarding the Disturbed Zone is provided in the CCA (Appendix GCR, 1996). This structurally disturbed zone (which was created by natural processes) is located in the Castile Formation. Borns et al. 1983 described two small Disturbed Zone areas south of the WIPP site. The Disturbed Zone is a complicated structure and the reflection survey was not adequate to resolve the minor details of the structure. However, the reflection survey detected a "blocky structure with abrupt dip changes and offset between units." (Long 1977b). Borns et al. 1983 interpreted the seismic character changes as the variation in thickness and/or acoustic properties. Core data obtained from later drilling supported the seismic interpretations (structural variations). The negative gravity anomaly coincided with the seismic results as "time structure syncline at the reflection time of the Rustler Formation (seismic line 77x2, Chaturvedi and Channell 1985)." Overall, the seismic reflection technique is more consistent in interpretation and more closely matches the core data than other geophysical methods used at the WIPP Site (DOE 1996, Appendix GCR).

4.2.5 Subsurface Reflection Seismic and Electromagnetic Techniques

It may be possible to use subsurface crosswell (between wells) geophysics to map detailed changes within the Culebra or Magenta under ideal conditions. Crosswell geophysics have advanced in their applications in recent years and are available using two methodologies: electromagnetics (EM) and seismic velocity.

Crosswell geophysics is performed by lowering a transmitter (an active source) down one well and a recording device down another well. Signals are transmitted from one well (either EM or seismic) and recorded in receivers in the second well. The transmission and recording are done at various depths in the wells in order to cover the desired portion of the subsurface. If the wells are close enough to each other, it is possible to determine changes in lithology or fluids between the two wells.

4.2.5.1 Crosswell Seismic Techniques

Crosswell seismic techniques have become more common during recent years (Hoversten et al. 2001). Energy sources, such as small airguns, piezoelectric sources, even small dynamite charges, are lowered into boreholes to transmit sound waves to a series or line of geophones, such as hydrophones, or piezoelectric receivers in another well, to record high quality inter-well subsurface seismic reflection information. Crosswell seismic methods overcome many of the problems associated with surface reflection seismic techniques. Irregularities of the near surface are removed using crosswell seismic methods, attenuation of sound waves is less and allows for recording higher frequency, and therefore more detailed data. However, processing of crosswell seismic data can be more difficult, because tube waves reflect up and down the borehole and other interfering waves can mask the high-frequency reflection data. Successfully removing these unwanted waves can be challenging. Based on the Agency's review of literature on crosswell seismic, because of limited energy source size and power, the Agency concluded the distance between wells may be limited to a maximum of 2,000 to 3,000 ft depending on the complexity of the lithology of the subsurface rock formations (Zhang 2002). Many crosswell surveys are less than 500 ft between wells (Liberty 2000 et al).

Many of the crosswell energy sources can develop more than 2000 hertz sound waves, but because of subsurface transmission frequency attenuation and other limitations, such as interference from tube waves, the actual working frequency range is often 1000 hertz or less. The vertical and horizontal resolution of crosswell seismic can be estimated using the same relationship used for reflection seismic methods (working resolution equals one-quarter of wavelength, and $W = V/F$, Section 4.2.4.1). Assuming an optimum working center frequency of 1000 hertz for the Culebra at a velocity of 15,000 ft per second, the best resolution or object definition would be approximately 3.75 ft under ideal conditions and over a distance of 100 to 200 ft between well bores. In practice, this resolution may be seen in wells that are very close together, on the order of hundreds of feet; 10-ft resolution has been seen in other situations with wells separated by 600 ft to 2000 ft (Li 2001, 2002, Hatch 2001, Zhang 2002). However, wells at WIPP are typically more than 1000 ft apart, so crosswell seismic may be impractical because of distance between wells and insufficient resolution of crosswell seismic and are generally not of sufficient borehole diameter to support crosswell tools.

Another limitation associated with using crosswell seismic can be attributed to the complexity of the subsurface lithology. Studies have shown that geologic complexity can negatively impact the quality and frequency content of crosswell seismic results, making interpretation difficult and sometimes ambiguous. Studies have also shown a great deal of directional variability in quality of the data in multi-well crosswell surveys due to changes in subsurface geology (Zhang 2002).

In conclusion, crosswell seismic surveys appear to be the most promising geophysical tool to search for karst at WIPP, because all other methods do not offer satisfactory resolution at the specified depths and size of the proposed karst features. However, crosswell seismic surveys are a relatively new technology and not completely developed. Crosswell seismic surveys have many limitations and restrictions:

- Two ideally located wells are required within a few hundred feet of each other
- Target definition and bedding resolution quality may vary because of complex lithology and distance between wells
- Power of the energy source may limit data quality and resolution

A small brine-filled void, karst, may not be discernable using this tool. In existing wells with degraded steel casing, crosswell seismic may not be possible because the degraded casing would attenuate the sound wave. Karst may not be easily identified using this technology, because seismic methods are sensitive to changes in velocity and density of the material, and the resolution of this tool is too low to see such changes at the depth of the Culebra at WIPP. No crosswell seismic studies have been carried out at WIPP.

4.2.5.2 Crosswell EM Techniques

Crosswell electromagnetic (CEM) tomography is also being developed for use between wells, and has been used since the early 1980s (Wilt 1995). Electromagnetic (EM) techniques are particularly sensitive to electrical conductivity, which is directly related to reservoir fluid properties, while seismic geophysical tools measure sound velocity and can provide information on subsurface structure and rock porosity. EM is used to measure fluid content properties of rock units, such as water saturation. EM can be used to distinguish oil and gas from other fluids (Kirkendall 2001). CEM is being tested to study the effectiveness of water and CO_2 floods to enhance oil recovery (Hoversten 2001). CEM can acquire much higher quality data and resolution than surface EM techniques, but CEM still has limitations.

CEM has many of the same challenges as crosswell seismic techniques. Distance between wells can negatively influence the quality of CEM data, and complex 3-dimensional geology can generate unrealistic artifacts in the recorded CEM data (Wilt 1995). Carbon-steel borehole casing can significantly attenuate and disperse the induced electromagnetic energy due to casing surface conductivity (Kirkendall 2001). Work is being carried out to overcome the steel casing effect.

CEM would have a very limited application for detecting karst at WIPP. A brine-filled karst void, if it existed, would not easily be seen at WIPP using CEM. The contrast of rock filled with brine and a brine-filled karst void would probably not be discernable even with the higher quality and resolution of CEM. No CEM studies have been carried out at WIPP.

4.2.6 Conclusions Regarding Geophysical Methods for Finding Karst

Magnetotelluric methods for detecting karst at WIPP have been considered (Section 4.1) and found to be unsuitable for this purpose, because of a lack of the necessary resolution at the depths of the Magenta and Culebra. Similarly, gravity surveys, magnetic surveys, and TDEM methods are unlikely to be useful for detecting karst in the Magenta or Culebra, because these surveys would not provide adequate resolution or specificity for karst. Seismic reflection methods cannot be used to search for or resolve karst in the Magenta or Culebra at WIPP, because the size of the proposed karst voids would be much smaller than the limits of resolution. Subsurface geophysical methods such as crosswell seismic studies or CEM similarly lack the required resolution for detecting karst voids in the Magenta or Culebra at the WIPP site.

5.0 CONCEPTUAL MODEL OF GROUNDWATER PROCESSES AT THE WIPP SITE

A conceptual model of groundwater processes at the WIPP site was developed to address the potential for karst formation at the WIPP site. In particular, the spatial orientation and potential hydrogeologic impacts of potential karst hydrogeologic units, including the Culebra and Magenta in the WIPP site area, were considered. EPA addressed specific karst-related using a conceptual model including the following:

- Whether evidence exists for past karst development at the WIPP site
- The potential for current and future karst development at the WIPP site
- The potential formation of "underground rivers" or other extensive karst features that would facilitate the rapid transport of radionuclides if they were released from WIPP

In Section 6.0, alternative conceptual models are presented to assess whether the alternative models adequately incorporate existing site hydrogeologic data.

5.1 SURFACE CHARACTERIZATION

The topography at the WIPP site can be described as gently rolling and sloping uplands with some depressions developed and limited stream development (Figure 5-1). The land surface generally slopes to the south and southwest, although a local topographic high exists on the site. The remainder of the topographic slope is to the southeast and northeast. There is a topographic high, Livingston Ridge, northwest of the site, adjacent to a topographic depression, Nash Draw. If groundwater flow follows the topography in the shallow Eolian, Santa Rosa, and Dewey Lake hydrogeologic units, the topographic highs and lows will control the near-surface groundwater flow directions in these shallow hydrogeologic units.

Locally, the streams dissect pedogenic, eolian, and alluvial unconsolidated units, and the Mescalero, Gatuna, Santa Rosa, and Dewey Lake lithologic strata. Regionally, the Pecos River and Nash Draw dissect the deeper geologic strata, locally exposing the Magenta and Culebra units in places. These dissected areas may serve as groundwater recharge or discharge areas to the surrounding hydrogeologic units, depending on the hydrologic system dynamics.

The slope gradient is mostly less than 2%, which favors vadose zone infiltration and evapotranspiration. Steeper slope gradients are observed around Nash Draw and the Pecos River Gorge, where the near-surface processes of runoff (interflow) and evapotranspiration are favored. The elevation across the WIPP site is nearly uniform, suggesting that precipitation would tend to be evenly distributed across the region. Minor variations could exist at the site, however.

Figure 5-1. Topographic Map of the WIPP Site and Vicinity

Note the Nash Draw depression and various playa lakes, including Salt Lake

The perennial stream in the region is the Pecos River. The segments of the Pecos River that are gaining or losing water have not been determined as part of this study, and much of the surface water flow is artificially controlled by dam releases. Much of the Pecos River flow is derived from headwater mountain hydrologic processes upgradient from the region. The Pecos River is in hydraulic contact with the Culebra and Magenta units along some reaches, surface flow paths, to the west and south of the WIPP site, and localized springs are known to occur at Malaga Bend (DOE 2004). The springs are among the few known groundwater discharge zones of the Culebra hydrogeologic unit in this region.

Other streams near the WIPP site in Nash Draw are ephemeral, lasting a short time, suggesting that rainfall events control the surface runoff. Locally, these streams and drainages may function as groundwater recharge or discharge areas, depending on hydrogeologic relations and plant distributions. However, based on size, drainage network, and location on the landscape, none of these ephemeral drainages geomorphically appear to be associated with major active “underground rivers.”

Several lakes and playas are observed in Nash Draw. These playas can be groundwater discharge or recharge areas, depending on landscape position in the hydrologic system. Groundwater discharge playas are indicated by the presence of water and phreatophytes (plants with deep root systems, e.g., cottonwoods) growing around the margins of the lakes in Nash Draw. Groundwater recharge and evaporation playas lack the phreatophytes and perennial water. Many of the playas in Nash Draw have perennial water and phreatophytes due to surface discharge from local potash operations, which will change the hydrologic relationship of the playa to the hydrologic system. Permanent lakes like Salt Lake in Nash Draw, located approximately 9 miles to the west to southwest of the WIPP site, are hydraulic head boundaries to the local, subregional, and regional hydrologic system. There has been no observation of “underground rivers” discharging into these lakes.

Evidence of springs, seeps, and phreatophyte community locations are important in defining local and subregional groundwater discharge areas for any system. Vegetation type can provide evidence to the salinity of the system. Some springs are noted in lower Nash Draw and the Malaga Bend area of the Pecos River. These springs are reported to be discharged from the Culebra aquifer in Nash Draw, and the Culebra and Magenta aquifer in the Malaga Bend area. To date, however, outlets for the Rustler members have not been definitively identified. As early as 1938, Robinson and Lang suggested that the Rustler waters from the Nash Draw area discharge in springs at Malaga Bend on the Pecos River, citing an increase in the chloride of the river water at this location as evidence. Morgan 1942 estimated that 350 tons of salt a day and 200 gallons per minute were being discharged via these springs. However, Theis et al. 1942 suggested that the salt water discharge at Malaga Bend comes from the brine aquifer at the Salado/Rustler contact, and that very little of the salt contribution to Malaga Bend is from the Culebra (the Magenta Member had not yet been recognized as a different layer within the Rustler Formation). Regardless of which layer the water in the springs comes from, Geohydrology Associates 1978, who lumped the Culebra, Magenta, brine aquifer, and alluvium as a single aquifer for their calculations, calculated that aquifer outflow at Malaga Bend Springs is only about 1% of the total of rainwater precipitated in the potential catchment area. The remaining 99% is lost to evapotranspiration. This volume of spring discharge is too small to be representative of “underground rivers.”

The dominant upland vegetation is a grassland shrub mix typical of eolian regions and the southern High Plains climatological region. Shrubs characteristic of the Chihuahuan desert are also observed. These species are usually associated with potential infiltration and recharge areas, and the infiltration processes are usually most active in the November through March time period when the plants are dormant. These species are also adapted to high evapotranspiration rates, which limit infiltration and recharge in these areas.

The phreatophyte community typically consists of Plains Cottonwoods, Willows, Tamarisk, and Mesquite. Wetlands will also show a variety of species including cattails, sedges, and other riparian species typical of saturated soils. Phreatophytes can be a good indicator of groundwater discharge zones or near-surface groundwater in arid lands. These phreatophytes are observed in areas where the water table is near the surface, such as southern Nash Draw, the springs at Malaga Bend, or along the Pecos River floodplain.

The mean annual precipitation at the WIPP site is about 13 inches per year, of which about 90% is lost to evapotranspiration (DOE 2004). Given the form, magnitude, and distribution of precipitation events, the maximum infiltration of precipitation into the subsurface will most likely be from November to March, as snow melts or more gentle frontal system rains. This amount and distribution of precipitation is too low for rapid karst development or "underground river" development.

The soils and geomorphology at the WIPP site are summarized in DOE 2004. The following features are of interest to karst hydrologists:

Eolian sand and blowouts: The thickness, distribution, and texture of these deposits indicate that zones of infiltration and zones of near-surface flow are possible.

Pedogenic deposits, specifically, the Mescalero Caliche: This caliche is well-developed, thick, and mostly continuous. As a result, where present, the Mescalero Caliche may locally serve as a hydrologic barrier to vertical infiltration of surface water into the underlying groundwater system. Caliche formation is probably occurring in the current climate.

Karst surface features, notably sinkholes and collapse valleys: Karst features can serve to disrupt continuity of hydrogeologic units, both confining unit and aquifer, as well as hydrologic systems. Nash Draw, hypothesized as a karst valley, may be one such feature that fully dissects the Magenta and younger units in some areas, therefore breaking up the regional/subregional continuity of their groundwater systems, if present. By comparison, sinkholes can serve as hydrologic conduits from the surface to the subsurface units, and can serve as either recharge or discharge features, depending on their position in the landscape and hydrologic system. Possible sinkhole-like surface features, surface depressions, have been observed on the WIPP site, for example at WIPP-13, WIPP-14 and WIPP-33. However, drilling at WIPP-14 showed that most of the underlying hydrostratigraphic units are intact, and that vertical transmission of water from the surface to deeper hydrogeologic units is unlikely. WIPP-33 is acknowledged by DOE to be karst, and is said to be the nearest karst feature to WIPP (DOE 2004, Chapter 2). Additional discussion pertaining to the aquifer testing conducted around WIPP-13 is presented in Section 6.

Paleospring deposits: These deposits, observed in upper Nash Draw (DOE 2004), have been hypothesized as potential paleospring gypsite deposits (Bachman 1985). These deposits may indicate locations where groundwater activity may have been greater in the geologic past. These particular gypsite deposits are located next to the Dewey Lake hydrogeologic unit, and may indicate groundwater activity in the Dewey Lake unit during past wetter climatic periods. Because there are no structural features in the area of these deposits, it is unlikely that hydrogeologic conduits and karst formation have been caused by groundwater discharge from deeper units (Magenta and Culebra, for example) to shallower units.

Linear drainage pattern and topographic features: The drainage pattern suggests regional and local fracture control of surface and groundwater flow. The Pecos River may be a regional fracture zone that promotes discharge from the regional groundwater system to the surface where the hydrogeologic units are connected to the Pecos River, such as Malaga Bend. This zone may serve as a subsurface conduit or French drain for the regional system. Locally, fracture patterns manifested as drainage patterns are observed from the air along the Livingston Ridge escarpment and across the WIPP site. The effect of fracture zones on groundwater will vary depending on the hydrologic system dynamics.

Karst processes in the vicinity of Nash Draw have been active throughout the geomorphic and geologic past, and have created various heterogeneities in the overlying hydrogeologic units (DOE 2004). However, it is unlikely that the deeper units are producing karst today, because most of the reactive water is considerably distant from the WIPP site, and the current Magenta and Culebra groundwater flow systems do not appear to have characteristics consistent with karst development (e.g., very long equilibration times are observed). The potential for karst formation would have been greatest approximately 22,000 to 18,000 years ago, when the last North American ice sheet reached its southern limit roughly 1500 km north of the WIPP, and precipitation was approximately twice that of the present (Corbet and Knupp, 1996).

The broad regional impacts to the area caused by human activity include potash mining and oil and gas development. Potash mining has resulted in the development of discharge lakes in Nash Draw and vicinity. Groundwater injection may affect the potentiometric surface of various aquifers between the surface and the targeted salt units in the subsurface. Concurrently, the mine discharge lakes created by this process may constitute hydrologic inputs, such as recharge into the local and regional groundwater systems. Similarly, oil and gas development may significantly change the groundwater systems, depending on whether the injection or withdrawal (pumping) process is being used at each well site. The exact effects of the potash lakes have not been determined as part of this study. However, these lakes have water chemistry characteristics that generally would not be favorable for promoting karst development, including high TDS and bicarbonate concentrations.

Construction at the WIPP site has included mine shafts, repository excavation, roads, buildings, and other facilities. These facilities could affect each hydrologic system differently based on design, hydrogeologic units breached, and position in hydrologic system. The hydrologic effects of these features are monitored by DOE (DOE 2004).

5.2 GEOLOGY AND HYDROGEOLOGY

The stratigraphic and lithologic units (soil and rock) have been determined using soils, geology, and geophysics databases by various investigators, and are summarized in DOE 2004. The local and regional structures that may affect the groundwater system at WIPP are also summarized in DOE 2004. The hydrogeology of the WIPP site was characterized by analyzing each hydrostratigraphic unit in terms of thickness, porosity, permeability, hydraulic conductivity and transmissivity, and storativity (DOE 2004). Most of these units were quantified based on aquifer tests, laboratory analysis, or parameter estimation and modeling (DOE 2004).

