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Assessment of the Potential for Karst in the Rustler Formation at the WIPP Site

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Abstract

This report is an independent assessment of the potential for karst dissolution in evaporitic strata of the Rustler Formation at the Waste Isolation Pilot Plant (WIPP) site. Review of the available data suggests that the Rustler strata thicken and thin across the area in depositional patterns related to lateral variations in sedimentary accommodation space and normal facies changes. Most of the evidence that has been offered for the presence of karst in the subsurface has been used out of context, and the different pieces are not mutually supporting.

Outside of Nash Draw, definitive evidence for the development of karst in the Rustler Formation near the WIPP site is limited to the horizon of the Magenta Member in drillhole WIPP-33. Most of the other evidence cited by the proponents of karst is more easily interpreted as primary sedimentary structures and the localized dissolution of evaporitic strata adjacent to the Magenta and Culebra water-bearing units. Some of the cited evidence is invalid, an inherited baggage from studies made prior to the widespread knowledge of modern evaporite depositional environments and prior to the existence of definitive exposures of the Rustler Formation in the WIPP shafts. Some of the evidence is spurious, has been taken out of context, or is misquoted.

Lateral lithologic variations from halite to mudstone within the Rustler Formation under the WIPP site have been taken as evidence for the dissolution of halite such as that seen in Nash Draw, but are more rationally explained as sedimentary facies changes. Extrapolation of the known karst features in Nash Draw eastward to the WIPP site, where conditions are and have been significantly different for half a million years, is unwarranted. The volumes of insoluble material that would remain after dissolution of halite would be significantly less than the observed bed thicknesses, thus dissolution is an unlikely explanation for the lateral variations from halite to mudstone and siltstone.

Several surficial depressions at WIPP, suggested to be sinkholes, do not have enough catchment area to form a sinkhole, and holes drilled to investigate the subsurface strata do not support a sinkhole interpretation. Surface drainage across the WIPP site is poorly developed because it has been disrupted by migrating sand dunes and because precipitation is not focused by defined catchment areas in this region of low precipitation and low-dip bedding, not because it has been captured by sinkholes. There are no known points of discharge from the Rustler Formation at WIPP that would indicate the presence of a subsurface karst drainage system.

The existing drillholes across the WIPP site, though small in diameter, are sufficient to assess the probability of karst development along the horizontal fractures that are common in the Rustler Formation, and the area of investigation has been augmented significantly by the mapping of four large-diameter shafts excavated into the WIPP repository. The general absence of dissolution, karsting, and related conduits is corroborated by the pumping tests which have interrogated large volumes of the Rustler Formation between drillholes. Diffusion calculations suggest that separate isotopic signatures for the water found in the fractures and the water found in the pores of the matrix rock between fractures are unlikely, thus the isotopic evidence for ancient Rustler formation waters is valid. Geophysical techniques show a number of anomalies, but the anomalies do not overlap to portray consistent and mutually supporting patterns that can be definitively related to karst void space at any given location. The coincidence of the Culebra and Magenta potentiometric heads between Nash Draw and the WIPP site is the inevitable intersection of two non-parallel surfaces rather than an indication of karst-related hydraulic communication between the two units.

The proponents of karst in the Rustler Formation at the WIPP site tend to mix data, to take data out of context, and to offer theory as fact. They do not analyze the data or synthesize it into a rigorous, mutually supporting framework. They assume that the existence of an anomaly rather than the specific characteristics of that anomaly proves the existence of intra-stratal karst in the Rustler Formation. In most cases, the interpretations of karst offered are non-unique interpretations of data for which more plausible interpretations exist.

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1.0 INTRODUCTION

This report has been assembled in response to a request from the U.S. Environmental Protection Agency (EPA) to address concerns about the possible existence of a karsted layer or layers within the Rustler Formation, expressed most comprehensively by Hill (1999) in an unpublished "Letter Report" to Sandia National Laboratories. Hill published a slightly revised and shorter version of this paper in 2003.

The Rustler Formation overlies the nuclear waste repository strata (which is within the Salado Formation) at the WIPP site in southeastern New Mexico. A karst development in the Rustler Formation at this site could conceivably alter flow pathways for leakage away from the WIPP site should the repository be breached and contaminants migrate as far upward as the Rustler Formation. The primary purpose of this report is to assess the evidence for karst development in the Rustler Formation at the WIPP site. The topics discussed here were specified by EPA and include those issues raised by the Hill report and by other proponents of karst at the WIPP site.

The data available for this assessment consist of the geological reports of the area, going back to potash resource characterization studies from the 1930's. Geologic studies include those specific to the nuclear "Gnome" experiment that was done in the early 1960's as part of the Plowshares program, as well as the more recent and more numerous WIPP-related studies. Where possible, the original core and outcrop descriptions and associated geologic project reports have been obtained. The original geophysical and hydrological studies that were undertaken to address the question of whether or not karst has been developed in the Rustler Formation at the WIPP site have also been assessed for their potential to clarify the geologic interpretations.