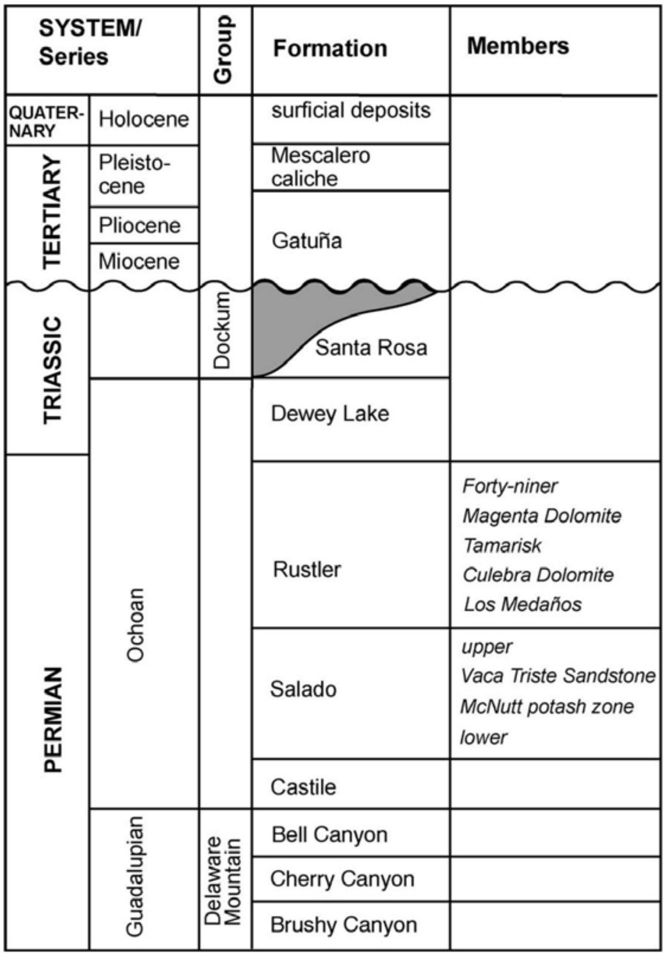


Figure 5-2. Site Geologic Column of the Permian through the Quaternary

The Permian is the thickest system in the northern Delaware Basin, and it is divided into four series from the base to top: Wolfcampian, Leonardian, Guadalupian, and Ochoan (Figure 5-2). According to Keesey 1976, the three lower series total 2,647 m (8,684 ft) near the site. The Ochoan Series at the top of the Permian is approximately 1,200 m (3,938 ft) thick at DOE-2, about 3.2 km (2 mi) north of the site center.The Rustler is the youngest evaporite-bearing formation in the Delaware Basin. Vine 1963 extensively described the Rustler in Nash Draw and proposed the four formal names and one informal term that were used for the stratigraphic subdivisions of the Rustler. These are as follows (from the base): Los Medaños, Culebra Dolomite Member, Tamarisk Member, Magenta Dolomite Member, and Forty-niner Member (Figure 5-3). A discussion of the hydraulic properties of all of the members of the Rustler is presented in Attachment B of this report. Since the Culebra and Magenta are more important with respect to groundwater flow and the potential formation of karst, however, a brief summary of their hydraulic characteristics is provided below.

The Culebra hydrogeologic unit has a bimodal transmissivity distribution (Figure 5-4). The low transmissivity measured values probably indicate porous-medium conditions, whereas the high transmissivities may indicate dual-porosity conditions due to fracturing (DOE 2004, Appendix PA, Attachment TFIELD; Chapter 7 of Beauheim and Ruskauff 1998). Aquifer tests showed differences in head declines with direction, which may be attributed to Culebra hydraulic conductivity heterogeneity (DOE 2004).

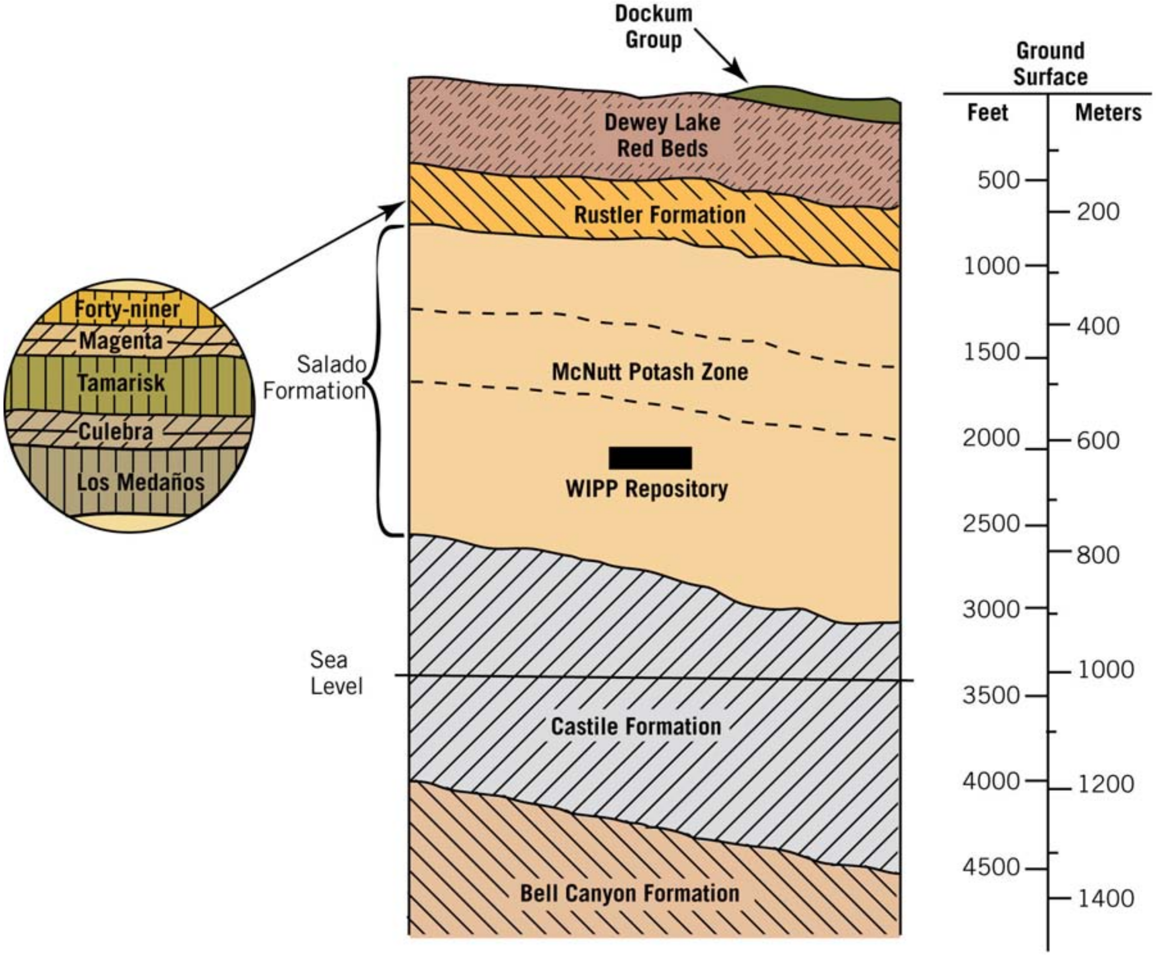


Figure 5-3. Stratigraphy at the WIPP Site

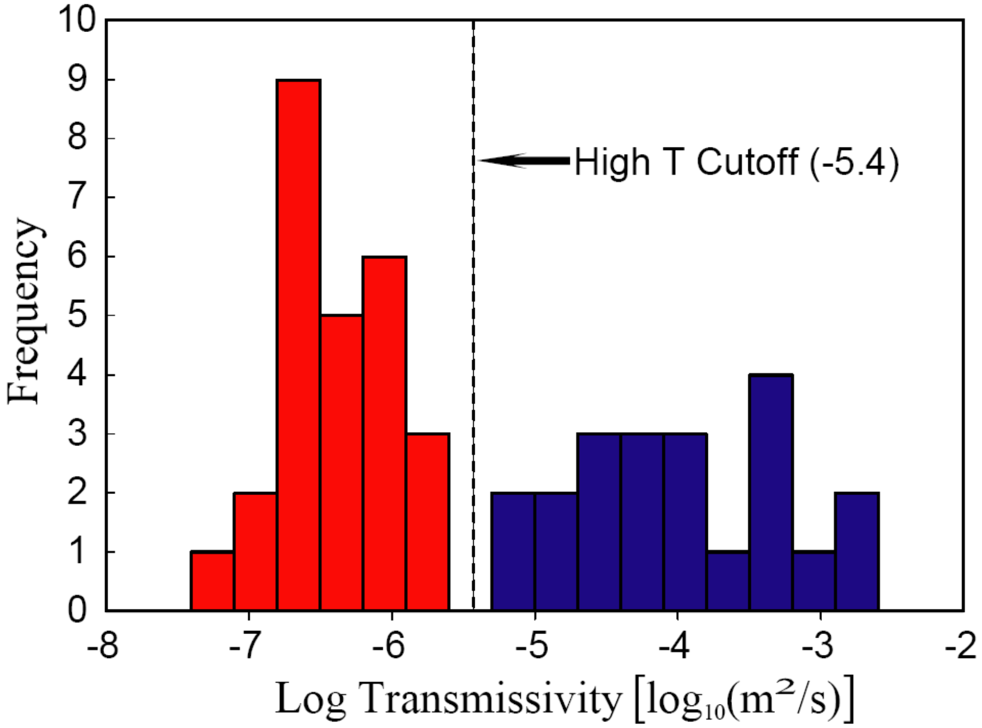


Figure 5-4. Histogram of Log$_{10}$ Culebra T

(TFIELD-5 in DOE 2004, CRA Appendix PA, Attachment TFIELD)

The Magenta hydrogeologic unit most likely functions as a porous medium. Transmissivities in the Magenta are low, with 16 of 18 reported values less than or equal to 1×10^{-6} m^2/sec (DOE 2004). Because there were such low flow conditions, standard aquifer tests were not conducted by DOE in the Magenta; slug-test were the only effective method to test these wells. Slug-test data are consistent with standard porous-medium type curves. Higher Magenta transmissivity values are observed in Nash Draw at WIPP-25 and WIPP-27, and may reflect the impact of dissolution and subsidence in this area (DOE 2004).

The hydrostructural units at the WIPP site, most notably the potential karst features observed at the surface at WIPP-14 and WIPP-33, were characterized by drilling for continuity and hydrogeologic framework and for hydrologic system attributes. The interpretation of the results of this drilling have been discussed and debated by DOE 2004, Hill 1999, and Snow 1998. Beauheim et al. 2000 points out that in WIPP-14 an interval of about 81 ft in the upper unnamed lower member, now called the Los Medaños Member, was reported as “mud” or variations of this in the drilling log based on the cuttings. This has been interpreted as a mud-filled cavern by Phillips 1998.

The geophysical logs for this interval, however, show an unaltered normal signature as observed in hundreds of other wells (near and far) and does not show any evidence of being a "mud-filled" cavern. This interval even includes an unmistakable anhydrite bed that is about 10-ft thick and is commonly referred to as "A-1." Phillips 1998 has not explained this contradictory evidence from the WIPP-14 geophysical logs in his interpretation of a mud-filled cavern in the Los Medaños Member. Furthermore, the presence of so-called "underground rivers," either hydrologically or lithologically, has not been directly shown by these drill holes, or other drill holes into the Culebra or Magenta hydrogeologic units.

5.3 HYDROLOGIC SYSTEMS

EPA conceptualized the modern hydrologic system around WIPP with respect to type and distribution of recharge and discharge for each of the hydrogeologic units. The conceptualization of these individual hydrogeologic units was then expanded to include the WIPP site groundwater flow system. Groundwater geochemistry and age were also considered in the hydrologic system evaluation.

5.3.1 Conceptual Model for Magenta Groundwater Flow System

Groundwater recharge to the Magenta appears to be mostly from regional sources to the north and northwest, and possibly the northeast, of the WIPP site (Corbet and Knupp, 1996). Based on the age of the groundwater, which is greater than 10,000 years, and the high TDS of the Magenta groundwater (DOE 2004), the water appears to have traveled slowly and over great distances from its source. One potential recharge source may be the interaquifer connection between the Capitan, Magenta, and Culebra hydrogeologic units to the north and west of the WIPP site (DOE 2004). This source of groundwater may explain why the regional heads of the Magenta and Culebra aquifers are similar, even though aquifer tests at the WIPP site indicate no hydraulic connection in this part of the regional system (DOE 2004). One local recharge zone located in the lower part of Nash Draw will add groundwater to the Magenta downgradient of the WIPP site. The relationship between the magnesium and potassium concentrations and the hydraulic properties of the hydrologic unit of the Magenta Dolomite Member is not as well defined as in other units, but does exist. The mineralization of the water and the combined concentrations of magnesium and potassium in the Magenta increase from the northwest to the southeast. The unusually large degree of mineralization in the water at test hole WIPP-27 may be caused by a relatively well-developed hydraulic connection between the Magenta and other rock units that contain highly mineralized water (Mercer 1983).

5.3.2 Conceptual Model for the Culebra Groundwater Flow System

Groundwater recharge to the Culebra is believed to be mostly from regional sources to the north and northwest of the WIPP site. Based on the age (greater than 10,000 years) and the high TDS chemistry of the Culebra groundwater (DOE 2004), the water appears to have traveled slowly and over great distances from its source. One potential recharge source may be interaquifer connection between the Capitan, Magenta, and Culebra hydrogeologic units to the north and west of the WIPP site (DOE 2004). As noted for the Magenta aquifer, this may explain why the regional heads of the two aquifers are similar, even though aquifer tests at the WIPP site indicate no vertical hydraulic connection in this part of the regional system. One possible local recharge zone, an area located in the lower part of Nash Draw (Figure 5-5), may add groundwater to the Culebra downgradient of the WIPP site. The chemistry of Culebra groundwater along these flow paths is affected by downgradient local recharge and has lower chloride, higher carbonate/bicarbonate, and lower TDS than the Culebra water at the WIPP site (Mercer 1983).

Important aspects of the Agency's conceptual understanding of the system are derived from the work conducted by Corbet 1997. In this effort, Corbet integrated the hydrochemical facies delineated by Siegel et al. 1991, with that of the hydrogeology to assess groundwater flow and recharge characteristics. As shown in Figure 5-5 below, Siegel et al. 1991 define four hydrochemical facies in the Culebra.

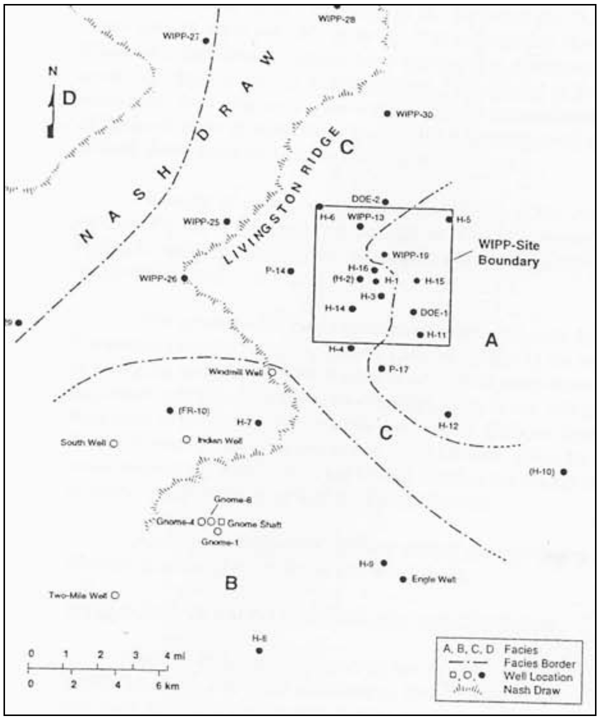


Figure 5-5. Four Hydrochemical Facies in the Culebra Siegel et al. 1991

The most important attributes of Facies A, B, and C with respect to our conceptual model and the potential for karst development are the following (insufficient information is available on Facies D groundwater to draw relevant conclusions):

- Facies A
    - Groundwater is very saline (2 to 3 molal) with Mg/Ca molar ratios of about 1.2 to 2.
    - Groundwater flow within this region is extremely slow; on the order of about 1 meter in 1,000 years.

  - Vertical leakage into the Culebra is extremely slow because the overlying anhydrite confining layers have not been fractured.

- Facies B
  - Contains relatively dilute $CaSO_4$-rich groundwater (ionic strength < 0.1 molal)
  - Hydraulic conductivity of the Culebra in this area is higher than in region of Facies A, because it has been enhanced by fracturing.
  - The modern-day flow direction is from northwest to southeast. Model simulations suggest, however, that flow directions in this portion of the Culebra were directed toward Nash Draw during wetter climates.
  - Because of enhanced hydraulic conductivity of the overlying anhydrites, the rate of vertical leakage into the top of the Culebra is possibly an order of magnitude faster than within the region of the Facies C groundwater.

- Facies C
  - Contains waters of variable composition with low to moderate ionic strength (0.3 to 1.6). Mg/Ca molar ratios of the fresher waters in this zone (ionic strength <1.25) range from about 0.3 to about 1.2. The most saline (NaCl-rich) water is found in the eastern edge of this zone, close to the locations where halite is observed in the Tamarisk Member.
  - Groundwater in this area flows, on average, from north to south.
  - The rate of lateral flow in this facies is faster than in Facies A, but slower than in Facies B.
  - Facies C water is primarily water that infiltrated the Dewey Lake Formation and then interacted with anhydrite and, in places, halite along its path to the Culebra.

The Culebra flow system is conceptualized as groundwater flowing from the north and northeast to the south and southwest. Minor flexures in the hydrostratigraphic units may locally deflect the Culebra flowpaths into a southerly, or even southeasterly direction, but the regional flow paths should trend toward the south to southwest based on the potentiometric surface. The groundwater flow, characterized as confined and dual-porosity, is slow with no evidence of rapid groundwater flow conduits or chemistry changes, and no evidence of vertical connection to adjacent aquifers.

The regional groundwater discharge areas of the Culebra at the WIPP site appear to be far to the south and east of the WIPP site (Corbett and Knupp, 1996). It is anticipated that Culebra water discharges vertically into surrounding units in the Texas area (Corbett and Knupp, 1996). In contrast to the Magenta, the Culebra does have subregional discharge zones observed as springs at the southwest end of Nash Draw and along the Malaga Bend area of the Pecos River. The discharge springs in Nash Draw may be the result of groundwater flow from the north or northwest, whereas the springs at Malaga Bend may be part of the greater WIPP subregional system. However, these discharges are relatively small and do not appear to have sufficient flow rates to indicate the presence of "underground rivers."

The Agency's conceptualization of temporal aspects of groundwater flow in the Culebra is based on a comprehensive investigation of past and future system behavior conducted by Corbett and Knupp 1996. Their work was performed to gain a better conceptual understanding of how changes in climate affect groundwater flow in the vicinity of the WIPP. Corbett and Knupp 1996 conducted a series of steady-state simulations to examine the sensitivity of simulation results to assumed values for hydraulic conductivity and recharge rate. Transient simulations, covering the time period from 14,000 years in the past to 10,000 years in the future, provided insight into how patterns of groundwater flow respond to changes in climate.

Simulation results suggest that rates and directions of groundwater flow in the Culebra change with time due to interaction between recharge, movement of the water table, and the topography of the land surface. A cooler and wetter climate in southeastern New Mexico during the late Pleistocene resulted in a groundwater flow system in which the water table was near the land surface and flow directions in the Culebra were controlled by local-scale features of the land-surface topography. When the water table is near the land surface, the gentle east-to-west slope of the land surface in the vicinity of the WIPP caused groundwater in the Culebra to flow toward and discharge into Nash Draw, a topographic depression. The water table dropped to a lower elevation and became smoother in response to a decrease in recharge that occurred over the period from 14,000 to 8,000 years ago.

Consequently, modern-day flow directions in the Culebra reflect regional rather than local features of the topography. Changes in groundwater flow, however, lagged behind changes in the rate of recharge. The present-day position of the water table is still adjusting to the decrease in recharge that ended 8,000 years ago. Groundwater inflow to the portion of the Culebra within the WIPP-site boundary is by a combination of lateral flow within the Culebra and extremely slow vertical leakage from overlying units. Nearly all outflow from this portion of the Culebra is by lateral flow. Therefore, contaminants introduced into the Culebra will travel toward the accessible environment along the Culebra, rather than by leaking upward or downward into other units. Natural changes in flow in the Culebra over the next 10,000 years will be small, and will mainly reflect future short-term wet periods such as have occurred over the past 8,000 years. Maximum future flow rates in the Culebra are expected to be less than two times greater than present-day rates.

Although much of the discussion pertaining to dissolution has been focused on carbonates, the dissolution of halite and gypsum is also relevant to the WIPP site. As noted by Powers and Holt (2000), four halite beds of the Permian Rustler Formation thin dramatically over short lateral distances to clastic (mudstone) beds. These mudstones have long been considered residues after post-burial dissolution of halite, assumed to have been deposited continuously across the area. Facies changes in response to depositional environments provide an alternative probably more accurate explanation for dramatic thinning of these halite beds.

Differences between these two explanations for the distribution of halite in the Rustler have broad implications. Hydraulic properties of the Culebra Dolomite Member vary by several orders of magnitude and have been related to post-burial dissolution of Rustler halite. If the halite beds are distributed as they were deposited, however, Culebra hydraulic properties are not related to post-burial dissolution of Rustler halite (Lorenz 2005).

The depositional model proposed by Powers and Holt 2000 accounts for sedimentary features of the Rustler mudstones. Marked facies and thickness changes are consistent with influence by subsidence boundaries, as found in some modern continental evaporites. A dissolution model accounts for limited brecciated zones along (depositional) halite margins, but bedding observed in the mudstones would not survive 90% reduction in rock volume (i.e., had dissolution been active in these units).

5.4 KARST DEVELOPMENT AND SO-CALLED "UNDERGROUND RIVERS" IN THE CURRENT AND FUTURE HYDROLOGIC SYSTEMS

Large-scale karst development (e.g., "underground rivers") requires abundant fresh water that is free to circulate through the karst-forming rocks. The water dissolves minerals in the rocks, and encourages the growth of vegetation and soil microbial activity that add extra carbon dioxide (CO_2) to the system. Karst development is greatest in humid, high-rainfall environments with abundant sources of fresh water.

The dissolution process is the dominant chemical driving mechanism in karst terrains. Calcite, as a matrix mineral, is more soluble then dolomite. The dominant solvent is rainwater, which is a mixture of water and atmospheric carbon dioxide that forms carbonic acid (H_2CO_3). Water and carbonic acid readily produce reactive water that has a pH of 5.7 or lower, depending on other constituents in the atmosphere. Therefore, rainfall is highly reactive with respect to karst development, and the maximum karst development will be where this water first comes in contact with the rock matrix (soil water vadose zone areas and areas of groundwater recharge). As the rain and soil water react with the rock, the pH will rise, the water will become saturated with respect to calcite, and the dissolution process will diminish or stop. The process can continue in areas where underground waters are mixed, if the resulting water mixture is again undersaturated with respect to calcite. This undersaturation would allow continued dissolution of the rock matrix, and generally occurs where relatively fresh water is introduced to water in an underground system that is saturated with respect to a particular material (e.g., halite).

The circulation rate of water though the rock matrix is important for dissolution to continue and for moving saturated water out of the system to be replaced by reactive fresh water. Older water that is saturated with respect to calcite and dolomite will produce little dissolution, and generally does not produce large-scale karst features such as underground rivers (Kaye 1957; Weyl 1958).

With respect to Magenta and Culebra recharge in the vicinity of WIPP, it appears that the WIPP site and Nash Draw are distinctly different. Nash Draw is a topographic depression that has been eroded and undergone dissolution in the past. These processes, in combination with dip, or tilt, of the Rustler Formation, have exposed the Magenta and Culebra and other parts of the Rustler Formation in some parts of Nash Draw. Thus, if there is a precipitation event in Nash Draw, the surface openings can capture the precipitation and the local system can respond quickly to the precipitation. This precipitation could thus have reactive water that could continue the dissolution process in Nash Draw.

In contrast, the Rustler Formation at the WIPP site is hundreds of feet below the surface. In order for the Rustler Formation to be recharged at the WIPP site, the precipitation must infiltrate through the Mesacalero Caliche, the Gatuna, the Santa Rosa, and then the Dewey Lake. Only then could the precipitation contribute to recharge of the Rustler Formation. Corbet 1997 estimates that Facies C groundwater, which is present in the west half of the WIPP site, to have a vertical specific discharge of 0.01 to 0.03 m/ 1000 years. He estimates that vertical specific discharge for groundwater in Facies A, which is present in the eastern half of the WIPP site, has even slower vertical movement. Thus, with such slow vertical flow from the surface to the Magenta and Culebra, and the need to cross the anhydrites above the Magenta, any water infiltrating from the surface at the WIPP site would be unable to dissolve the Magenta or Culebra and create karst. Precipitation events at the WIPP site would thus not be reflected in discharges in Nash Draw.

In addition, recent work highlights just how limited recharge is in the desert southwest. According to Walvoord and Scanlon 2004, “diffuse recharge through the basin floor probably contributes only minimally to the total recharge in arid and semiarid basins,” such as in the WIPP area. Evidence from multi-year studies indicates that vegetation has the ability to capture all available soil moisture within the root zone and that groundwater recharge rates are extremely small, or even negative, with current flux estimates across the water table on the order of 0.01 to 0.1 mm yr^{-1} (*Ibid*).

5.4.1 Magenta Dolomite

Nash Draw

Karst formation in the Magenta may be observed at the southern end of Nash Draw and in the surrounding area where local recharge to the aquifer may be occurring (Figure 5-1). However, this part of the Magenta flow system is downgradient from the WIPP site, and will not affect the WIPP site groundwater system. “Underground rivers” are not observed in this recharge area, but ephemeral lakes and losing ephemeral streams may be observed during wet years or during intense thunderstorm activity. It is also anticipated that some potash mine lakes may also increase groundwater recharge to the Magenta aquifer. However, potash effluent is probably not able to significantly dissolve rock, due to high TDS and carbonate/bicarbonate concentrations.

WIPP Site

Areas of regional recharge derived from surface precipitation or surrounding connecting aquifers, which may contain reactive water, such as fresh water for the Magenta, are located more than 20 km northwest from the WIPP site. Recharge that comes from such a distance is not likely to cause modern karst formation or “underground river” development over the WIPP site, because the long travel time to reach the WIPP site would create unreactive water. Local infiltration of precipitation through the overlying strata at the WIPP site does not appear to be significant for recharge, karst, or “underground river development” in the Magenta. The reactivity of any infiltrated fresher water would be expected to be altered by interaction with the Mescalero caliche or other calcium carbonates in the eolian materials or soils. The Mescalero Caliche, Santa Rosa, Dewey Lake, and Upper Rustler units are expected to physically serve as a barrier to infiltration as deep as the Magenta at the WIPP site. The Magenta water chemistry and old age indicate that no mixing is occurring with surface precipitation, and that this water would not be expected to dissolve dolomite (DOE 2004).

The Magenta is a thin, nearly flat-lying unit functioning essentially as a porous medium, with minimal or no interconnected fracture contributions, based on data from well logs, surface features, and aquifer tests. No major hydrostructures (fracture zones or faults) have been reported or verified. The Magenta rock matrix does not appear to have favorable chemical or physical characteristics for producing karst or "underground rivers" at the WIPP site.

The Magenta groundwater flow system at the WIPP site does not favor karst or "underground river" development, because it is characterized as being low gradient with poor circulation of fluids. The groundwater chemistry shows little variation in composition at the WIPP site, suggesting that no high-circulation, reactive water from "underground rivers" or sinkhole conduits is mixing with the low-gradient, slow-moving matrix water of the regional system. In addition, there is no evidence of major regional fault zones traversing the site. Any groundwater discharge zones in the Magenta are significantly far from the WIPP site to the southwest near Nash Draw, and the observance of major springs or "underground rivers" discharging to the surface are not documented.

The interconnection of the Magenta and the underlying Culebra unit groundwater at the WIPP site is considered unlikely near the WIPP site. Although the potentiometric heads of both units are similar at some well locations, aquifer tests conducted in the Culebra hydrogeologic unit at the WIPP site indicate that there is no apparent connection between the Magenta and Culebra units (DOE 2004). Similar observations are made at the two wells drilled at WIPP-14 and WIPP-33.

5.4.2 Culebra Dolomite

Nash Draw

Karst formation in the Culebra can be observed at the southern end of Nash Draw and surrounding area, where local recharge to the aquifer may be occurring (Figure 5-1). However, this part of the Culebra flow system is downgradient from the WIPP site, and will not affect the groundwater system on-site. Major "underground rivers" are not observed in this recharge area, but permanent (Salt Lake) and ephemeral lakes, and losing ephemeral streams may be observed during wet years or during intense thunderstorm activity. Some potash mine lakes may also increase groundwater recharge to the Culebra aquifer in this area. However, potash water is probably not reactive due to high TDS and carbonate/bicarbonate concentrations.

WIPP Site

As with the Magenta, the areas of Culebra regional recharge derived from surface precipitation or surrounding connecting aquifers are located far from the WIPP site, and are not considered significant for causing modern karst formation and "underground river" development. Local recharge to the Culebra by infiltration of precipitation through the overlying strata at the WIPP site is also not considered significant for recharge or karst development. The reactivity of the infiltrated water would be expected to be altered by interaction with the Mescalero Caliche or other calcium carbonates in the eolian materials or soils. The Mescalero Caliche, Santa Rosa, Dewey Lake, and Upper Rustler units thus appear to serve as a barriers to vertical infiltration of fresh water as deep as the Culebra unit. In addition, the Magenta and the Tamarisk confining units would be expected to serve as barriers stopping infiltration to the Culebra. The Culebra water's unchanging chemistry within a geochemical facies and old age indicate that no mixing is occurring with surface precipitation (Corbet 1997).

The Culebra rock matrix does not appear to have favorable chemical or physical characteristics for producing large-scale karst or "underground rivers" at the WIPP site (Corbet, 1997). The Culebra is a thin unit functioning as a dual-porosity hydrogeologic unit (equivalent porous media with fracture contributions) based on well logs, surface features, and aquifer tests. The Culebra aquifer has a hydraulic conductivity approximately an order of magnitude higher than the Magenta (DOE 2004).

The Culebra groundwater flow system is characterized as being low gradient with poor circulation of fluids, which does not favor karst or underground river development. The groundwater chemistry shows little variation in composition at the WIPP site, suggesting that no high-circulation, reactive water from "underground rivers" or sinkhole conduits is mixing with the low-gradient, slow-moving matrix water of the regional system. In addition, there is no evidence of major regional fault zones traversing the site. Locally, reactive water is mixing with the regional system at the southern end of Nash Draw, causing the removal of halite and its replacement by carbonate. However, this part of the system still has low-gradient groundwater circulation within the system. Therefore, localized small-scale karst development may be occurring at the southern end of Nash Draw, but "underground rivers" are unlikely. Furthermore, this southern part of the Culebra hydrologic system would have no effect on the performance of the WIPP repository, because the recharge areas and areas of geochemical mixing are far away and downgradient of the site.

With respect to the potential for karst development in the future, mean annual precipitation 22,000 to 18,000 years ago, when the last North American ice sheet reached its southern limit roughly 1500 km north of the WIPP, was approximately twice that of the present (Swift 1993). Data from plant and animal remains and paleo-lake levels permit quantitative climate reconstructions which confirm the interpretation that conditions were cool and wet during glacial maxima (Swift 1993). Relatively short-term climatic fluctuations in southeastern New Mexico have occurred throughout the Pleistocene and Holocene with periodicities on the scale of thousands of years (Swift 1993). The causes of these nonglacial fluctuations are, in general, unknown, but paleoclimatic data indicate that precipitation may have approached glacial highs for relatively short periods (1000 to 2000 years) at some times during the Holocene (Swift 1993). Based on the past record, fluctuations of this sort are possible and perhaps likely during the next 10,000 years. These fluctuations will, however, on a scale of 10,000 years be short-lived, and the potential for karst development would be far less than experienced during the continuously high precipitation during the Pleistocene.

6.0 COMPARISONS WITH ALTERNATIVE CONCEPTUAL MODELS

The conceptual model described in Section 5.0 indicates that karst is not present at WIPP and will not form at the WIPP site and influence groundwater transport from the repository. Other conceptual models have been proposed for the WIPP site that include the potential for karst effects on groundwater transport (Snow 1998; Hill 1999). These models were reviewed to determine if they include any credible evidence that karst processes could affect groundwater transport at the WIPP site during the 10,000 year regulatory period.

6.1 SNOW 1998 CONCEPTUAL MODEL

Snow 1998 presented a conceptual model that hypothesized the presence of karst at the WIPP site. In this paper, titled "Hydrological Conditions at the WIPP Site at Variance with the Assumptions of DOE in its Performance Assessment," Snow speculated on the potential implications of hypothetical karst to the overall performance of the repository. Major assumptions of Snow's hypothesis include the following:

- The WIPP site lies within the recharge area for an unconfined karst aquifer
- Culebra has fractures (voids) and conduits caused by dissolution
- Dissolution from recharge has produced fracture enlargements sufficient to conduct storm waters directly to the phreatic and vadose zones

Beauheim et al. 2000 provide a critique of Snow's assertions; a brief discussion of Snow's arguments and Beauheim's rebuttal is presented below.

6.1.1 Presence of Point Recharge in the Vicinity of the WIPP Site

Snow notes (p.7) that, although there are no tests of vadose zone conductivity, there are observations suggesting local conduits of great infiltration capacity. Snow further indicates that Phillips 1987 has demonstrated that the Mescalero Caliche is discontinuous, so rainwater is funneled through discrete water conduits through the Dewey Lake sediments and down several hundred feet to the water table. At WIPP-33, Snow (p.7) suggests that an alluvial-filled depression is present that totals 29 ft in height occurring in the Dewey Lake, Forty-niner, and Magenta strata. Snow believes that these typify dissolution conduits (i.e., karst) found elsewhere in the vicinity of the WIPP site.

Snow (p.8) ties the significance of the direct conduits for recharge to recharge estimates which he states are "proportionately linked to travel times." He also points out that "if the model is conceptually wrong for the 10,000 year period of concern, when the water table is likely to have recovered from man-made disturbances, then the current gradients and the measured transmissivities are incorrect." Beauheim et al. 2000 (p. 2) refute Snow's claims pertaining to enhanced recharge through dissolution features by stating that, "Other than the area around WIPP-33, no geologic or geophysical evidence has been found to support the existence of sinkholes or other subsidence features. Nor are "discrete conduits" needed to conduct whatever recharge occurs in the semiarid WIPP environment to the water table in the Dewey Lake; the permeability of the upper Dewey Lake is more than adequate for the task, albeit at a slower rate than discrete conduits." Beauheim et al. 2000 (p. 2) also state that "Snow's claim of a 7-ft cavern in the Dewey Lake in WIPP-33 is false (see Sandia National Laboratories and U.S. Geological Survey, 1981)."

Although DOE agrees with Snow that dissolution has occurred in the vicinity of WIPP-33, DOE believes that the dissolution is contained within a localized area and is not representative of more widespread karst formation as Snow contends. DOE also indicates that recharge does not need to be localized and focused into small areas to account for the volume of water reaching the water table. Beauheim 2000 (p. 2) makes the following observations to refute Snow's claim that high-angle dissolution features connect all of the Rustler members and Dewey Lake:

- No response to rainstorms has ever been observed in wells monitoring the Culebra, Magenta, or Los Medaños Member.

- The vertical fracture described by Snow (p. 6) was open at the surface because the halite filling was partially dissolved by water seeping downward on the shaft wall from the Culebra.

- If the units were all connected, the hydraulic heads would all be the same; or at least very similar. In fact, with the exception of the northwest corner of the WIPP Site, the heads in the Magenta and Culebra are very different.

- Culebra and Magenta water quality at H-6 are also distinctly different.

- Hydraulic tests indicate storativities representative of a confined system and no partial-penetration responses have been observed.

After reviewing the available information, the Agency concludes that dissolution has occurred in the immediate vicinity of WIPP-33. There is no evidence, however, that dissolution is pervasive or has led to connected pathways (e.g., "underground rivers"). From the perspective of performance assessment, this lack of interconnection between localized dissolution features will render any effects on travel times insignificant. If, in fact, point recharge is occurring, the effects have already been taken into account in hydraulic gradients measured in the Culebra and used in the WIPP performance assessment.

6.1.2 Dissolution Channels and Fracture Enlargements of the Culebra

Snow (p.2) notes that it would be worthwhile to inquire how the fracture characteristics differ between the Culebra and Magenta dolomites and the thicker intervening anhydrites. Snow further speculates that mechanical differences among the rocks have led to different fracture spacings. Snow (p.2) subsequently makes the following arguments that the Culebra has conduits:

- The fracture spacings are large enough that they have been missed during drilling

- Coring has revealed that openings in each fracture are limited laterally by the infillings of gypsum

- Conduits following bedding must connect to steep dissolution openings that cross the bedding, providing recharge and discharge connections to major karst channels near the water table

Although Beauheim 2000 does not comment specifically on any of Snow's arguments above, he does question how Snow can in one instance acknowledge that the hydraulic conductivity in the Culebra is modest (Snow 1998, p. 2) "since it takes years to come to steady-state, untypical of karst conditions," and under other circumstances argue that the system will quickly equilibrate (Snow 1998, p. 2) under wetter conditions.

Based upon the available information, the Agency concludes that Snow never really makes a cohesive argument that there are karst features in the Culebra. Most of his discussion is describing fractures in the Culebra and their frequency. In fact, his belief that there are recharge conduits, in conjunction with his observation that the system responds so slowly, leads to an internally inconsistent conceptual model. If recharge were quickly reaching the Culebra and there are karst features in the Culebra, the system would quickly equilibrate and, because of the low-storage properties of the Culebra and Magenta, the potentiometric surface would rise very quickly following a rain event. Furthermore, as discussed in the next section, Snow's main arguments are geared towards the presence of karst features above the Culebra, near the water table.