Several subtle but important problems with the geologic interpretations that have been made at WIPP are discussed here. First, many of the early geologists working in the WIPP area (e.g., Vine, Jones, Gard) were educated and made their descriptions of the strata prior to the proliferation of studies and resulting knowledge of modern sedimentary depositional environments that started in the late 1960's and 1970's. These geologists did not have the background or training to properly interpret the signatures of many of the evaporitic depositional and diagenetic environments represented by the sedimentary textures in cores and outcrops that they studied.

For example, Gard (1968) invoked a cumbersome, hypothetical system of localized, temporary uplifts during deposition of the Salado Formation in order to explain the evidence he found for subaerial exposure such as desiccation cracks and truncated bedding found in the halite deposits in the Gnome shafts. This was because the prevailing theory at the time was that all bedded halites were deposited in marine environments. Studies that have both developed and used more recent sedimentology concepts, such as those by Smoot and Lowenstein (1991), Harville and Fritz (1986), and Powers and Holt (2000), have shown that, in fact, the thick Ochoan evaporites were deposited in irregularly exposed and flooded salt pans marginal to marine environments. These studies explain Gard's evidence for subaerial exposure much more neatly and logically, and are consistent with modern sedimentary principles.

Second, most of the early WIPP geology reports used the prevailing geological conventions which blurred the distinctions between lithologies, facies, and depositional/diagenetic environments, i.e., between basic data and interpretations. Under these conventions, it was acceptable to label a unit either descriptively by its lithology, by a lithologic shorthand that also implied an origin but that wasn't proven, or by an imprecise combination of the two.

Some of these early, unsupported interpretations have become entrenched in the literature, where they have caused confusion because later authors have assumed that they are proven concepts. Some of these interpretations have even been extrapolated to superficially similar lithologic units where there is even less basis for the implied interpretation of origin.

Finally, until drilling of the large-diameter shafts at the WIPP site, most of the important, diagnostic sedimentary structures in the Rustler Formation were obscured. Samples were either too small (e.g., four-inch diameter and smaller core) or too weathered (outcrop) to display or preserve such structures. This left the early geologists dependent on the less definitive, gross-scale geologic relationships as the basis for many of their sedimentological interpretations. Although the gross-scale relationships are important, the range of possible interpretations that can be made based on these relationships can now be culled and the interpretations significantly refined using the exposures of previously unknown structures, textures, and sedimentary assemblages available in the WIPP shaft excavations. These features are especially useful in making comparisons to the data available from recent studies of analogous modern evaporite depositional environments.

2.0 APPROACH

An objective assessment of the evidence for karst in the Rustler Formation has been attempted, along with an assessment of whether or not the undisputed evidence for karst at Nash Draw implies that karst is widely developed in the Rustler Formation elsewhere, specifically in the subsurface under the WIPP site.

Different approaches taken by various scientists are also compared in the discussions presented here, assessing the approaches in light of accepted practice. The presentation of unsupported statements, and the substitution of theory for evidence, are unacceptable scientific methods that would not stand up to rigorous peer review. Much of the evidence offered for the existence of karst in the Rustler Formation at the WIPP site is speculative, or at best, speculative analogy, and what evidence exists for karst is commonly contradictory and subject to other, more plausible interpretations. An attempt is made here to assess the reliability and origin of the data that have been used to make various interpretations, and to assess whether those interpretations are proven, probable, plausible, merely possible, or even untenable. In this report, indirect evidence is not given equal weight with direct evidence, and possible geological models are not equated with proven or plausible models.

In assessing the issues raised by Hill's (1999) report, an attempt has been made to find the original data and descriptions that underpinned the early interpretations, and to determine whether or not they are now assumed to be factual merely because they are entrenched due to constant repetition, and whether there was originally a valid basis for making these interpretations. An example is the repeated designation of some of the Rustler lithologies that are dominated by siliciclastics as "dissolution residue," discussed below. The interpretations have also been assessed as to whether or not they are defendable in light of subsequent advancements in geologic knowledge and the acquisition of new data, or whether they are just convenient, inherited labels. It appears that many of the interpretations have been overextensions of what the data will actually support.

Specific issues raised by the Hill (1999) "Letter report" to Sandia National Laboratories that are addressed below include whether or not there is direct, subsurface evidence for karst at the WIPP site, the significance of specific topographic depressions in the land surface, the importance of small-scale gravity anomalies, the interpretation of data (cores, mud logs, cuttings, etc.) found in the well reports, and the validity of interpretations of some deposits found in cores as insoluble "residue" derived from recently dissolved halite beds.