6.1.3 Evidence for Karst Features in the Phreatic and Vadose Zones

Snow 1998 (p. 6) presents a number of lines of conjecture for karst features being present in the phreatic zone including:

- Work by Phillips 1998 in which he describes information from boreholes and the shaft as "cavernous zones"

- Heads in the Culebra and Magenta are equal in wells H-6, WIPP-13, WIPP-33 and WIPP-25 which (according to Snow) attest to the vertical hydraulic connections across the Tamarisk

- Evidence of dissolved fracture fillings in the Culebra everywhere except east of the site

Beauheim et al. 2000 (p. 7) responds to Snow's assertions by first questioning many of the conclusions made by Phillips 1987 regarding potential cavernous zones upon which Snow has based his arguments. For example, Phillips includes "washouts" in the ventilation shaft, lack of core in some drillholes, cuttings reported as "mud," loss of circulation, and lost core as his principal evidence of cavernous zones. According to Beauheim, core was never collected from the intervals in WIPP-14 that Phillips claims were lost; the washout in the ventilation shaft occurred while drilling with a 6-ft diameter drill bit; the shaft was later mined exposing those units as mudstone that Phillips claims are karst; and geophysical logs in WIPP-14 indicate a normal signature although Phillips contends that an interval around 81 ft is a mud-filled cavern.

DOE has reported cavernous porosity at WIPP-33 which was evident by the drill stem dropping in the cavernous zones as reported by the project (DOE 2004). No other drillholes within the Land Withdrawal Area (LWA) encountered open cavernous porosity and drops in the drilling string.

With respect to Snow's assertion that heads are equal in the Magenta and Culebra at Wells H-6, WIPP-13, WIPP-33, and WIPP-25, Beauheim (p.3) points out that no Magenta monitoring has ever been performed at WIPP-13, and no monitoring of either the Culebra or Magenta was performed before WIPP-33 was plugged and abandoned, so Snow's assertion of equal heads at those two wells is baseless. Magenta and Culebra heads are, in fact, equal within measurement uncertainty at Wells H-6 and WIPP-25. The degree of hydraulic connection between the Culebra and Magenta at WIPP-25 in Nash Draw is uncertain. The water qualities from the two units are similar, although not identical (Lambert and Robinson 1984). At H-6, however, hydrologic data indicate that the Culebra and Magenta are clearly not well connected despite the similar heads. During the WIPP-13 multipad pumping test, approximately 18 ft of drawdown was observed in H-6a and H-6b, both completed in the Culebra, while no response was observed in H-6c completed to the Magenta (Beauheim 1987b). Culebra and Magenta water qualities at H-6 are also distinctly different (Randall et al. 1988).

As discussed in Section 5.0, the Agency's conceptualization of the Rustler sedimentology is based on findings by Powers and Holt 2000 that indicate that halite is distributed nearly as it was originally deposited. Snow, however, believes that this assumption is wrong, and that dissolution is responsible for the current distribution of halite. Beauheim (p. 6) sums up the shortcomings with the 15 references used by Snow to support his case as follows:

(1) Not one of the references deals with the observations of the large-diameter shafts at WIPP

(2) Only Ferrall and Gibbons 1980 and Lowenstein 1987 provide any indications of sedimentologic observations from these units

(3) Without the shaft observations, the cores provide limited information on the scale of the bedding, channels, and other sedimentary features reported by Holt and Powers (1984, 1986, 1988, and 1990)

As far as recharge to the vadose zone is concerned, Snow cites Phillips 1998 in presenting evidence that the Mescalero caliche is discontinuous at the site and that this may help funnel recharge to the underlying units. Beauheim (p. 8) responds that breaks in the Mescalaro and other caliches in the area are a well-known phenomenon. So-called "flower pots," and other breaks in caliche, are observable in many areas. DOE, however, does consider the Mescalero a barrier that reduces recharge. Furthermore, there is no evidence that there is significant collapse, especially deep-seated, in the bedrock underlying the caliche within the LWA.

6.2 HILL 1999 CONCEPTUAL MODEL

Hill 1999 presented a conceptual model for a general karst system at the WIPP site. Hill interprets the presence of karst based on the following information:

- Topographic Depressions East of Nash Draw
- Negative Gravity Anomalies
- Lack of Surface Runoff
- Recharge and Discharge Characteristics
- Culebra and Magenta Head Relationships
- Spatial Variability in the Chemistry of the Culebra Formation Waters
- Potential for Karst at WIPP-13, WIPP-14 and H-3

Lorenz et al. 2005 prepared an independent assessment of the potential for the occurrence of karst in the vicinity of the WIPP site. As part of that assessment, Lorenz addressed the arguments made by Hill 1999. The most relevant aspects of these findings are presented below.

6.2.1 Topographic Depressions East of Nash Draw

Hill 1999 (pp. 36–37) suggests that several topographic depressions at the WIPP site are evidence for the collapse of karst caverns at depth, presumably within the Rustler Formation.

Hill notes that the largest topographic depressions at WIPP seem to be at WIPP-14 and at WIPP-33. Lorenz 2005 (p. 21) responds that in order for a lowering of the ground surface to be related to collapse of the underlying strata, those underlying strata must have been removed or displaced, and will commonly have been brecciated.

Lorenz (p. 22) observes that wells drilled in these depressions to sample and test for karst have not encountered either displaced strata or breccias (see below). He further comments that Hill 1999 (Figure 8, p. 18 and Figure 17, p. 41) draws hypothetical, funnel-shaped dissolution structures (Figure 6) to explain why the investigation wells could have missed evidence for karst, and then to suggest that karst is likely in the subsurface since the wells must have missed the karst. A funnel-shaped geometry is incompatible with the cylindrical or inverted-funnel shape common to most sink-hole collapse features. Moreover, the funnel shape, widest at the top, is unlikely since this is the level of the low-solubility sandstones, siltstones, conglomerates, and shales layers that overlie the Rustler Formation at the WIPP site. Hill has not described a plausible process by which a funnel geometry might form in these strata.

6.2.2 Negative Gravity Anomalies

Hill (1999, pp. 37–40; 2003, p. 205) asserts that negative gravity anomalies indicate the presence of karst across the WIPP site. Most of Hill's discussion revolved around the WIPP gravity survey (Barrows et al. 1983). Hill (1999, pp. 37–40; 2003, p. 205) cites the Barrows et al. 1983 report as showing four "sharp" negative gravity anomalies that are "consistent with" solution caverns, although only the WIPP-14 and WIPP-33 anomalies were discussed and attributed to subsurface karsting by Barrows et al. 1983.

Lorenz 2005 (p. 74) believes that the Barrows et al. 1983 discussions are convoluted and sometimes contradictory, and that their interpretations are not definitive. Lorenz (p. 74), for example, indicates that there are discrepancies in Barrows et al.'s discussions of the comparison of density logs between holes and how or whether they indicate karst in the Rustler Formation. Barrows et al. 1983 noted that the WIPP-34 velocity survey logged through the Dewey Lake

Formation has slower overall travel times than the WIPP-13 velocity survey (Barrows et al. 1983, Figure 3.1-3 and discussions on p. 54), indicating that the strata at WIPP-34 are anomalously less dense than normal and inferring that this difference accounts for the deeper local "seismic time structures" at this site. Barrows et al. subsequently portray the same WIPP-34 density log as a normal-response log through the Dewey Lake-Rustler section, suggesting that by comparison, a lower-density log response in the WIPP-14 hole indicates that there is missing material. They extrapolated this to an interpretation of mass removal by karst processes in the vicinity of WIPP-14.

Barrows et al. 1983 calculated that the depth to the top of the "causative structure" that is responsible for the WIPP-14 gravity anomaly is shallow, not more than 225 ft below the surface. This depth puts the inferred deficiency in mass, i.e., karst, within the Dewey Lake Formation, reported to lie between the depths of 141-639 ft in this hole (SNL and USGS 1981). This does not correlate to the two zones (300–400 ft, and 650–750 ft) where Barrows et al. calculated the presence of mass deficiencies from the density logs, or with the concept of karst development being in the Rustler formation.

Barrows et al. 1983 noted that seismic data at the WIPP site above the Castile Formation "are considered too unreliable to map" (1983, p. 16), yet later in the report (p. 57) used this shallow seismic data in the vicinity of WIPP-14 to infer that "a seismic time syncline [is] coincident with the [shallow] negative gravity anomaly. Both the seismic time syncline and the negative anomaly are explained by lateral velocity and inferred density variations comparable to those observed in uphole velocity surveys."

The gravity anomaly at WIPP-33 is outside the WIPP Land Withdrawal Boundary and was not covered by the main gravity map (Barrows et al. 1983, their Figures 2.1-3 and 2.1-4). Rather, this anomaly was documented in an associated reconnaissance gravity survey consisting of two intersecting 2-dimensional vertical gravity profiles specifically shot to assess the topographic depression. The gravity signature of the anomaly shows closure in all four directions in the two gravity lines (Barrows et al. 1983, their Figure 2.3.1-3, p. 50), so it is probably roughly circular and perhaps 1,500 ft across. The overlying topographic depression is about 8 ft deep and 200 ft in diameter, reasonably well centered on the gravity anomaly. Barrows et al. calculated that the top of the "causative structure" for the gravity anomaly, inferred to be void space related to karst, is at a depth of 450 ft. This gravity anomaly coincides with a surface depression, and the WIPP-33 drillhole encountered bit drops in the Forty-Niner and Magenta Members of the Rustler, suggesting subsurface void space at several intervals between the depths of 420-470 ft. This is consistent with the Barrows et al. gravity calculations of the depth of void space, and there are possible overlaps between this gravity anomaly and the resistivity anomaly noted in the northwest corner of WIPP, suggestive of water-filled, high-porosity features at an unspecified depth (Elliott Geophysical 1977).

This is also the approximate domain of interconnected natural fractures in the Culebra Member described by Beauheim and Ruskauff 1998 on the basis of hydrology tests. However, the core and geophysical logs from this hole document depths for the penetrated stratigraphic tops that are on trend with those of surrounding boreholes, i.e., the stratigraphic tops are not lower than normal, not downthrown into a karst-related depression.

Hill 1999 suggests that two other gravity anomalies at and near WIPP also indicate the locations of subsurface karst. These locations are around the WIPP-13 and H-3 drillholes. Hill 1999 (p. 48) states that, "both WIPP-13 and H-3 are located within negative gravity features (sinkholes?)."

Lorenz 2005 (p. 78) noted that the Rustler strata cored in both these holes show some disruption, possible indications of dissolution but more plausibly interpreted as syndepositional (i.e., at the time of deposition) disruption, because they are overlain by undisrupted strata with primary depositional structures. Although Holt and Powers 1988 inferred some stratigraphic displacement of the angular sulfate fragments encountered in the WIPP-13 core just below the contact with the A-3 sulfate of the Tamarisk, they also reported two thin anhydrite beds and a polyhalite bed to the east in a stratigraphically equivalent halite bed. Lorenz concluded that this angular fragment can as easily represent a stratigraphically in-place remnant of one of these thin units, as Holt and Powers 1988 and Powers and Holt 2000 described how the polyhalite, and presumably the upper anhydrites, converge with the base of A-3 westward from the depositional center of the unit. In addition, Lorenz believed that the shaft mapping shows a thin sulfate bed in this stratigraphic position, with a breccia and conglomerates at the base of A-3 and overlain by an erosional surface. Lorenz concluded that both holes encountered normal stratigraphic successions, and the cored breccias are too thin and too deep to have affected the gravity survey.

6.2.3 Lack of Surface Runoff

Hill 1999 (p. 40–42) suggests that (1) because the WIPP site "is characterized by almost no surface runoff," despite 12 inches of annual precipitation, and (2) because the chloride mass balance techniques used by Campbell et al. 1996 suggested that infiltration of water through the soil is not the major source of recharge into the Rustler Formation ["…our data do not support direct infiltration through the overlying soil as the major source of aquifer recharge…", page 164], that therefore, recharge of the subsurface Rustler units must be through surface runoff that flows primarily into sinkholes, and that there must be sinkholes and an associated subsurface karst system at the WIPP site.

On page 80, Lorenz 2005 presented a series of arguments for the lack of surface runoff at the WIPP site which are summarized as follows. The poor development of surface drainage over the WIPP site is due to the absence of requirements for such a drainage network. The low rate of precipitation, the presence of sandy surficial deposits that quickly soak up precipitation, the low dip of the strata that does not funnel drainage in any particular direction, and the shifting of dune sands that blocks drainage as it develops, combine to prevent an organized drainage system from forming in this area. It is not necessary to postulate a complex process of stream capture by an organized system of sinkholes and subsurface drainage to explain this pattern.

6.2.4 Recharge and Discharge Characteristics

Hill 1999 (p. 44 and Appendix A) suggests that records of rainfall near the WIPP site from September of 1986 through December of 1988 can be correlated with discharge variations at the Malaga Bend springs. Discharge from these numerous and obscure springs in the alluvium at and below the riverbed was calculated by subtracting flow in the Pecos River measured at gauging stations below the springs from river discharge measurements made above them.

Hill 1999 found a 90- to 94-day lag-time response between precipitation in the area east of Carlsbad and discharge pulses at Malaga Bend in five out of eight cases, "suggestive of a possible connection" between the WIPP site and Malaga Bend. Hill did not discuss the numerous other rainfall spikes in the records that are not associated with river discharge peaks, and she did not try to correlate the volume of rainfall with volume of spring discharge. She also noted, but did not account for, the fact that Pierce Canyon, south of the WIPP site and the only large drainage east of the Pecos for miles around, also empties into the river between the two gauging stations.

Hill 1999 acknowledged that her study was poorly controlled and that it might not be statistically meaningful, since it did not account for factors such as irrigation, Pecos flood pulses, or industry water withdrawals at Nash Draw, and because it made no differentiation between precipitation over Nash Draw (where sinkhole catchment of drainage is known) and precipitation over the WIPP site where she was trying to prove the connection. She nevertheless justified the study with the statement that "The purpose of the above exercise is to show that actual measurements of recharge/discharge should be made in any serious attempt of studying karst at the WIPP site" (Hill 1999, p. 47), and although she did not in fact do this herself, the reader is ultimately left with the impression that in Hill's opinion, the data support the presence of karst in the Rustler at the WIPP site.

On pages 82-99, Lorenz presented information pertaining to recharge and discharge within the WIPP area which is summarized as follows. The relatively small volumes of water and brine that are being discharged from the few known and potential Rustler discharge sites are consistent with the volumes of water that would be remnant from local precipitation after evapotranspiration. Lorenz believed that this supports the hypothesis that water gets from the surface into and through the Rustler, and to the discharge points, but did not specify a recharge mechanism. Recharge mechanisms might include localized sink holes or more widespread percolation.

However, what little definitive data exist suggest that recharge, flow, and discharge within the Rustler Formation are relatively rapid within the confines of Nash Draw, but that the same aquifer horizons are entirely different systems with different characteristics to the east, under the WIPP site. There, a higher degree of mineralization of the formation waters, lower measured hydraulic conductivities, and isotopic studies support a system of slow groundwater flow. The potentiometric head data suggest that flow in the Rustler members is slow, but that it would flow to the south (Culebra) and west (Magenta). The data suggest that if a karst conduit system exists in the Rustler Formation, it is confined to the Nash Draw area.

6.2.5 Culebra and Magenta Head Relationships

Hill 1999 suggests that the hydraulic heads are also equal in the vicinity of H-6 and WIPP-13, inferring that this indicates hydraulic communication between the two units ("…that the integrity of the Magenta and Culebra as distinct water-bearing zones has been breached…" (Hill 1999, p. 56)). Hill then suggests that this implies the development of karst passageways at depth.

Lorenz 2005 acknowledged that the uncertainty ranges on Magenta and Culebra heads do in fact overlap at H-6 and WIPP-25. However, Lorenz also believed that this by itself does not prove that hydraulic connectivity exists between the two members. Lorenz provided the following rationale to support this point. The plane of the Magenta potentiometric head slopes down to the west (Lorenz 2005, Figure 24) and therefore must cross the southward-sloping Culebra regional trend somewhere (Lorenz 2005, Figure 23). The crossover line is not a physical intersection; it is a line on a map where the two potentiometric surfaces would intersect. It trends north-south and occurs several miles west of the WIPP site, with a local bend to the east caused by an embayment in the regional Magenta potentiometric surface near the northwest corner of the WIPP site (Lorenz, Figure 24). The crossover line follows the trend of Livingston Ridge northwest of the WIPP site and includes WIPP-25, extends from there almost as far east as H-6, then bends northwestward under Nash Draw. At WIPP-25, drilled in an area of recognized karst and collapse, where both hydraulic heads and water chemistries from the Culebra and Magenta are similar (Lambert and Robinson, 1984) and where hydraulic connectivity between the members might in fact be expected, the absence of any response in the Magenta while the Culebra was pumped recently (Lorenz 2005, Figure 21) shows that the degree of actual hydraulic connection is at best low.

At H-6, Mercer 1983 (p. 61) noted significant differences in sodium chloride concentrations between the Magenta and Culebra in the adjacent test wells H-6a and H-6b, i.e., Culebra water samples contain 16 times as much dissolved sodium as do samples from the Magenta (18,000 vs. 1,100 mg/L), and over 23 times as much chloride (28,000 vs. 1,200 mg/L) (Mercer 1983; Randall et al. 1988). In addition, pumping tests provide definitive evidence for the absence of a connection between the two members at H-6 (see Lorenz Figures 21 and 22). During the WIPP-13 multipad pumping test of the Culebra, approximately 18 ft of drawdown was observed in H-6a and H-6b, both completed in the Culebra at that time, but no response was observed in H-6c, completed in the Magenta (Beauheim, 1987b). Lack of connection between Culebra and Magenta has also been repeatedly demonstrated during the Water Quality Sampling Program pumping of both the Culebra and Magenta on the H-6 hydropad. Thus, the lack of responses in other Rustler members when specific members are pumped at WIPP-25 and H-6 shows that the members are not well connected and that karst conduits are not present.

In summary, Lorenz stated (p. 118) the following:

> *The coincidence of the Culebra and Magenta potentiometric heads between Nash Draw and the WIPP site is also mistakenly cited as evidence for karst conduits linking the two units. Rather, it is the inevitable intersection of two non-parallel surfaces. In addition to the fact that the surfaces diverge westward as well as eastward, water chemistry and well-test data support the existence of two separate and non-communicating water bodies in the two units.*

6.2.6 Spatial Variability in the Chemistry of the Culebra Formation Waters

Hill 1999 (p. 64) suggests that spatial and/or temporal changes in water chemistry and salinity are characteristic of karst, due to local influxes of fresh water at sink holes that would mix erratically at depth with long-term residence matrix water already in the system. Hill then cites examples of spatial variability in the chemistry of the Culebra formation waters and argues that they indicate the development of a subsurface karst system at and near the WIPP site.