3.0 GEOLOGIC EVIDENCE CITED FOR KARST AT WIPP

3.1 Introduction

The Late Permian and younger strata at the WIPP site in southeastern New Mexico (Figure 1), including the Rustler Formation, are relatively flat-lying, having structural dips of only a few degrees, generally towards the east. Many of the formations and lithologic units within the formations are homogeneous and laterally extensive for miles or even tens of miles. The inclined strata have been truncated by erosion, with successively older units exposed at the surface westward (Figure 2). Various units of the Rustler Formation have been exposed at Nash Draw, west of the WIPP site, and the exposure has led to dissolution of the evaporitic strata and deeper local erosion. East of Nash Draw and across the WIPP site, erosion has beveled but has not removed the clastic strata of the Permian Dewey Lake and Triassic Santa Rosa Formations, which overlie the Rustler Formation.

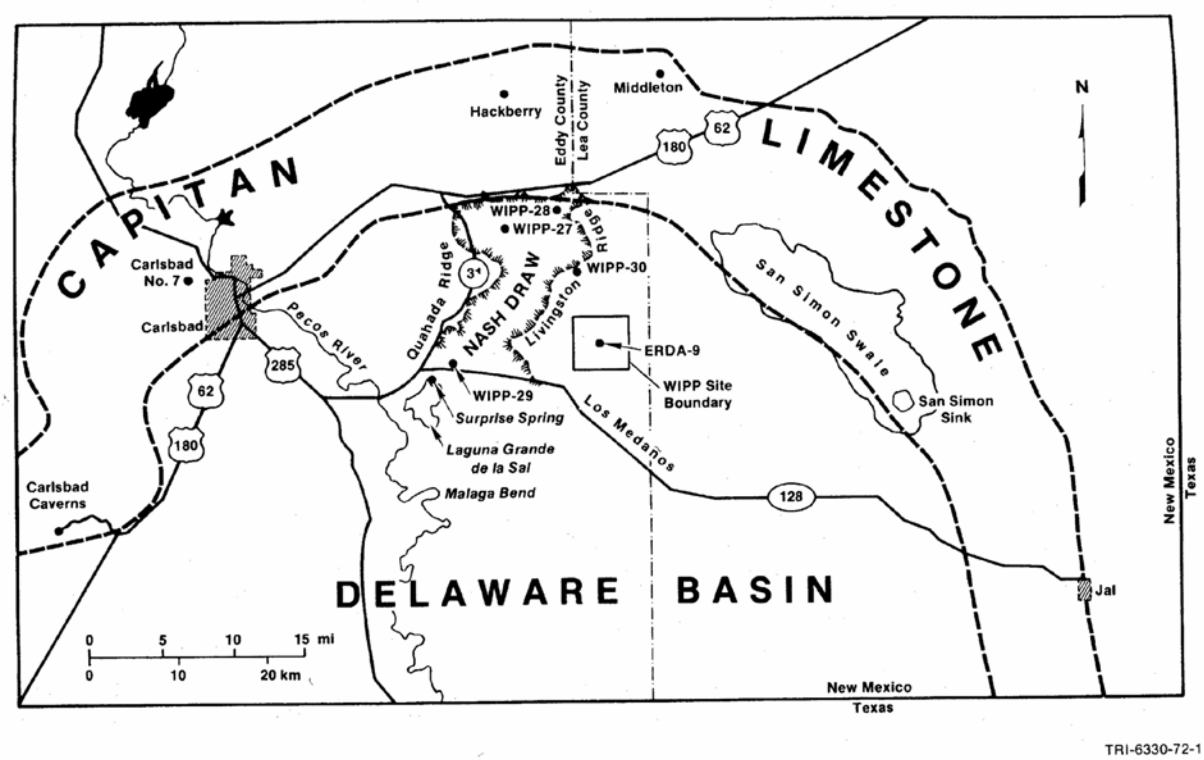


Figure 1. Location map for the WIPP site, southeastern New Mexico (from Siegel et al., 1991).

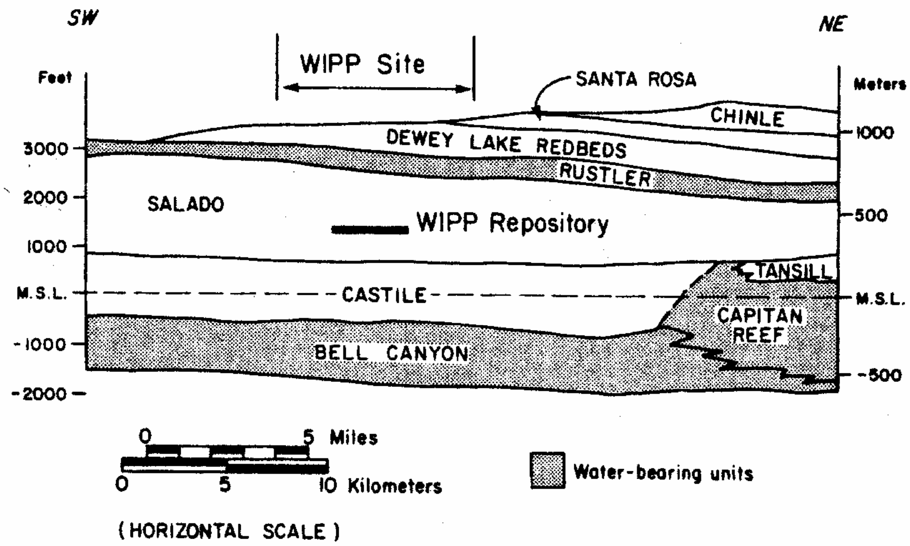


Fig. 2. Stratigraphy of the Ochoan series (Upper Permian) evaporite beds in the Delaware Basin. Castile, Salado, Rustler, and Dewey Lake Redbeds formations belong to the Ochoan Series.

Figure 2. Schematic southwest-northeast cross section across the WIPP site (from Chaturvedi and Rehfeldt, 1984).

Although lateral continuity and homogeneity of bedding are common attributes of the local Permian strata, they are not universal, nor are they universal in geologic strata world-wide. The lateral variability within the evaporitic to muddy Forty-niner, Tamarisk, and Los Medaños Members of the Rustler Formation (Figure 3) contrasts with the lateral homogeneity of the intervening, dolomitic Culebra and Magenta Members of the formation. Some of the lateral variability in the evaporites in the vicinity of Nash Draw, where the formation has been exposed to weathering and erosion at the surface, can be related to relatively recent dissolution. In the subsurface, however, most of this variability is the result of lateral variations in depositional facies. Historically, the subtle distinction between primary lateral variability created by facies changes and the secondary variability imposed on the strata by local dissolution has been blurred or ignored by various authors, and some clarification of that distinction is attempted here.

The term “karst” includes a wide range of features developed during the dissolution of rocks, usually of the more soluble carbonate and evaporitic lithologies, by various types of naturally occurring, mildly acidic fluids, most commonly rainwater. Karst includes features that range from minimal karst development, as in the local enhancement of the widths of existing fractures (Figure 4), to enlargement of these conduits and development of cavernous pathways in the strata, to near-complete removal of the soluble strata with only scattered remnants left to prove that the strata once existed.

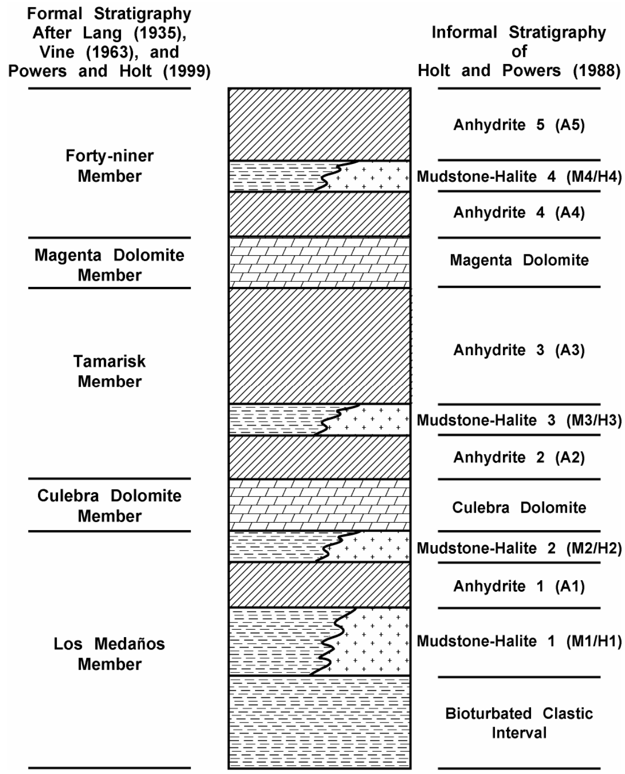


Figure 3. Stratigraphic nomenclature and schematic lithology of the members of the Rustler Formation.

Most of the discussion of karst at the WIPP site revolves around the presence or absence of features suggested to be indicative of an intermediate stage of karst development. However, evidence for karst at this site is ambiguous, which has allowed different authors, and sometimes even the same authors in different papers, to present different concepts of what the hypothetical karst might look like at WIPP site.

Hill (1999, page 3-5; 2003, page 201) lists the following as "characteristics" of intrastratal karst:

1. it can form within the vadose zone, at or near the water table, or in the phreatic zone
2. it usually does not have surface expression, i.e., it is concealed karst
3. it can form at depth
4. it is difficult to detect
5. it is widespread in evaporite rocks