Hill 1999 cites Chapman 1988 as mapping regions of low salinity and facies changes from Na-Cl to $Ca\text{-}SO_4$ over the region of the H-1, H-2, and H-3 drillholes. Lorenz notes that the fact that water chemistry varies does not necessarily prove the presence of karst at depth. Chapman 1988 observed linear correlations between TDS and chloride content and between chloride and sodium in Culebra waters, and took these relationships to indicate that the increase in salinity eastward in the Culebra is due to dissolution of halite. She also observed that a parallel increase in potassium and magnesium is "probably due to the dissolution of evaporite minerals co-existing with the halite." From these, she inferred that the "major hydrochemical facies change from Na-Cl to $Ca\text{-}SO_4$" is due to the influx of a large quantity of low-TDS water, suggesting recharge through gypsum caves. Lorenz offers other explanations to explain the geochemical data, and points out that in the absence of sedimentological data, the data showing a change from sodium-chloride to calcium-sulfate waters may be explained in several ways; such as the removal of halite in the calcium-sulfate area or non-deposition of halite. The mere absence of halite does not dictate a choice between these two options. However, making the choice has important implications: if the halite was there and has been removed, karst features could have been developed in the overlying strata during the dissolution phase. If the halite was never there, as argued above in this report, then the strata were not subjected to halite dissolution and karst is unlikely to have developed. Calcium-sulfate waters could have developed where salt was never present and where low-mobility waters took on the general character of the host rock during long residence times. Additional discussion of these issues is presented in Section 5.3

6.2.7 Potential for Karst at WIPP-13, WIPP-14 and H-3

The cores from several holes (WIPP-13, WIPP-14, and H-3) have been cited by Hill 1999 and 2003 as showing evidence for karsted strata, and well tests at these sites have been suggested to be anomalous, the anomalies taken to be support for possible karst. These examples are examined below.

The WIPP-13 drillhole was sited to investigate the possibility that a resistivity anomaly reported by Elliott Geophysical 1977 was caused by a geological feature similar to the breccia pipes known elsewhere in the basin (SNL and USGS 1979). A subsequent gravity survey (Barrows et al. 1983) indicated that the resistivity anomaly is located within the area of a broader gravity anomaly, further piquing interest in this site. Lorenz 2005 noted that the drillhole, however, penetrated a normal stratigraphic section with only localized, apparent brecciation of a thin sulfate bed within the Tamarisk mudstone unit.

Hill 1999 suggests that the disrupted bedding in cores from this hole, and the pumping tests at this site that produced anomalous (to her) responses, indicate karst. Hill cites the presence of well-test variations to support an interpretation of karst in the Rustler Formation at this site.

As noted above, Hill 1999 (pp. 59–61) suggests that there were significant variations during a pumping test at WIPP-13. Beauheim 1987c did report a no-flow boundary, indicating a decrease in Culebra transmissivity somewhere "fairly close to WIPP-13," but a no-flow boundary indicates a barrier to flow, not an open, karst-type pathway. Such boundaries can be caused by sealed faults and sedimentary limits to a reservoir, or by other types of lateral decreases in permeability. Lorenz 2005 (p. 107) concludes that, "The observed responses are not consistent with the presence of fluid-filled, large-scale void spaces and conduits, which would have dampening effects on the magnitude of pressure responses due to the larger reservoir volumes involved."

Hill 1999 (p. 38) notes the presence of "collapse breccia and mixing of stratigraphic units" in core from the WIPP-13 drillhole, arguing that these indicate the presence of karst, if not in the wellbore itself, at least in the nearby strata. Hill 1999 (p. 47) cites Holt and Powers 1988 as the reference for this core description, quoting (p. 5-13), "The strata [in the A2 anhydrite of the Tamarisk Member] are commonly wavy, may be locally contorted, or discontinuous, and in some extreme cases, can exhibit dipping strata (up to 80° in WIPP-13)."

Lorenz 2005 (p. 109) observes that the breccias found in WIPP-13 could be interpreted in several different ways. The lower interval is most easily explained as a limited zone of dissolution adjacent to the water-bearing Culebra, whereas the upper interval is probably of syndepositional origin. Some of the well-test data are ambiguous, but they are not suggestive of karst-type flow of the Rustler waters. The large-scale exposures of sedimentary and syn-sedimentary features, and the definitive data on the stratigraphic succession offered by the shaft exposures show that widespread karst-type dissolution is not present in the Rustler Formation at the WIPP site.

The WIPP-14 drillhole was sited to investigate the possibility that a circular surface topographic depression, about 700 ft in diameter, 10 ft deep, and located above the axis of a much larger gravity anomaly, is large enough to have collected sufficient water to create a major sinkhole. Hill 1999 suggests that the conversion of anhydrite to gypsum in certain beds, and a calculated mass deficiency related to that conversion, indicate karst in the subsurface even though the hole did not penetrate or recover evidence for karst.

Lorenz 2005 (p. 110) responds with the following discussion: "Most of the units above the Rustler were cored in WIPP-14, but only the top and bottom of the Rustler Formation itself were cored, as intended (see Appendix B, page 1; Sandia National Laboratories and D'Appolonia Consulting Engineers, 1982). The lithology penetrated by the rest of the hole was reconstructed from cuttings and the geophysical logs. The core and logs from the WIPP-14 drillhole document a normal stratigraphic section at this location, i.e., the stratigraphic tops have not been displaced relative to their expected depths projected from nearby control points, and bedding is in a normal, flat-lying attitude (Sandia National Laboratories and D'Appolonia Consulting Engineers, 1982; Bachman, 1985). The daily drilling reports and the geologist's lithologic log record no unusual lost-circulation or fluid-entry zones, and core recovery percentages were consistently high. The geophysical logs run in the hole also indicate normal lithologies, normal depths, and no anomalous hole diameters."

Hill 1999 (p. 38) suggests that the WIPP-14 borehole "did not intersect karst, but it did intersect 9.5 ft of gypsum and 10 ft of gypsiferous anhydrite in the Forty-niner Member directly overlying the Magenta dolomite," and that this is the same interval of the bit drops encountered when drilling WIPP-33, "where one should expect to find karst." The lithologic log for this hole (Sandia National Laboratories and D'Appolonia Consulting Engineers, 1982, Table 3) shows that gypsum and gypsiferous anhydrite were indeed encountered above both the Magenta and Culebra, for a few tens of feet before reverting to thick anhydrites. Lorenz 2005 (p. 110) notes that the presence of gypsum in these intervals is not unexpected since the Magenta and Culebra are water-bearing, and hydrated anhydrite (i.e., gypsum) in these positions is normal. Thus, the presence of gypsum is not a strong argument for the presence of karst in or near this drillhole.

Hill 1999 (p. 38), described the H-3 and WIPP-13 drillholes together, claiming that the presence of "collapse breccia and mixing of stratigraphic units" in these two drillholes indicated karst development in the Rustler Formation. As noted above, Lorenz 2005 (p. 115) pointed out that the brecciation of strata in these holes can be readily attributed to local dissolution adjacent to the Magenta and Culebra, and to synsedimentary disruption of the strata. Beauheim and Holt 1990 (p. 159; 161) suggested that, "Features attributable to dissolution of halite and attendant collapse are found within the interval M-3/H-3;" this interval correspond to a highly transmissive zone in the Culebra in the southern part of the WIPP site. These features, however, are not attributable to karst in the area.

7.0 SUMMARY AND CONCLUSIONS

EPA reviewed existing data related to karst at the WIPP site and evaluated the potential existence or formation of preferential groundwater transport pathways, such as "underground rivers," in the Magenta or Culebra units during the 10,000 year regulatory time frame. This review included an evaluation of geophysical methods that may be used for detecting karst in these units at the WIPP site.

The use of magnetotelluric methods for detecting karst at the WIPP site was evaluated, including the proprietary Z-SCAN technology proposed by commenters. Magnetotellurics cannot be used to resolve karst features, if present, in the Culebra or Magenta members of the Rustler Formation. The proposed karst voids would be too thin to be distinguishable from host rocks at average depths for these formation members in the WIPP area, because MT methods do not appear to be able to resolve features the size of the speculated karst voids, and because karst features would have too low of a contrast with the surrounding lithology to be distinguished uniquely from changes in lithology or other natural features in the subsurface.

Other potential geophysical methods that might be used to detect karst features in the Magenta or Culebra units were also evaluated. This evaluation included the use of gravity surveys, magnetic surveys, Time Domain Electromagnetics Induction (TDEM), seismic reflection techniques, subsurface reflection seismic techniques, and subsurface electromagnetic techniques. EPA determined that it is unlikely for these methods to able to 'see' karst in the Magenta or Culebra because of limited resolution.

A conceptual model of groundwater flow in the Magenta and Culebra hydrologic units is discussed to assist in evaluating the potential for karst to be present at the WIPP Site. Major components of this conceptual model fall into three broad categories. First, although dissolution has occurred in the immediate vicinity of WIPP-33, there is no evidence that dissolution is pervasive or has led to connected pathways. Second, observations pertaining to recharge and discharge indicate that karst is unlikely to be present or form at a later date at the WIPP site. Third, there are no indications that high-angle dissolution features connect all of the Rustler members and Dewey Lake. Specific aspects of these conclusions are summarized below.

No Evidence for Dissolution Channels and Fracture Enlargements of the Culebra

- Karst processes may be active at the southern end of Nash Draw where the Culebra and Magenta hydrogeologic systems appear to be receiving recharge from the surface water. If "underground river" development were to occur in these units, it would be taking place at this location, but is unlikely because of limited water availability. This area is downgradient and about 10 miles south of the WIPP site, and karst and underground river development in this area would not affect the performance of the repository.

- Karst processes in the vicinity of Nash Draw have been active throughout the geomorphic and geologic past, and have created various heterogeneities in the overlying hydrogeologic units. It is unlikely, however, that the deeper units are producing karst today, because most of the reactive water is considerably distant from the WIPP site, and the current Magenta and Culebra groundwater flow systems do not appear to have characteristics consistent with karst development. Instead observations include evidence of very long equilibration times which preclude karst development.

- The potential for karst formation would have been greatest approximately 18,000 to 22,000 years ago, when the last North American ice sheet reached its southern limit roughly 1500 km north of the WIPP, and precipitation was approximately twice that of the present.

- The Magenta hydrogeologic unit most likely functions as a porous medium. Transmissivities in the Magenta are low, with 16 of 18 reported values less than or equal to 1×10^{-6} m^2/s. Slug-test data are consistent with standard porous-medium type curves.

- The Culebra hydrogeologic unit has a bimodal transmissivity distribution. The low transmissivity values probably indicate porous-medium conditions, whereas the high transmissivities may indicate dual-porosity conditions due to fracturing. The conceptual model used in the performance assessment assumes the dual-porosity, higher transmissivity interpretation.

- The hydrostructural units at the WIPP site, most notably the irregularities observed at WIPP-14, were investigated by drilling and for hydrologic system attributes. The geophysical logs for this interval show a normal signature as observed in hundreds of other wells (near and far). Furthermore, the presence of "underground rivers," either hydrologically or lithologically, has not been directly shown by these drill holes, or other drill holes into the Culebra or Magenta hydrogeologic units.

- The depositional model proposed by Powers and Holt (2000) accounts for sedimentary features of the Rustler mudstones. Marked facies and thickness changes are consistent with influence by subsidence boundaries, as found in some modern continental evaporites. A dissolution model accounts for limited brecciated zones along (depositional) halite margins, but bedding observed in the mudstones would not survive 90% reduction in rock volume i.e., had dissolution been active in these units.

- Other than the area around WIPP-33, no geologic or geophysical evidence has been found to support the existence of sinkholes or other subsidence features. Nor are "discrete conduits" needed to conduct whatever recharge occurs in the semiarid WIPP environment to the water table in the Dewey Lake.

- Carbonate rocks with shaley interbeds, and argillaceous or dolomitic carbonate rocks, like at WIPP, do not dissolve as quickly in circulating water as do massive or relatively pure limestones. No pure carbonates are found at the WIPP site. The Culebra and Magenta are argillaceous and arenaceous dolomites.

- The Culebra takes years to come to steady-state after it has been stressed (e.g., aquifer testing); this is very atypical of karst conditions.

Groundwater Recharge and Discharge Characteristics

- Infiltration of precipitation and reactive water (i.e., fresh water) that could possibly recharge and karstify the Culebra and Magenta units is extremely unlikely at the WIPP site. The physical and chemical interactions of surface waters with the Eolian, Mescalero Caliche, Santa Rosa, and Dewey Lake units added together would likely inhibit vertical movement of infiltrating water, or would deflect this water, resulting in potential horizontal movement, thus further decreasing any vertical infiltration. These barriers would prevent surface infiltration of precipitation, and may provide chemical interaction with the precipitation.

- Tests and drilling at WIPP-14 and WIPP-33 show that large quantities of precipitation and reactive water do not reach the Culebra and Magenta units through the limited number of sinkholes and collapse features observed near the WIPP site. These features are not providing reactive water to the Culebra and Magenta units, and will not affect the repository performance.

- Groundwater recharge to the Magenta is probably from regional sources to the north and northwest, and possibly the northeast, of the WIPP site. Based on the measured age of the groundwater, which is greater than 10,000 years, and the high TDS chemistry of the Magenta groundwater, the water appears to have traveled slowly and over great distances from its source.

- Based on the past record, increases in precipitation are possible and perhaps likely during the next 10,000 years. These fluctuations will, however, on a scale of 10,000 or more years, be short-lived and the potential for karst development will be far less than experienced during the continuously high precipitation during the Pleistocene.

- Breaks in Mescalearo (and other) caliche do occur in the area. In general, however, the Mescalero is wide-spread and does act as a barrier to limit recharge. Furthermore, there is no evidence that there is significant collapse, especially deep-seated, in the bedrock underlying the caliche within the LWA.

- The poor development of surface drainage over the WIPP site is due to the absence of requirements for such a drainage network. The low rate of precipitation, the presence of sandy surficial deposits that quickly soak up precipitation, the low dip of the strata that does not funnel drainage in any particular direction, and the shifting of dune sands that block drainage as it develops, combine to prevent an organized drainage system from forming in this area. It is not necessary to postulate a complex process of stream capture by an organized system of sinkholes and subsurface drainage to explain this pattern.

- In addition, recent research confirms expectations of low recharge at the WIPP site. Low current flux estimates in the desert southwest are similar to the findings from the modeling conducted by Corbet 1997. Vegetation alone may be extremely effective at preventing downward movement of moisture, and coupled with the surficial characteristics, the vegetation also contributes to a lack of surface runoff. The deep vadose zone and high evapotranspiration over the WIPP site point to limited infiltration;

thus karst formation due to infiltration from the surface at the WIPP site is highly implausible and not supported by all of the evidence.

Lack of Connection of Dewey Lake and Rustler Members by Karst Features

- No response to rainstorms has been observed in wells monitoring the Culebra, Magenta, or the Los Medaños Member.

- Potentiometric heads of the Culebra and Magenta are similar only in the northwest corner of the WIPP site; furthermore, aquifer tests conducted in the Culebra hydrogeologic unit at the WIPP site indicate that there is no vertical connection between the Magenta and Culebra units. Similar observations are made at the two wells drilled at WIPP-14 and WIPP-33.

- Culebra and Magenta water quality at H-6 are distinctly different

- Hydraulic tests indicate storativities representative of a confined system and no partial-penetration responses have been observed

Careful review of the totality of historical data from the WIPP site indicates that karst and "underground river" processes will not affect groundwater transport from the repository at WIPP during the 10,000 year regulatory time period. Some uncertainty exists related to the location of regional recharge and discharge of both the Culebra and Magenta flow systems. The conceptual model indicates that the regional recharge to both units is most likely from other vertical or lateral hydrogeologic sources located to the north and northwest of the WIPP site, and that the regional discharge of both units is most likely vertically or laterally to other hydrogeologic units located to the south, southeast, and east. The hydrochemistry of both aquifers suggests that this process is located far away from the WIPP site, water movement is extremely slow, and the water is not sufficiently reactive to develop karst or "underground rivers" at the WIPP site. Therefore, karst processes are very unlikely to affect repository performance.

Overwhelming historical information provided by the hydrologic testing of the wells at and around WIPP support EPA's conclusions regarding karst. Large-scale pumping tests have been conducted at WIPP since the 1980s, as well as recent years, and have provided the basis for the hydrologic characterization of the Culebra. These tests have interrogated large volumes of water in the Culebra and have identified that the Culebra acts as either a single (matrix porosity) system where the flow and transport is through the rock matrix, or as a dual-porosity system in which there is movement of water and contaminants into and out of the rock matrix and through fractures. Pump tests have characteristic responses that permit these interpretations. They do not show indications of karst development. If there were karst, especially the purported "underground rivers," the testing would have shown evidence of them. There are fractures, but no pervasive karst development indicated. These tests also indicate that the Culebra and Magenta are relatively independent of one another, because the Magenta shows no response when the Culebra is stressed, pumped.

EPA's re-evaluation of karst again concludes that the WIPP site does not exhibit evidence of karst; it is highly unlikely that reactive water could reach and dissolve the Rustler dolomites; and the hydrologic regime at WIPP is adequately modeled without modeling karst features. This evaluation has reaffirmed our original decision and has even strengthened our understanding that karst processes will not affect containment of radionuclides at WIPP.

8.0 REFERENCES

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

Bachman, G.O. 1985. Assessment of Near-Surface Dissolution at and Near the Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico. SAND84-7178, Sandia National Laboratories, Albuquerque, New Mexico. WPO 24609.

Barrows, L.J., 1982. WIPP Geohydrology-The implications of Karst. Unpublished manuscript (Reproduced in EEG-32, 1985).

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

Bartel, 1989. Unpublished Contractor Report , prepared for Sandia National Laboratory, Albuquerque,NM.

Beauheim, R.L., 1987a. Analysis of Pumping Tests of the Culebra Dolomite Conducted at the H-3 Hydropad at the Waste Isolation Pilot Plant (WIPP) Site. SAND86-2311. Albuquerque, New Mexico: Sandia National Laboratories.

Beauheim, R.L., 1987b. Interpretation of the WIPP-13 Multipad Pumping Test of the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) Site. SAND87-2456. Albuquerque, New Mexico: Sandia National Laboratories.

Beauheim, R.L., 1987c. Interpretations of Single-Well Hydraulic Tests Conducted At and Near the Waste Isolation Pilot Plant (WIPP) Site, 1983-1987. SAND87-0039. Albuquerque, New Mexico: Sandia National Laboritories.

Beauheim, R.L. and R.M. Holt. 1990. Hydrogeology of the WIPP Site: Geological and Hydrological Studies of Evaporites in the Northern Delaware Basin for the Waste Isolation Pilot Plant (WIPP) Site, New Mexico, in Powers, D., Holt, R.L. Beauheim, and N. Rempe, eds., Geological and Hydrological Studies of Evaporites in the Northern Delaware Basin for the Waste Isolation Pilot Plant (WIPP) Site, New Mexico. Field Trip #14 Guidebook. Dallas, Texas: Geological Society of America (available from Dallas Geological Society). 131-179

Beauheim, R.L, D.W. Powers and K.W. Larson. 2000. Evaluation of D.T. Snow Paper "Hydrological Conditions at the WIPP Site at Variance with the Assumptions of DOE in its Performance Assessment."

Beauheim, R.L., and G.J. Ruskauff.. 1998. Analysis of Hydraulic Tests of the Culebra and Magenta Dolomites and Dewey Lake Redbeds Conducted at the Waste Isolation Pilot Plant Site: Sandia Report SAND98-0049, 226 p.

Borns, D. J., L.J. Barrows, D.W. Powers, and R.P. Snyder, 1983. Deformation of Evaporites near the Waste Isolation Pilot Plant (WIPP) Site. SAND82-1069, SNL, WPO 27532.

Borns . D. J. and Stormont ,J.C. 1988 . An Interim Report on Excavation Effect Studies at the Waste Isolation Pilot Plant: The Delineation of the Disturbed Rock Zone. SAND-87-1375. Sandia National Laboratories, Albuquerque,NM.

Caginard, L., 1953, Basic Theory of the Magneto-telluric Method of Geophysical Prospecting, Geophysics, Vol.18, pp. 605–635.

Campbell, A.R., F.M. Phillips, and R.J. Vanlandingham. 1996. Stable Isotope Study of Soil Water, WIPP Site New Mexico: Estimation of Recharge to Rustler Aquifers, Radioactive Waste Management and Environmental Restoration. Vol. 20, 153–165

Chapman, J.B., 1988. Chemical and Radiochemical Characteristics of Groundwater in the Culebra Dolomite, Southeaastern New Mexico: Environmental Evaluation Group. Albuquerque, New Mexico, EEG-39, 63 p.

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

Citizens for Alternatives to Radioactive Dumping and the Sister of Loretto (CARD) 2004. WIPP Scientific Testing, Review and Analysis Project 2002. Proposal by Citizens for Alternatives to Radioactive Dumping (CARD) and the Sisters of Loretto(SP), November 7. (Note: Presented to EPA in July 2004 public meeting), Docket A-98-49, Item II-B3-76

Corbet, T.F. 1997. Integration of Hydrogeology and Geochemistry of the Culebra Member of the Rustler Formation in the Vicinity of the Waste Isolation Pilot Plant (USA). Sandia National Laboratories, USA, in Use of Hydrogeochemical Information in Testing Groundwater Flow Models; Tehcnical Summary and Proceedings of a Workshop, 1-3 September 1997, Borgholm, Sweden. Nuclear Energy Agency Organisation for Economic Cooperation and Development.

Corbet, T.F. and Knupp, P.M., 1996. The Role of Regional Groundwater Flow in the Hydrogeology of the Culebra Member of the Rustler Formation at the Waste Isolation Pilot Plant (WIPP). Southeastern New Mexico, Sandia National Labs. Albuquerque, New Mexico. SAND96-2133, 148 p.

Digital Magnetotelluric Technologies (DMT). 2005. Environmental High-Resolution Magnetotellurics. http://www.dmttechnologies.com/home.html, accessed December 12, 2005.

Dobrin, M.B. 1960. Introduction to Geophysical Prospecting, McGraw Hill Book Co.

DOE (U.S. Department of Energy). 1988. "Final Report for Time Domain Electromagnetic (TDEM) Surveys at the WIPP site."

DOE (U.S. Department of Energy). 1996. Title 40 CFR 191 Compliance Certificate Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. Carlsbad, New Mexico: U.S. Department of Energy Waste Isolation Pilot Plant, Carlsbad Area Field Office.

DOE (U.S. Department of Energy). 2004. Title 40 CFR 191 Parts B and C Compliance Recertification Application, U.S. Department of Energy Carlsbad Area Field Office, March 2004. Docket A-98-49, Item II-B2-27

Dual Laterolog/Micro Laterologs, WIPP wells B-25 and 13, run by Schlumber and DresserAtlas 1978 and 1979 provided by Sandia National Laboratories.

EAR88 "Final Report for Time Domain Electromagnetic (TDEM) Surveys at the WIPP site," SAND87-7144, June 1988; SAND92 -0700, 1992, "Preliminary Performance Assessment for the Waste Isolation Pilot Plant."

Elliot. 1977. Evaluation of the proposed Los Medanos nuclear waste disposal site by means of electrical resistivity surveys, Eddy and Lee Counties, New Mexico: Report (in two volumes) submitted to SNL.

EPA (U.S. Environmental Protection Agency). 1997. Compliance Application Review Documents for the Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations: Final Certification Decision. CARD No. 14: Content of Compliance Certification Application. EPA Air Docket III-B-2. U.S. Environmental Protection Agency Office of Radiation and Indoor Air. Washington, DC.

EPA (U.S. Environmental Protection Agency). 1998a. Response to Comments. Criteria for the Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with 40 CFR Part 191 Disposal Regulations: Certification Decision. Docket No. A-93-02, V-C-1, Office of Radiation and Indoor Air, May 1998.

EPA (U.S. Environmental Protection Agency). 1998b. *Technical Support Document for Section 194.14: Content of Compliance Certification Application*. Docket No. A-93-02, V-B-3, Office of Radiation and Indoor Air, May 1998.

EPA (U.S. Environmental Protection Agency). 1998c. Technical Support Document For Section 194.23 May 1998 Docket: A-93-02 Item V-B-30: Review of TDEM Analysis of WIPP Brine Pocket. U.S. Department of Energy (DOE).

Ferrall, C.C., and J.F. Gibbons. 1980. Core Study of Rustler Formation over the WIPP Site. SAND79-7110. Albuquerque, New Mexico: Sandia National Laboratories.

Gamble, et al., 1979. Magnetotelluric with a remote magnetic reference, Geophysics, V.44, pp.53–68.

Geohydrology Associates, Inc. 1978. Ground-Water Study Related to Proposed Expansion of Potash Mining Near Carlsbad, New Mexico: 110 p.

Greenwald, J. 2005. Citizens for Alternatives to Radioactive Dumping (CARD), McMullen, P., and the SL Loretto Community. Comments on EPA's Recertification of WIPP. Docket A-98-49 Item II-B3-88

Griswold, G.B. 1977. Site selection and valuation studies of the Waste Isolation Pilot Plant (WIPP), Los Medanos, Eddy County , New Mexico: SAND77-0946, Sandia Laboratories, Albuquerque, New Mexico.

Hatch, R. and J. Meyer. 2001. Strategic Infill Drilling Targeted Using Crosswell Seismic - 'Two Case Studies.' TomoSeis - A Core Laboratories Company.

Hermance, J. F. and R.E. Thayer. 1975. The telluric-magnetotelluric method, Geophysics 40, pp. 664–668.

Hern, J.L., Powers, D.W., and Barrows, L.J. 1979 , Seismic Reflection Data Report Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico. SAND79-0264, Vols.1 and 2 Sandia National Laboratories, Albuquerque, NM.

Hill, C.A. 1999. Intrastratal Karst at the WIPP Site. (Unpublished) Letter Report to Sandia National Laboratories, Contract # BF-4451. Docket A-98-49, Item II-B3-76

Hill, C.A., 2003 Intrastratal Karst at the Waste Isolation Pilot Plant Site, Southeastern New Mexico: Oklahoma Geological Survey Circular 109. Docket A-98-49, Item II-B3-95.

Holt, R.M. and D.W. Powers. 1984. Geotechnical Activities in the Waste Handling Shaft. DOE-WTSD-TME-038, U.S. Department of Energy, Carlsbad, New Mexico.

Holt, R.M. and D.W. Powers. 1986. Geotechnical Activities in the Exhaust Shaft, DOE-WIPP-86-008, 4pp.

Holt, R.M. and D.W. Powers. 1988. Facies Variability and Post-Depositional Alteration Within the Rustler Formation in the Vicinity of the Waste Isolation Pilot Plant, Southeastern New Mexico. DOE-88-004, Carlsbad, New Mexico: Westinghouse Electric Corporation for U.S. Department of Energy, 148 pp. & Appendixes.

Holt, R.M. and D.W. Powers. 1990. Geological Mapping of the Air Intake Shaft at the Waste Isolation Pilot Plant. DOE/WIPP 90-051. Carlsbad, New Mexico: U.S. Department of Energy.

Hoversten, G.M., R. Gritto, T.M. Daley, E.L. Majer, and L.R. Myer. 2001. Crosswell Seismic and Electromagnetic Monitoring of CO2 Sequestration. Lawrence Livermore National Laboratory LBNL-51281

Jennings, J.N. 1971. Karst. M.I.T. Press, Cambridge, Massachusetts.

Kaye, C.A. 1957. The Effect of Solvent Motion on Limestone Solutions. Journal of Geology 65:34-47.

Keesey, J. J. 1976. Hydrocarbon Evaluation, Proposed Southeastern New Mexico Radioactive Material Storage Site, Eddy County, New Mexico. SAND71-7033. Vols. I and II. Sipes, Williamson, and Aycock, Midland, Texas.

Keller, G.V. 1987, Rock and Mineral Properties, in Electromagnetic Methods in Applied Geophysics Theory: M.N.Nabighian,Ed., Society of Exploration Geophysics, Tulsa Oklahoma,v.1,p.1351.

Keller, G.V. 1989. Practical hand book of physical properties of rocks and minerals: CRC Press, Boca Raton, Florida, pp. 359–427.

Kirkendall,B. and J.Roberts, 2001. Probing the Subsurface with Electromagnetic Fields, Report for Lawrence Livermore National Laboratory, S&TR November 2001. http://www.llnl.gov/str/November01/Kirkendall.html

Lambert, S.J., and K.L. Robinson. 1984. Field Geochemical Studies of Ground waters in Nash Draw, Southeastern New Mexico. SAND83-1122. Albuquerque, New Mexico: Sandia National Laboratories.

Leigh, C., J. Kanney, L. Brush, J. Garner, R. Kirkes, T. Lowry, M. Nemer, J. Stein, E. Vugrin, S. Wagner, and T. Kirchner. 2005. *2004 Compliance Recertification Application Performance Assessment Baseline Calculation.* Sandia National Laboratories, Carlsbad, New Mexico, ERMS 541521.

Li, G.,G.Burrowes, E. Majer,T.Davis. 2001, Weyburn Field Horizontal-to- Horizontal Crosswell Seismic Profiling : Part 3- Interpretation, 71st Ann. Internat. Mtg. Soc. Of Expl. Geophys. 468-471

Li, G., and E. Majer, 2003. Coiled Tubing Deployment makes Crosswell Seismic Surveying in Horizontal Wells: The Leading Edge, 22, no.5, 454-458.

Liberty, L. M., W. P. Clement, and M. D. Knoll. 2000. Crosswell seismic reflection imaging of a shallow cobble-and-sand aquifer: An example from the Boise Hydrogeophysical Research Site: Proceedings of SAGEEP2000, The Symposium on the Application of Geophysics to Engineering and Environmental Problems, February 20–24, 2000, Arlington, Virginia, pp. 545–552.

Long, G.J., and Associates, Inc., 1977b. Letter report from J. L. Hern of G. J. Long and Associates, Houston, Texas, to W. D. Weart of Sandia National Laboratory, New Mexico.

Lorenz, J.C., 2005. Pre-Publication Draft: Assessment of the Potential for Karst in the Rustler Formation at the WIPP Site. SAND2005-7303. Albuquerque, New Mexico: Sandia National Laboritories.

Lorenzo, J., and R. Zapata. 2003. Index to some notes that accompany lectures in the course on seismic acquisition and processing entitled Reflection Seismology (Geol 4068, Fall 2003), Louisiana State University, web address: http://www.geol.lsu.edu/Faculty/Juan/ReflectSeismol03/LectureIndex.htm

Lowenstein, T.K. 1987. Post Burial Alteration of the Permian Rustler Formation Evaporites, WIPP Site, New Mexico: Textural, Stratigraphic and Chemical Evidence. EEG-36. Santa Fe, New Mexico: Environmental Evaluation Group.

Mercer, J. W., 1983. Geohydrology of the Proposed Waste Isolation Pilot Plant, Los Medanos Area, Southeastern New Mexico: U.S. Geological Survey, Water Resources Investigative Report 83-4016. 113 p.

Monroe, W.H. 1969. Evidence of Subterranean Sheet Solution Under Weathered Detrital Cover in Puerto Rico. In Problems of Karst Denudation. Internat. Speleol. Congress., 5th, Stuttgart.

Morgan, A.M., 1942. Solution-Phenomena in the Pecos Basin in New Mexico, Reports and papers. Transactions of the American Geophysical Union, National Research Council, Hydrology, Dallas, 1941, pp. 27–35.

Phillips, R.H. 1998. Cavernous Zones at the WIPP Site, submitted to EPA by Citizensfor Alternatives to Radioactive Dumping (CARD), February 26, 1998. Docket Attachment 4 to IV-G-17, 13 pp.

Powers, D.W., and R.M. Holt. 2000. The Salt that Wasn't There: Mudflat Facies Equivalents to Halite of the Permian Rustler Formation, Southeastern New Mexico. Journal of Sedimentary Research, 70(1): 29-36.

Randall, W.S., M.E. Crawley and M.L. Lyon. 1988. 1988 Annual Water Quality Data Report for the Waste Isolation Pilot Plant. DOE/WIPP 88-006. Carlsbad, New Mexico: Westinghouse Electric Corporation for the DOE.

Robinson, T.W., and W.B. Lang. 1938. Geology and Ground-Water Conditions of the Pecos River Valley in the Vicinity of Laguna Grande de la Sal, New Mexico, with Special Reference to the Salt Content of the River Water: Biennial Report of the State Engineer of New Mexico, pp. 79–100.

Siegle, M.D., K.L. Robinson, and J. Myers. 1991. Solute Relationships in Groundwaters from the Culebra Member of the Rustler Formation near the WIPP Site, Southeastern New Mexico, in M.D. Siegle, S.J. Lambert, and K.L. Robinson, eds., Hydrogeochemical Studies of the Rustler Formation and Related Rocks in the WIPP Area, Southeastern New Mexico. SAND88-0196. Albuquerque, NM: Sandia National Laboratories.

Skokan, C. K., M.C. Pheifer, G.V. Keller, and H.T. Andersen. 1989. "Studies of Electrical and Electromagnetic Methods for Characterizing Salt Properties at the WIP Site, New Mexico." SAND87-7174. Sandia National Laboratories, June 1989.

Sandia National Laboratories and US Geological Survey. Basic Data Report for Drillhole WIPP-33, SAND 80-2011 (Albuquerque, NM: Sandia National Laboratories, 1981).

Sandia National Laboratories and D'Appolonia Consulting Engineers, Basic Data Report for Drillhole WIPP -14, SAND82-1783 (Albuquerque, NM: Sandia National Laboratories,1982).

SNL and USGS (Sandia National Laboratories and U.S. Geological Survey). 1979. Basic Data Report for Drillhole WIPP 28 (Waste Isolation Pilot Plant – WIPP). SAND79-0282. Albuquerque, New Mexico: Sandia National Laboratories.

SNL and USGS (Sandia National Laboratories and U.S. Geological Survey). 1981. Basic Data Report for Drillhole WIPP 33 (Waste Isolation Pilot Plant – WIPP). SAND80-2011. Albuquerque, New Mexico: Sandia National Laboratories.

Snow, D.T., 1998. General Hydrological Conditions at the WIPP site: Unpubllished report dated February 26, 1998, in files of the Environmental Evaluation Group. Albuquerque, New Mexico. 11 p.

Swift, P. N., 1993. Long-Term Climate Variability at the Waste Isolation Pilot Plant, Southeastern New Mexico, USA. Environmental Management. Vol. 17, No. 1, pp. 83–97.

Telford, W. M., L.P. Geldart and R.E.Sheriff, 1995. Applied Geophysics, Cambridge University Press.

Theis, C.V., A.M. Morgan, W.E. Hale, and O.J. Loeltz. 1942. Ground-Water Hydrology of Areas in the Pecos Valley, New Mexico: The Pecos River Joint Investigation, Reports of the Participating Agencies, June 1942, National Resources Planning Board, pp. 38–75.

Vozoff, K., 1991. The Magnetotelluric method, chapter 8, Electromagnetic method in applied geophysics - Applications part A and part B, edited by Corbett, J.D., published by Society of Exploration Geophysicists, pp.641–71.

Walvoord, M. A. and Bridget R. Scanlon. 2004. Hydrologic Processes in Deep Vadose Zones in Interdrainage Arid Environments. *Groundwater Recharge in a Desert Environment: The Southwestern United States*, James F. Hogan, Fred M. Phillips, Bridget R. Scanlon, Editors. American Geophysical Union, Washington, DC.

Weyl, P.K. 1958. The Solution Kinetics of Calcite. Journal of Geology 66:163-176.

Williams, J.M., and Rodriguez, B.D. 2004. Magnetotelluric Survey to locate the Archean/Proterozoic Suture zone in north eastern Nevada, U.S.G.S Open-file Report 2004-1215.

Wilt, M.J., D.L. Alumbaugh, H.F. Morrison, A. Becker, K.H. Lee and M. Deszcz-Pan. 1995. Crosswell electromagnetic tomography: System design considerations and field results.

WinGLink Integrated Geophysical Interpretation System; Geosystem srl, Milan, Italy.

Xiao, W. 2004. Magnetotelluric Exploration in the Rocky Mountain Foothills, Alberta, Department of Physics, University of Alberta, Edmonton, Alberta

Zhang, W., G. Li, J. Cody - PanCanadian Energy Corp., J. Meyer - TomoSeis Inc. a Division of Core Laboratories. 2002. Understanding Reservoir Architectures at Christian Lake, Alberta with Crosswell Seismic Imaging.

ATTACHMENT A

HYDRAULIC TESTING OF THE RUSTLER FORMATION

HYDRAULIC TESTING OF THE RUSTLER FORMATION

B.1 HYDROLOGY OF THE RUSTLER FORMATION

The Rustler is of particular importance for WIPP because it contains the most transmissive units above the repository (Figure B-1). Fluid flow in the Rustler is characterized by very slow rates of vertical leakage through confining layers and faster lateral flow in conductive units. Because of its importance, the Rustler continues to be the focus of DOE studies to better understand the complex relationship between hydrologic properties and geology.