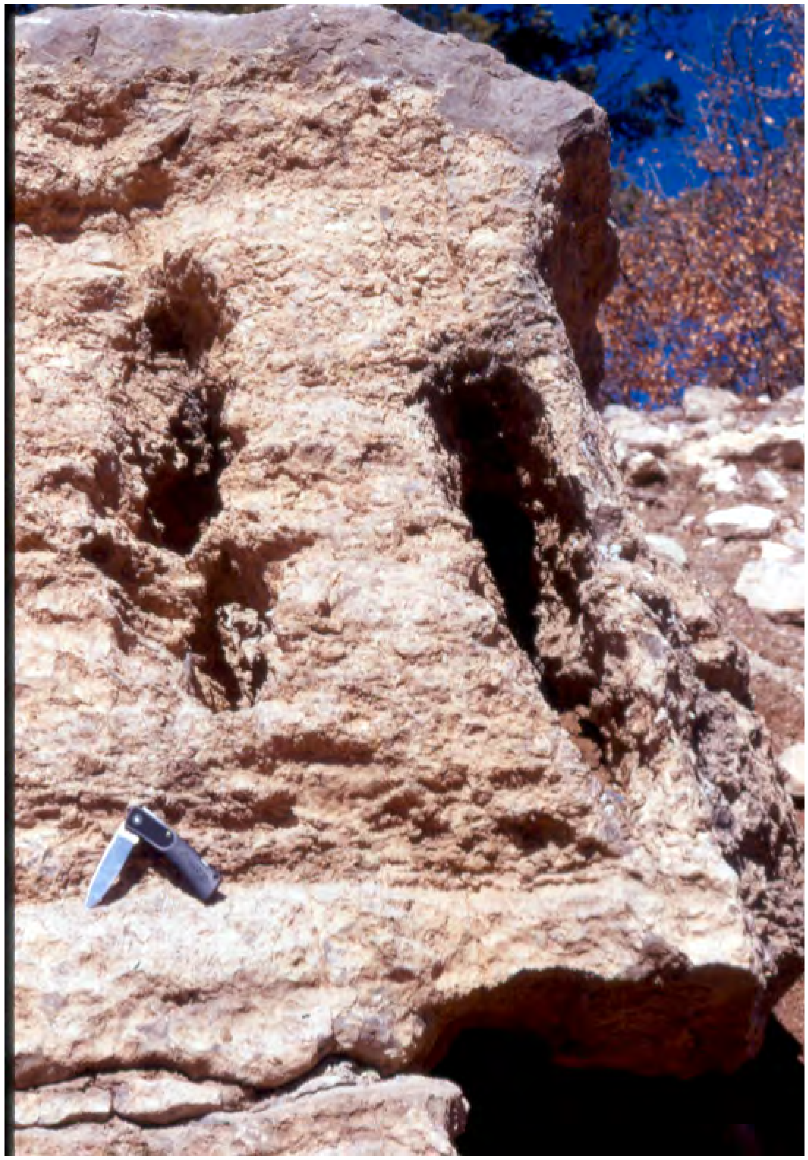


Figure 4. Solution-enhanced fractures in the Madera Limestone: the beginning of karst. (Road cut on route NM 217 east of Albuquerque.)

These are not "characteristics" in a strict sense of the term, the list is not used rigorously, and the characteristics are not definitive. The fact that a feature can form in any position relative to the water table, points one and three, does not help to define it. "Widespread," point five, is a subjective term and is not equivalent to "universal" as implied by the tenor of the report. Obscuration, points two and four, is a key point for Hill, leading to convoluted arguments that the lack of specific evidence supporting the presence of karst at WIPP does not negate the possibility that it is present, and therefore seeming to allow an unrestricted lateral extrapolation of the definitive evidence for karst features in Nash Draw across several miles and into the subsurface at the WIPP site.

Numerous karst-related terms are defined by Hill (1999, pages 3-6) in a mixture of descriptive, genetic, and synonymous terms. Hill defines "karst" geomorphically as a landscape characterized by closed depressions, disrupted surface drainage, and underground caves and drainage systems. The first two of the features are not uniquely indicative of karst: although closed depressions and disrupted surface drainage may be the result of a process that produces cavernous karst in underlying strata, they can also result from other processes such as the irregular coverage of a land surface by glacial till or windblown sand dunes, or tectonically by structural reversal of low-angle bedding dips.

The 1972 AGI Glossary of Geology (Gary et al., 1972), in the definition of karst, specifies an origin as a dissolution product and includes the resulting surficial geomorphic features such as disrupted drainage as part of the characteristics of karst. Although the disrupted surface drainage described by Hill is both real and widespread at the WIPP site, and although it is similar to that created by karst processes, such features can be created by processes other than dissolution so they are not unique evidence for dissolution.

Hill defines "paleokarst" as a karst that is no longer in contact with a flowing hydrologic system, implying that dissolution is no longer actively removing rock, but whether above or below the water table is not specified. Hill defines "intrastratal karst" as a layer that has been partially dissolved in the subsurface, beneath undissolved strata that cover and obscure it. These are generally accepted terms.

3.2 Geologic Evidence for Karst at the Surface

Specific, local, surficial features have suggested to several authors, as summarized by Hill (1999, 2003), that karst may be developed in the subsurface at and near the WIPP site. In extrapolating the widely recognized karst sinkholes, caves, and collapse features that are present at Nash Draw eastward to the WIPP site, Hill (1999) suggests that 1) five or six topographic depressions may be the surface expressions of strata collapsed over caverns (sinkholes) in the Rustler Formation on the northwest corner of the WIPP site, and 2) that a disappearing stream (a "doline"), described by Phillips (1987) as entering one of these topographic depressions, is where surface drainage is captured by the inferred subsurface karst conduit system.

The following discussion examines the surficial evidence for karst at and near the WIPP site, and compares the well developed karst features in the Rustler Formation in Nash Draw with the local and more ambiguous features claimed as evidence for karst in the areas east of Nash Draw, near and at the WIPP site.

3.2.1 Nash Draw

Nash Draw is a surface depression, about 20 miles long and 5-12 miles wide. It lies west of the WIPP site (Figure 1, Figure 5a) and is generally agreed to have been caused by the removal of evaporites from within the partially exposed Rustler Formation and from the upper parts of the underlying Salado Formation, by weathering, dissolution, and erosion (Bachman, 1981, 1985, 1990; Mercer, 1983). Unchallenged karst features in and immediately around Nash Draw include numerous caves (many containing secondary clay deposits), sinkholes, fractured and brecciated strata, and saline springs.

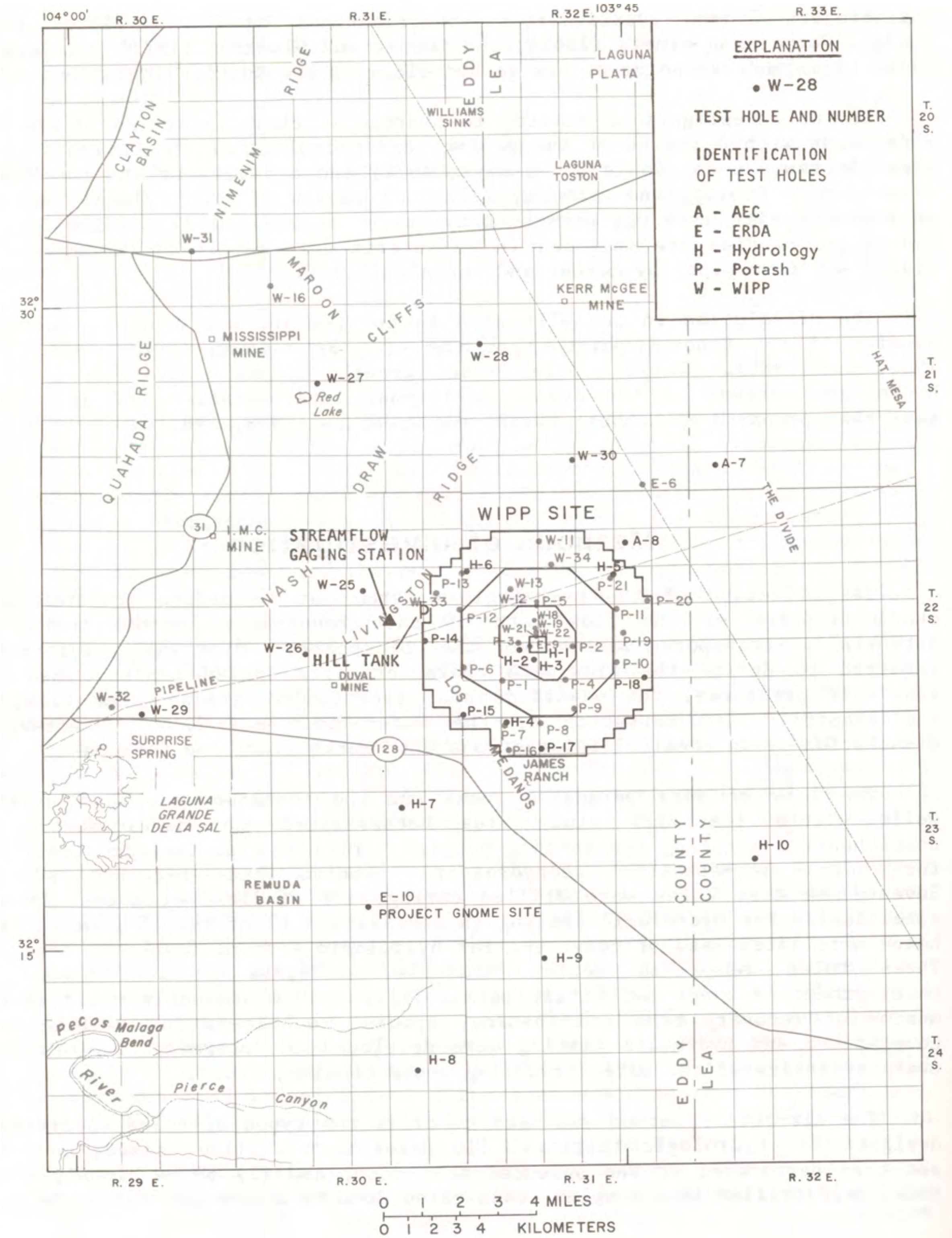


Figure 5a. Location map of geographic features at the WIPP site (from Mercer (1983), his Figure 1a). The outline of the WIPP area has changed since 1983; see Figure 5b.