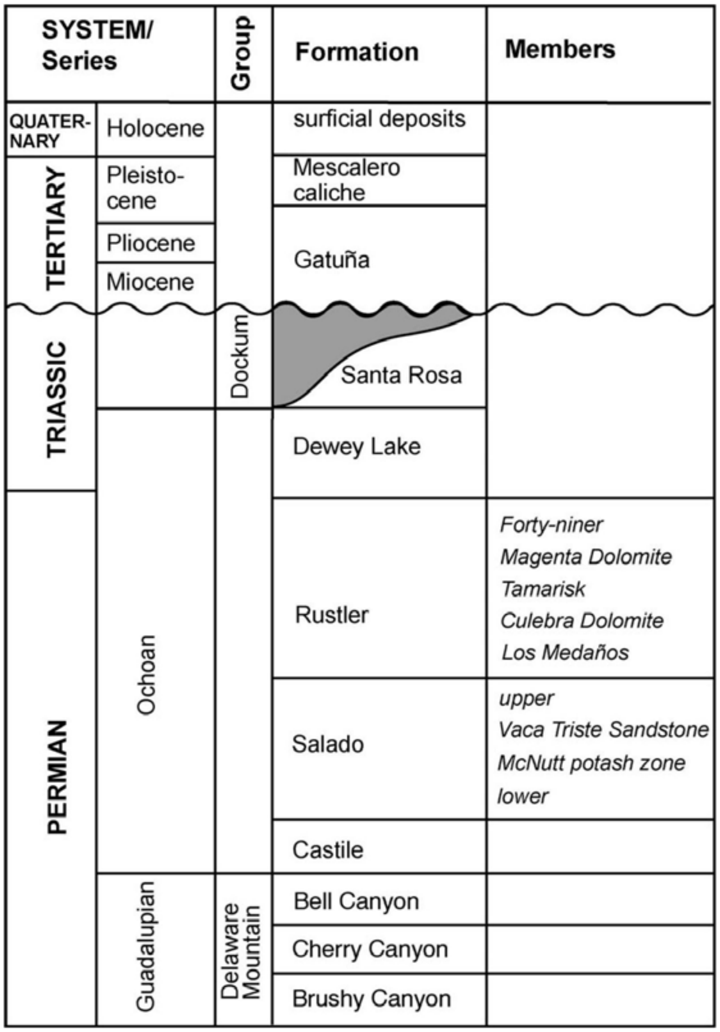


Figure B-1. Upper Stratigraphy in the Vicinity of the WIPP Site

B.1.1 Los Medaños

The unnamed lower member was named the Los Medaños by Powers and Holt 1999. Overall, the Los Medaños acts as a confining layer, although its composition varies.

The basal interval of the Los Medaños, approximately 19.5 m (64 ft) thick, is composed of siltstone, mudstone, and claystone and contains the water-producing zones of the lowermost Rustler. Transmissivities of 2.9×10^{-10} m^2/sec (2.7×10^{-4} ft^2/day) and 2.4×10^{-10} m^2/sec (2.2×10^{-4} ft^2/day) were reported by Beauheim 1987 from tests at well H-16 that included this interval (Figure 1-2). The porosity of the Los Medaños was measured in 1995 as part of testing at the H-19 hydropad (TerraTek 1996). Two claystone samples had effective porosities of 26.8% and 27.3%. One anhydrite sample had an effective porosity of 0.2%. The transmissivity values correspond to hydraulic conductivities of 1.5×10^{-11} m^2/sec (4.2×10^{-6} ft^2/day) and 1.2×10^{-11} m^2/sec (3.4×10^{-6} ft^2/day). In our current conceptual model we believe that the hydraulic conductivity in the lower portion of the Los Medaños increases to the west in and near Nash Draw, where dissolution at the underlying Rustler-Salado contact has caused subsidence and fracturing of the sandstone and siltstone.

The remainder of the Los Medaños contains mudstones, anhydrite, and variable amounts of halite. The hydraulic conductivity of these lithologies is extremely low. It is for this reason the Los Medaños acts as a confining unit.

B.1.2 Culebra Dolomite

The Culebra is of particular interest because it is the most transmissive saturated unit above the WIPP repository. The two primary types of field tests used to characterize the flow and transport characteristics of the Culebra are hydraulic tests and tracer tests. Extensive testing of the Culebra has been performed at 43 well locations to determine its hydraulic properties.

The hydraulic testing consists of pumping, injection, and slug testing of wells across the study area. The most detailed hydraulic test data exist for the WIPP hydropads. The hydropads generally comprise a network of three or more wells located within a few tens of meters of each other. Long-term pumping tests have been conducted at hydropads H-3, H-11, and H-19 and at well WIPP-13 (Beauheim 1987b; 1989; Beauheim et al. 1995; Meigs et al. 2000).

These pumping tests provided transient pressure data at the hydropad and over a much larger area. Tests often included use of automated data-acquisition systems, providing high-resolution (in both space and time) data sets of pump test results. In addition to long-term pumping tests, slug tests and short-term pumping tests have been conducted at individual wells to provide pressure data that can be used to interpret the transmissivity at that well (Beauheim 1987a). Additional short-term pumping tests have been conducted in the WQSP wells (Beauheim and Ruskauff 1998). Detailed cross-hole hydraulic testing has been conducted at the H-19 hydropad (Beauheim 2000).

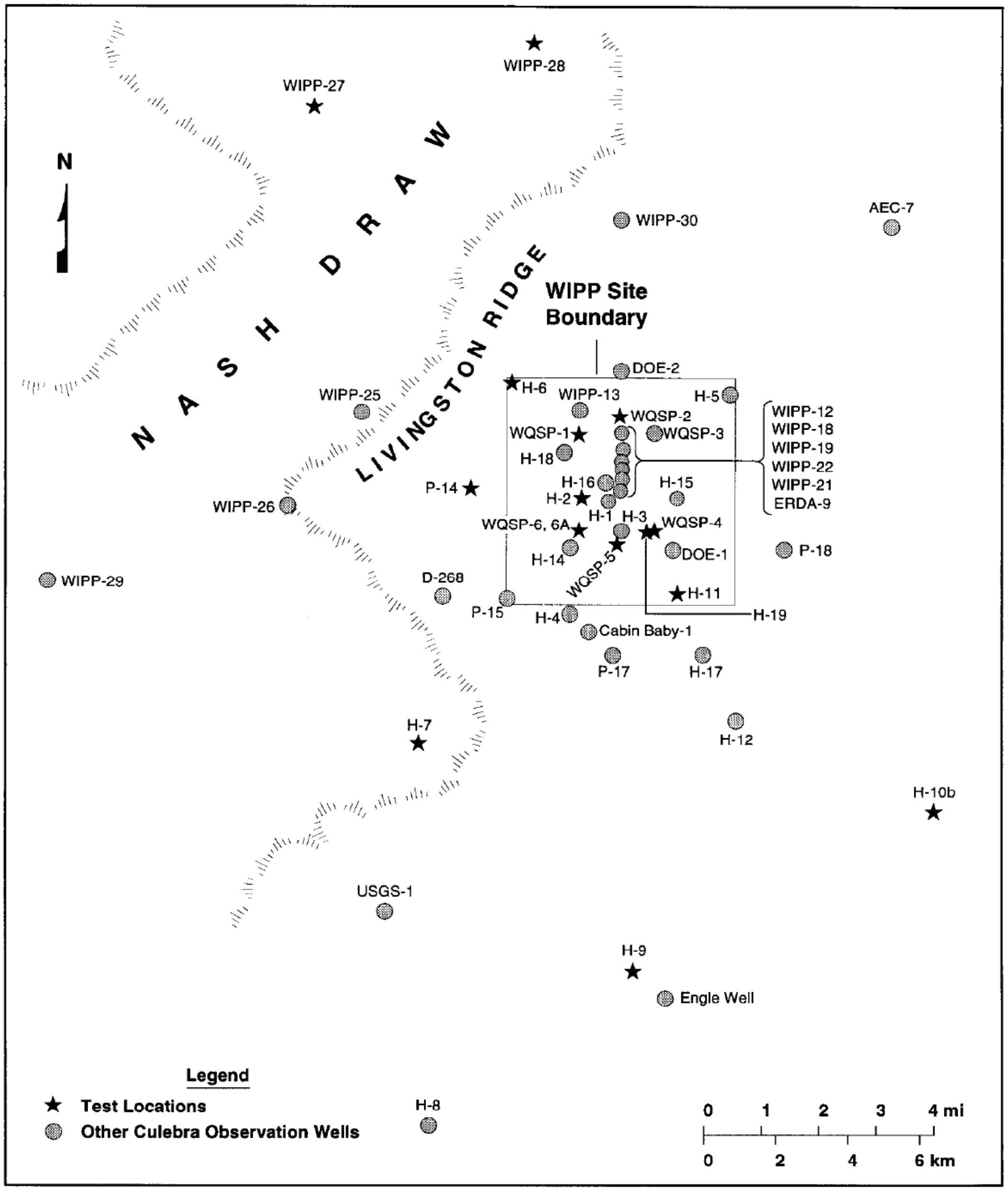


Figure B-2. Locations of Wells and Hydropads in the Vicinity of the WIPP Site

The hydraulic tests are designed to yield pressure data for the interpretation of such characteristics as transmissivity, permeability, and storativity. The pressure data from long-term pumping tests and the interpreted transmissivity values for individual wells are used for the generation of transmissivity fields in PA flow modeling. Some of the hydraulic test data and interpretations are also important for the interpretation of transport characteristics.

Culebra transmissivity varies over three orders of magnitude on the WIPP site itself and over six orders of magnitude in the vicinity of the WIPP with lower transmissivities east of the site and higher transmissivity west of the site in Nash Draw (Figure B-3) (e.g., Beauheim and Ruskauff 1998).

Transmissivities are from about 1 × 10^{-9} m^2/sec (1 × 10^{-3} ft^2/day) at well P-18 east of the WIPP site to about 1 × 10^{-3} m^2/sec (1 × 10^{3} ft^2/day) at well H-7 in Nash Draw (Figure B-4).

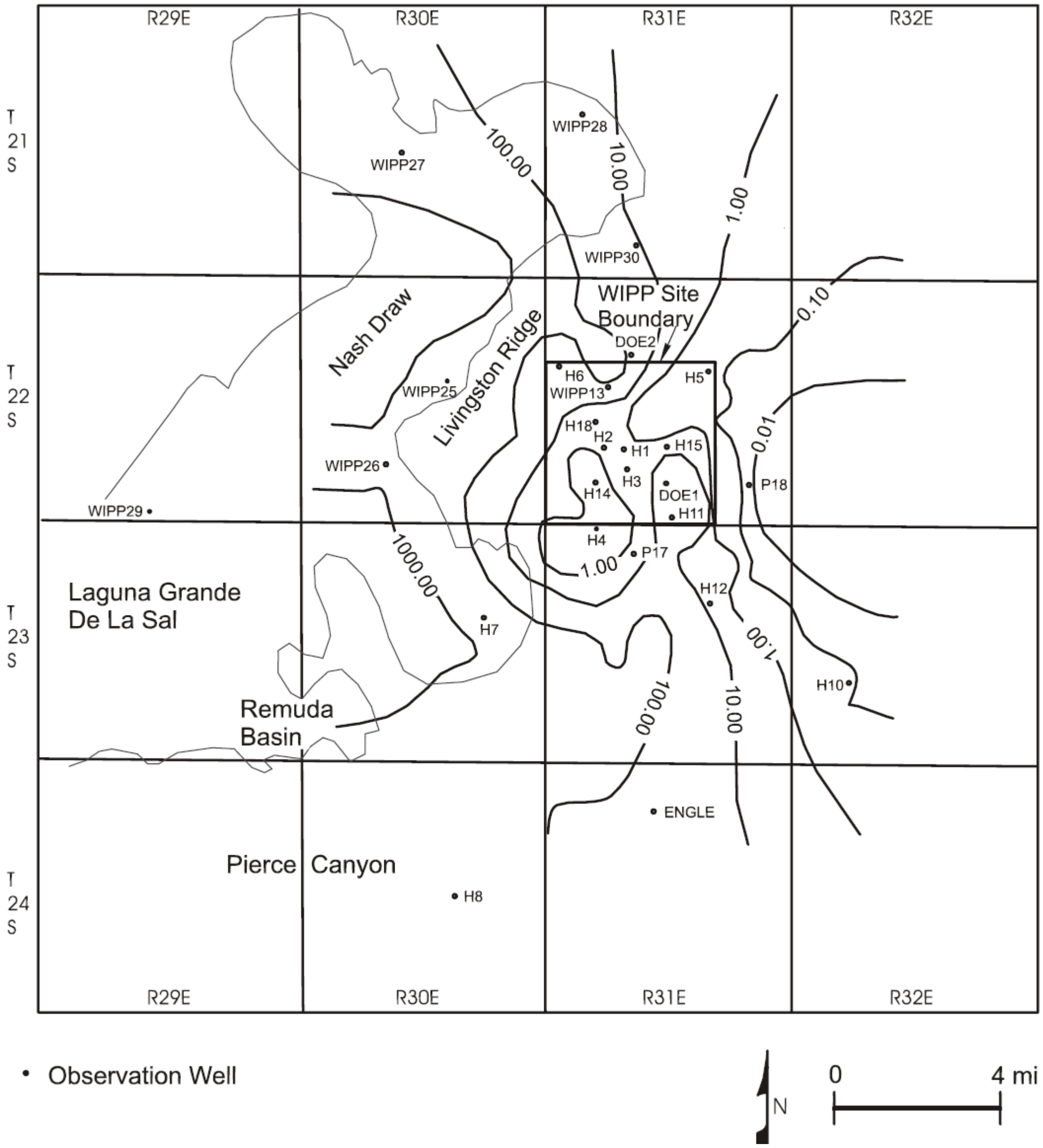


Figure B-3. Transmissivities of the Culebra (ft^2/day)

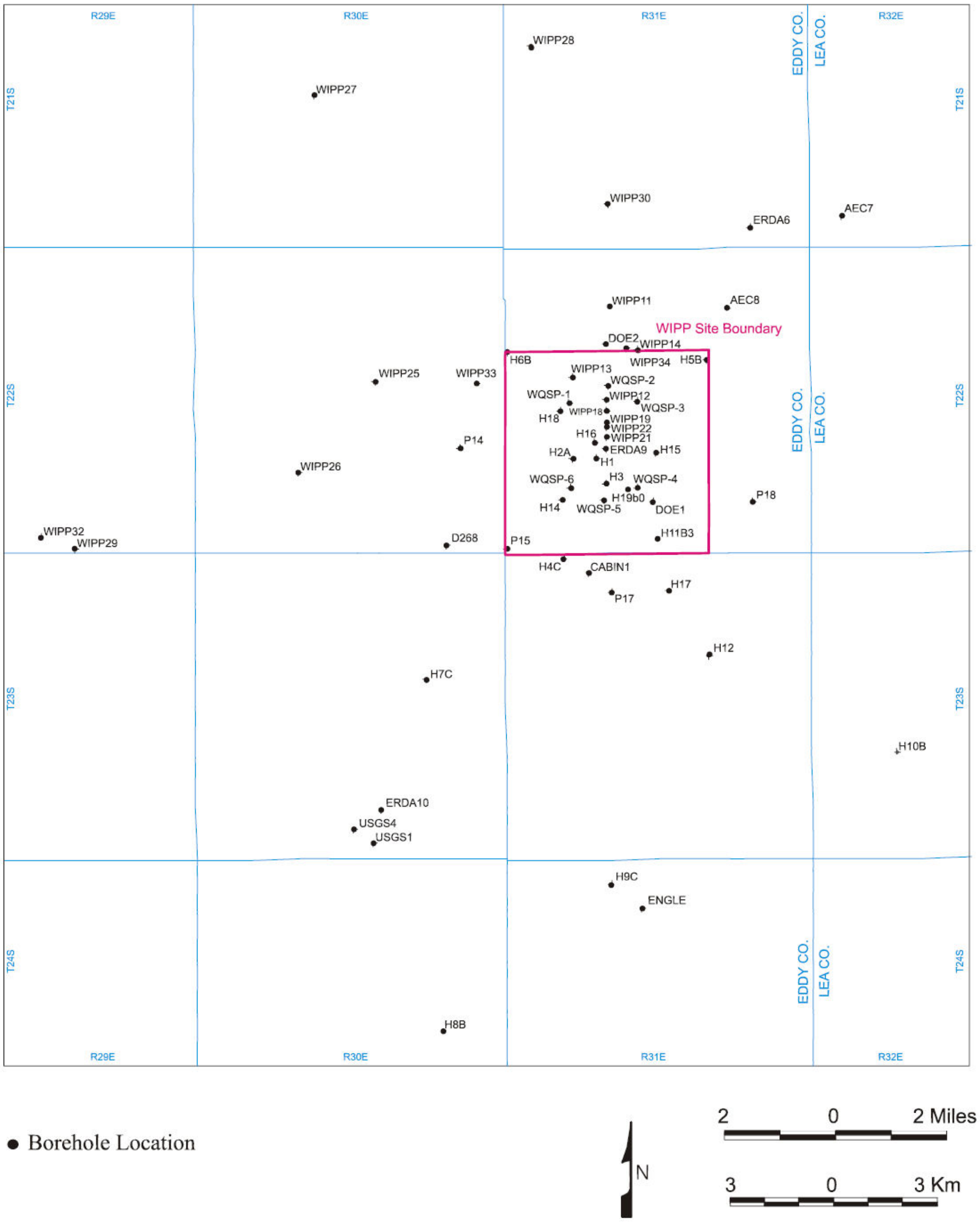


Figure B-4. WIPP Site and Vicinity Borehole Location Map

To evaluate transport properties of the Culebra, a series of tracer tests were conducted at six locations (the H-2, H-3, H-4, H-6, H-11, and H-19 hydropads) near the WIPP site. Tests at the first four of these locations consisted of two-well dipole tests and/or multiwell convergent flow tests and are described in detail in Jones et al. 1992. Tracer tests at the H-19 hydropad and additional tracer tests performed at the H-11 hydropad are described in Meigs et al. 2000. The 1995-1996 tracer test program consisted of single-well injection-withdrawal tests and multi-well convergent-flow tests (Meigs and Beauheim 2001). Unique features of this testing program include the single-well test at both H-19 and H-11, the injection of tracers into six wells during the H-19 convergent-flow test, the injection of tracer into upper and lower zones of the Culebra at the H-19 hydropad, repeated injections under different convergent-flow pumping rates, and the use of tracers with different free-water diffusion coefficients.

B.1.3 Tamarisk

Attempts were made by DOE to measure the hydraulic properties of the Tamarisk in two wells, H-14 and H-16. The tests were focused on a 2.4-m (7.9-ft) sequence of the Tamarisk that consists of claystone, mudstone, and siltstone overlain and underlain by anhydrite. Permeability was too low to measure in either well within the time allowed for testing; consequently, Beauheim 1987a estimated the transmissivity of the claystone sequence to be one or more orders of magnitude less than that of the tested interval in the Medaños (that is, less than approximately 2.7×10^{-11} m^2/sec [2.5×10^{-5} ft^2/day]). The porosity of the Tamarisk was measured in 1995 as part of testing at the H-19 hydropad (TerraTek 1996). Two claystone samples had an effective porosity of 21.3% to 21.7%. Five anhydrite samples had effective porosities of 0.2% to 1.0%.

B.1.4 Magenta

The Magenta Dolomite Member of the Rustler Formation is a persistent and distinctive clastic carbonate bed with thin laminae of anhydrite. The Magenta ranges in thickness from 20 to 30 ft and is present throughout most of the study area. The Magenta is the uppermost water-producing horizon in the Rustler Formation. Stratigraphically, it occurs between the thick anhydrite beds of the Tamarisk and Forty-niner Members (Figure B-1). Water, when present, usually occurs in the thin silt beds or silty dolomite, but also has been found along bedding planes between rock units and in fractures. The Magenta, where it was tested, was always under confined conditions except where it was extensively fractured and altered. In test holes H-7A, WIPP-26 (W-26 in Table B-1), and WIPP-28 (W-28), the dolomite was virtually unsaturated and was extensively fractured; the underlying anhydrite was fractured and in places altered to gypsum (Mercer 1983). The water formerly present in the Magenta in this area probably drained through the fractures into the underlying units.

The structure of the Magenta Dolomite, particularly in Nash Draw, appears to be related to the presence or absence of evaporite dissolution. The Magenta in the northern and central parts of Nash Draw and along the eastern boundary is present in the subsurface as a relatively continuous bed; however, in the vicinity of test hole WIPP-29 (W-29) and south to Malaga Bend, most of the Magenta has been stripped away by erosion (Mercer 1983). There are isolated blocks scattered throughout this area; the Magenta is present along the sides of karst sinks and in other collapsed features as breccia (Bachman 1981). These same features were described by Vine 1963 as domal structures.

Outcrops of the Magenta are present along the western side of Nash Draw below Quahada Ridge (DOE 2004). Although relatively continuous, they do show effects of weathering and are quite fractured, but are not saturated. A reasonable conclusion is that the dissolution responsible for the formation of Nash Draw fractured the Magenta and brecciated the underlying anhydrite, subsequently draining the water into lower units. These fractures later were filled with secondary minerals. Evidence for this type of occurrence can be found in the cores taken from test holes in the area (DOE 2004). An isolated occurrence of spring remnants was found along Livingston Ridge (Bachman 1981). These spring deposits are represented by a northeast-trending alignment of gypsite mounds. The spring deposits are believed by Bachman 1981 to have resulted from the evaporation of sulfate-bearing water that had drained from the surface through fractures in the Rustler Formation, particularly in the vicinity of test hole W-33. An additional source for the water could be from subsurface drainage from the fractured Magenta.

To the east of Nash Draw, in the vicinity of and including the WIPP site, the Magenta generally dips gently to the east. Although some flow along Livingston Ridge may be in fractures, the core samples and hydraulic tests at the WIPP site indicate the flow in the Magenta probably is within the silt beds and the silty dolomite, with some minor flow along bedding planes (DOE 2004). Fracture flow probably is predominant in Nash Draw but not at the WIPP site.

The potentiometric map, representing freshwater equivalent heads, indicates a flow system with some variability in permeability across the WIPP site (Figure B-5). The contours show the gradient across this area to be 16 to 20 ft per mile on the eastern side and steepening to about 32 ft per mile along the western side near the boundary of Nash Draw. This steepening of gradient may reflect the drainage of ground water from the Magenta into lower units through the fractures associated with Nash Draw dissolution activity or may only reflect a decrease in permeability. The gradient in Nash Draw of about 13 ft per mile indicates a more uniform permeability than at the WIPP site (DOE 2004). The Magenta, as an identifiable continuous bed, is not present below the central part of Nash Draw because erosion has removed all strata down to the Tamarisk Member of the Rustler (DOE 2004).

The contours on the potentiometric-surface map for the Magenta Dolomite Member (Figure B-5) indicate that water moves westward across the WIPP site towards Nash Draw, where it probably flows through fractures into lower units. In the northeast end of Nash Draw, the water flow generally is to the southwest, probably moving down through fractures into lower units in the central part of the draw.

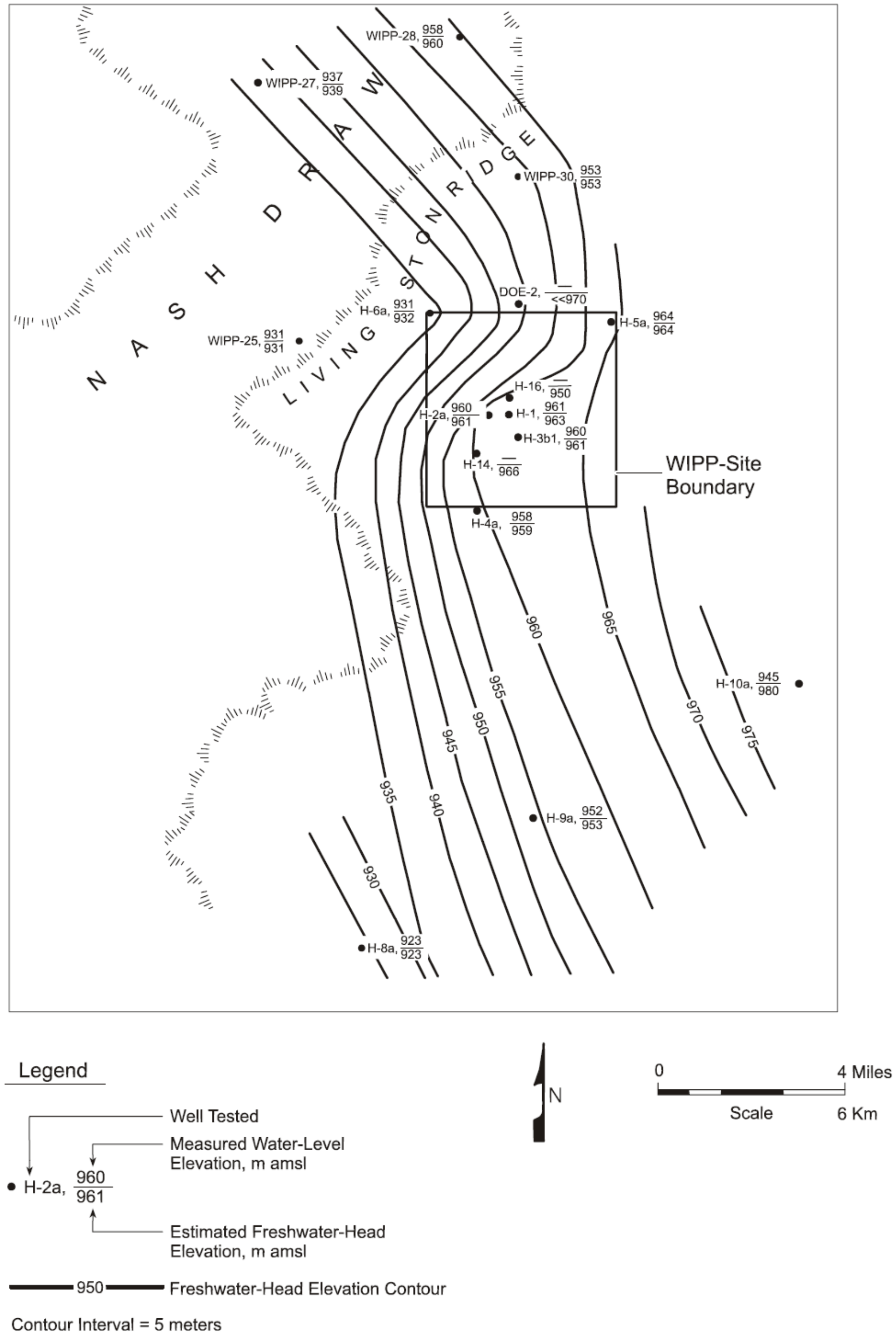


Figure B-5. Potentiometric Surface (1982) of the Magenta Dolomite Member of the Rustler Formation

(Source: Mercer 1983)

Values of transmissivity for the Magenta Dolomite Member that were available for the CCA are included in Table B-1. In Nash Draw, these values range from 53 ft squared per day (ft^2/day) in test hole WIPP-27 (W-27 in Table B-1) to 375 ft^2/day in test hole WIPP-25 (W-25); the large values probably are the result of increased permeability in fractured rock. The transmissivity calculated for test hole WIPP-25 (W-25) is the largest value recorded in the region for the Magenta; this test probably was affected by vertical leakage along fractures that connect with the underlying Culebra. The Magenta is unsaturated in test hole WIPP-26 (W-26) as a consequence of fracturing caused by dissolution in lower beds. These fractures drained water from the unit; however, core analyses have indicated that these fractures were later filled with gypsum (DOE 2004). Evaluation of the core from test hole WIPP-28 (W-28) indicated that bedding-plane partings and fractures were filled with gypsum, which would significantly decrease the permeability; vertical fracturing was not as evident as in test hole WIPP-26 (W-26) (*ibid*). The Magenta also was unsaturated in test hole H-7a at the margin of Nash Draw south of the WIPP site (*ibid*). DOE believes that the groundwater at test hole H-7a also probably drained into lower units, the subsequent alteration of the rocks considerably decreasing the vertical permeability. The core showed that this dolomite has been altered extensively to a partly cemented dolomite mud with the thin anhydrite beds that have been altered to gypsum (*ibid*). Like the other cores, secondary filling of gypsum sealed the fractures.

At the time of the CCA, hydraulic tests for the Magenta in the WIPP site area had been conducted in seven test holes; transmissivity values from these tests ranged from $4 \text{ x } 10^{-3}$ ft^2/day in test hole WIPP-30 (W-30) to $3 \text{ x } 10^{-1}$ ft^2/day in test hole H-6a (Table B-1). Hydraulic tests from the regional test holes south of the site showed that the transmissivity ranged from $6 \text{ x } 10^{-3}$ ft^2/day in test hole H-8A to 1.0 ft^2/day in test hole H-9a (Table B-1).

Hydraulic data are now available from 22 wells, including 7 wells recompleted to the Magenta between 1995 and 2002 (Table B-2). According to Mercer 1983, transmissivity ranges over five orders of magnitude from 1×10^{-9} to 4×10^{-4} m^2/sec (4×10^{-3} to 3.75×10^{2} ft^2/day). A slug test performed in H-9c, a recompleted Magenta well (Figure B-4), yielded a transmissivity of 6×10^{-7} m^2/sec (0.56 ft^2/day), which is consistent with Mercer's findings (SNL 2003). The porosity of the Magenta was measured in 1995 as part of testing at the H-19 hydropad (TerraTek 1996). Four samples had effective porosities ranging from 2.7% to 25.2%. The hydraulic transmissivities of the Magenta, based on sparse data, show a decrease from west to east, with slight indentations of the contours north and south of the WIPP that correspond to the topographic expression of Nash Draw. In most locations, the hydraulic conductivity of the Magenta is one to two orders of magnitude less than that of the Culebra.

Table B-1. Hydraulic Properties of the Rustler Formation Members

[Transmissivity is expressed in feet squared per day]

Test hole	Magenta Dolomite Member		Culebra Dolomite Member		Rustler-Salado Contact Residuum	
	Transmissivity	Storage	Transmissivity	Storage	Transmissivity	Storage
H-1	0.05	-	0.07	10^{-4}	0.0003	-
H-2A	.01	10^{-4}				
H-2B			0.4	10^{-9}		
H-2C					0.0001	-
H-3	.1	10^{-5}	19.0	-	0.0003	10^{-4}
H-4A	.06	10^{-6}				
H-4B			0.9	10^{-9}		
H-4C					0.0006	10^{-4}
H-5A	.1	10^{-5}				
H-5B			0.2	10^{-5}		
H-5C					.00003	10^{-3}
H-6A	.3	10^{-5}				
H-6B			73.0	-		
H-6C					.003	10^{-6}
H-7A	Unsaturated	-				
H-7B			1000+	-		
H-7C					0.73	-
H-8A	.006	10^{-5}				
H-8B			16.0	-		
H-8C					0.003	-
H-9A	1.0	10^{-9}				
H-9B			231	-		
H-9C					0.0002	-
H-10A	0.01	10^{-3}				
H-10B			0.07	10^{-4}		
H-10C					0.00009	-
P-14			140	-	0.05	-
P-15			0.07	10^{-4}	0.0004	-
P-17			1.0	10^{-6}	0.0002	10^{-4}
P-18			0.001	-	0.00003	10^{-5}
W-25	375	-	270	-	5.0	10^{-3}
W-26	Unsaturated	-	1250	-	0.4	-
W-27	53	-	650	-	0.0002	-
W-28	Unsaturated	-	18	-	0.87	-
W-29	Not present		1000	-	8	-
W-30	0.004	-	0.3	10^{-4}	0.2	10^{-4}

Table B-2. Hydraulic Properties of the Magenta

Magenta Well	Magenta Thickness (ft)	T (ft²/day)	T Reference
C-2737	23	no test	
DOE-2	23.8	1E-03	Mercer 1983
H-1	26	5E-02	Mercer 1983
H-2a	28	1E-02	Mercer 1983
H-2b1	28	2.1-2.7E-3	SAND89-0869
H-3b1	25	1E-01	Mercer 1983
		1.4-1.8E-1	SAND89-0869
H-4a	25	6E-02	Mercer 1983
H-4c	26	no test	
H-5a	27	1E-01	Mercer 1983
H-5c	24	no test	
H-6a	19	3E-01	Mercer 1983
H-6c	24	no test	
H-7a	23	[1]NA	
H-8a	22	6E-03	Mercer 1983
H-9a	31	1	Mercer 1983
H-9c	31	5.6E-01	Pfeifle & Chace 2003
H-10a	24	1E-02	Mercer 1983
H-11b2	26	no test	
H-14	25.6	5.3-5.6E-3	SAND87-0039
H-15	25	no test	
H-16	25.4	2.4-2.8E-2	SAND87-0039
H-18	23	no test	
H-19b1	25	3.8E-01	SAND98-0049
WIPP-18	24	no test	
WIPP-25	26	375	Mercer 1983
WIPP-26	29	NA	
WIPP-27	18	53	Mercer 1983
WIPP-28	25	NA	
WIPP-30	24	4E-03	Mercer 1983

[1] NA – Not Available

B.1.5 Forty-Niner

The Forty-niner is a confining hydrostratigraphic layer about 20-m (66 ft) thick throughout the WIPP area and consists of low-permeability anhydrite and siltstone. Tests by Beauheim 1987a in H-14 and H-16 yielded transmissivities of about 3×10^{-8} to 8×10^{-8} m^2/sec (3×10^{-2} to 7×10^{-2} ft^2/day) and 3×10^{-9} to 6×10^{-9} m^2/sec (5×10^{-3} to 6×10^{-3} ft^2/day), respectively, for the siltstone unit of the Forty-niner. Tests of the siltstone in H-3d provided transmissivity estimates of 3.8×10^{-9} to 4.8×10^{-9} m^2/sec (3.5×10^{-3} to 4.5×10^{-3} ft^2/day) (Beauheim et al. 1991). The porosity of the Forty-niner was measured as part of testing at the H-19 hydropad (TerraTek 1996). Three claystone samples had effective porosities ranging from 9.1% to 24.0%. Four anhydrite samples had effective porosities ranging from 0.0% to 0.4%.

REFERENCES

Bachman, G.O. 1981. *Geology of Nash Draw, Eddy County, New Mexico*. Open-File Report 81-31. U.S. Geological Survey, Denver, Colorado.

Beauheim, R.L. 1986. *Hydraulic-Test Interpretations for Well DOE-2 at the Waste Isolation Pilot Plant (WIPP) Site*. SAND86-1364. Sandia National Laboratories, Albuquerque, New Mexico. ERMS 227656.

Beauheim, R.L. 1987a. *Interpretations of Single-Well Hydraulic Tests Conducted at and Near the Waste Isolation Pilot Plant (WIPP) Site, 1983–1987*. SAND87-0039. Sandia National Laboratories, Albuquerque, New Mexico. ERMS 227679.

Beauheim, R.L. 1987b. *Analysis of Pumping Tests of the Culebra Dolomite Conducted at the H-3 Hydropad at the Waste Isolation Pilot Plant (WIPP) Site*. SAND86-2311. Sandia National Laboratories, Albuquerque, New Mexico.

Beauheim, R.L. 1987c. *Interpretation of the WIPP-13 Multipad Pumping Test of the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) Site*. SAND87-2456. Sandia National Laboratories, Albuquerque, New Mexico.

Beauheim, R.L. 1989. *Interpretation of H-141b4 Hydraulic Tests and the H-11 Multipad Pumping Test of the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) Site*. SAND89-0536. Sandia National Laboratories, Albuquerque, New Mexico.

Beauheim, R.L. 2000. Appendix E, Summary of Hydraulic Tests Performed at Tracer-Test Sites. In Interpretations of Tracer Tests Performed in the Culebra Dolomite at the Waste Isolation Pilot Plant Site. Meigs, L.C., Beauheim, R.L., and Jones, T.L., eds. SAND97-3109. Albuquerque, New Mexico: Sandia National Laboratories.

Beauheim, R.L., L.C. Meigs, G.J. Saulnier, Jr., and W.A Stensrud 1995. *Culebra Transport Program Test Plan: Tracer Testing of the Culebra Dolomite Member of the Rustler Formation at the H-19 and H-11 Hydropads on the WIPP Site*. ERMS 230156. Carlsbad, New Mexico: Sandia National Laboratories, WIPP Records Center.

Beauheim, R.L., and G.J. Ruskauff, 1998. *Analysis of Hydraulic Tests of the Culebra and Magenta Dolomites and Dewey Lake Redbeds Conducted at the Waste Isolation Pilot Plant Site*. SAND98-0049. Albuquerque, New Mexico: Sandia National Laboratories.

Beauheim, R.L., T.F. Dale, and J.F. Pickens 1991. *Interpretations of Single-Well Hydraulic Tests of the Rustler Formation Conducted in the Vicinity of the Waste Isolation Pilot Plant Site, 1988-1989*. SAND89-0869. Sandia National Laboratories, Albuquerque, New Mexico.

DOE (U.S. Department of Energy) 2004. Title 40 CFR 191 Parts B and C Compliance Recertification Application, U.S. Department of Energy Carlsbad Area Field Office, March 2004.

Jones, T.L., V.A. Kelley, J.T. Pickens, D.T. Upton, R.L. Beauheim, and P.B. Davies, 1992. *Integration of Interpretation Results of Tracer Tests Performed in the Culebra Dolomite at the Waste Isolation Pilot Plant Site*. SAND92-1579. Sandia National Laboratories, Albuquerque, New Mexico.

Meigs, L.C., and R.L. Beauheim, 2001. *Tracer Tests in a Fractured Dolomite, Experimental Design and Observed Tracer Recoveries*. Water Resources Research, Vol. 25, No. 5, pp. 1113–1128.

Meigs, L.C., R.L. Beauheim, and T.L. Jones, eds., 2000. *Interpretation of Tracer Tests Performed in the Culebra Dolomite at the Waste Isolation Pilot Plant*. SAND97-3109. Albuquerque, New Mexico: Sandia National Laboratories.

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

Powers, D.W., and R.M. Holt 1999. *The Los Medaños Member of the Permian Rustler Formation*. New Mexico Geology, Vol. 21, No. 4, pp. 97–103.

SNL (Sandia National Laboratories) 2003. Sandia National Laboratories Technical Baseline Reports, WBS 1.3.5.3, Compliance Monitoring; WBS 1.3.5.4, Repository Investigations, Milestone RI 03-210, January 31, 2003. ERMS 526049. Carlsbad, New Mexico: Sandia National Laboratories, WIPP Records Center.

TerraTek, Inc., 1996. *Physical Property Characterization of Miscellaneous Rock Samples*. Contract AA-2896. Contractor Report TR97-03 to Sandia National Laboratories. ERMS 238234. Salt Lake City, Utah.

Vine, J.D. 1963. Surface Geology of the Nash Draw Quadrangle, Eddy County, New Mexico. U.S. Geological Survey Bulletin 1141-B. U.S. Government Printing Office, Washington, DC.