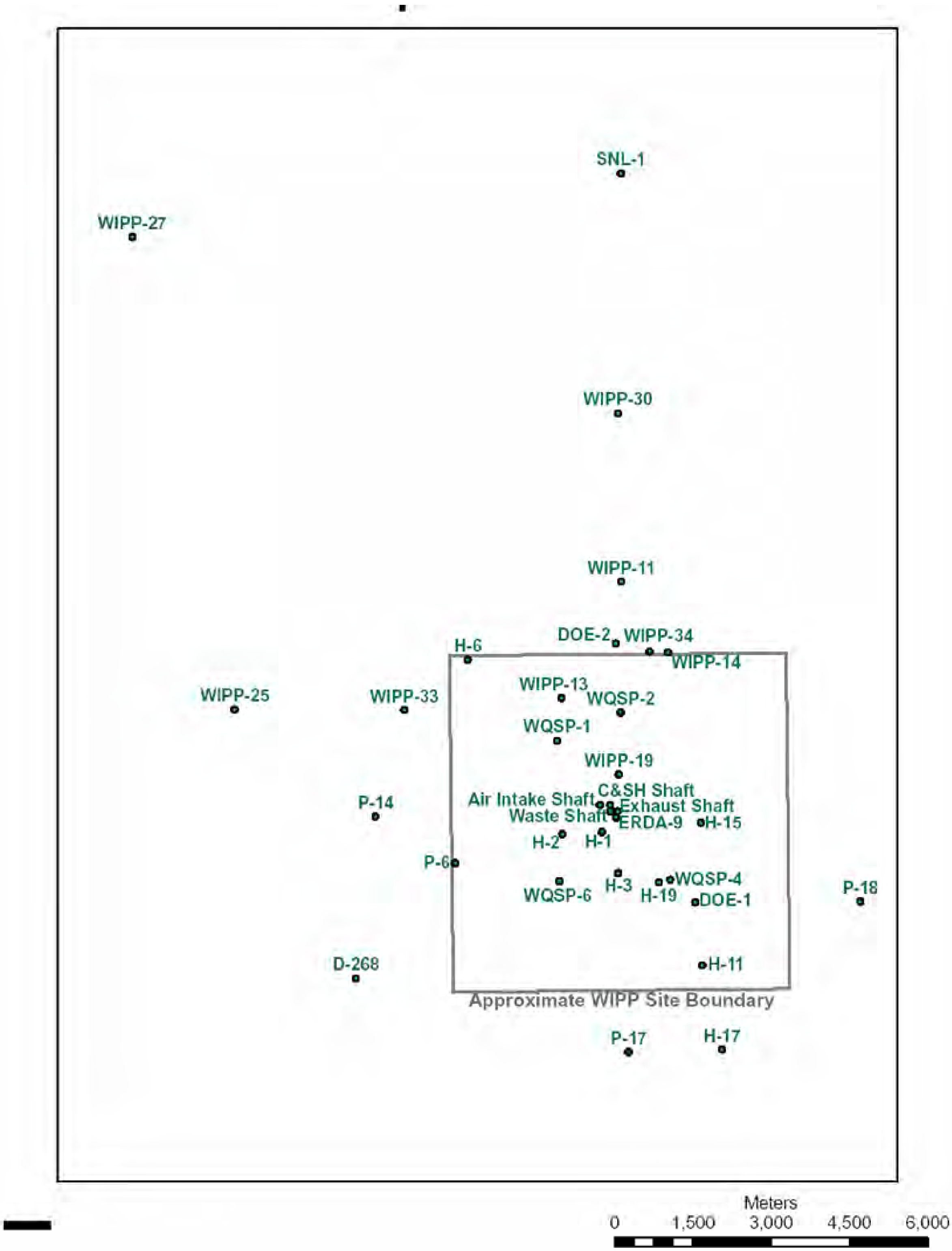


Figure 5b. Location map of the WIPP-area drillholes discussed in the text.

Dissolution is also indicated by significant thinning of the Rustler Formation in this area, with related subsidence of the overlying strata as well as displacement and fracturing of the insoluble Rustler beds that are/were interbedded with the soluble halite and anhydrite/gypsum units. Locally, the interval between the Magenta Dolomite and the Culebra Dolomite Members, normally a few tens of meters thick in the subsurface, has been thinned by dissolution of the interlayered evaporitic strata to the point where the dolomites are separated in outcrop by as little as a meter.

Analysis of crosscutting and superimposed geological relationships allowed Bachman (1985) to determine that Nash Draw and the related karst features began to form when erosion by westward-flowing streams unroofed the soluble evaporitic units of the Rustler Formation 500,000-600,000 years ago. Most of the dissolution that formed Nash Draw took place during this time, but the process is interpreted to still be active, albeit at a much slower rate, in the Nash Draw area (Bachman, 1981). The evidence offered for present-day dissolution is the presence of active, salt-saturated springs in several places around the draw. One reference (Geohydrology Associates, 1978) has suggested that the existing sinkholes are being actively enlarged but that no new sinkholes are forming, although no data are offered to support this interpretation.

Similar, unequivocal dissolution features (sinkholes, caves, disrupted strata, and thinned strata) are present in other areas where the Rustler Formation is exposed at the surface, notably in the area of Malaga, 10-12 miles southwest of the WIPP site (Reddy, 1961; Mercer, 1983; Bachman, 1980).

However, the evidence for extrapolating this well-developed karst system eastward to the WIPP site is not definitive. Arguments to the effect that "there is no reason NOT to expect karst development eastward" (Phillips, 1987), just because the soluble strata are there and because globally such strata often have karst features superimposed onto them, are specious. There are many areas of unkarsted evaporite deposits worldwide, and geologic conditions at the WIPP site are not the same as the conditions at Nash Draw.

3.2.2 Topographic Depressions East of Nash Draw

Hill (1999, p. 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. 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.

Wells drilled in these depressions to sample and test for karst have not encountered either displaced strata or breccias (see below). Hill (1999: her Figure 8, page 18 and Figure 17, page 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.

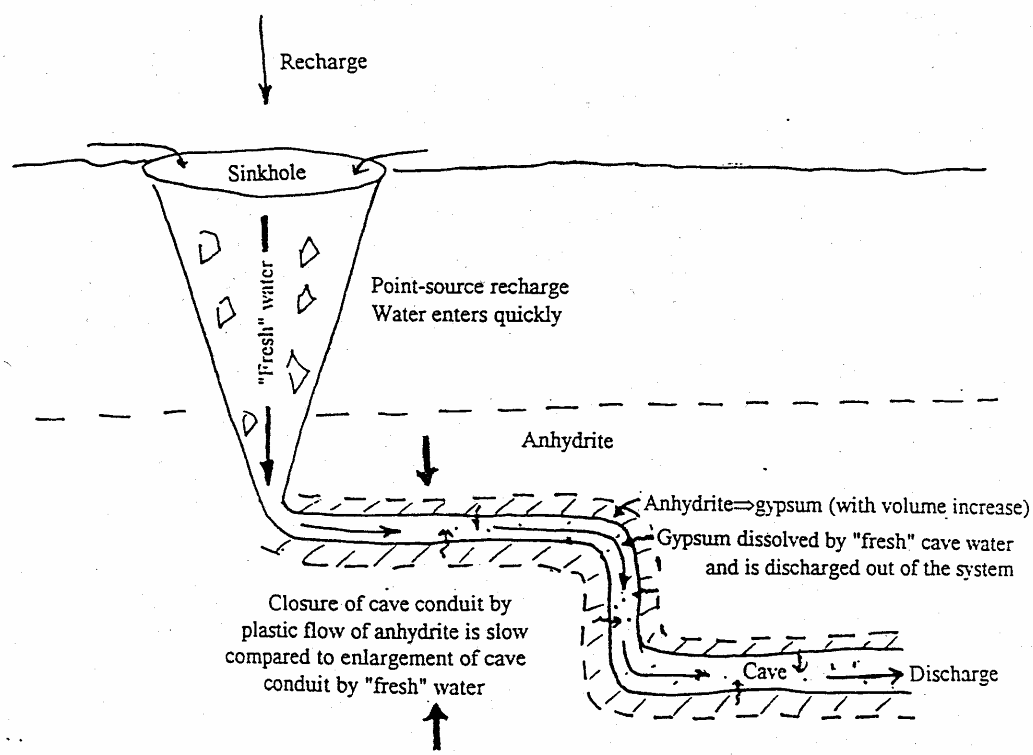


Figure 8. Diagram showing how circulating water causes cave passages to "escape" annealing and clogging with gypsum. Intrastratal evaporite karst can form extremely quickly; thus, the passage doesn't have time to anneal shut (opposing arrows). "Fresh" water input into a phreatic intrastratal karst system at a time of a heavy surface rain causes any dissolved anhydrite/gypsum to be discharged from the system.

Figure 6. Conceptual model of sinkhole formation, from Hill (1999), her Figure 8/page 18. The model does not account for the presence of insoluble sandstone layers at the top of the system. See text for discussion.

3.2.3 Disappearing Streams ("Dolines")

3.2.3.1 The Phillips thesis

Perhaps the most extensive presentation of the hypothesis that surface topographic depressions at WIPP might indicate collapse over subsurface voids caused by dissolution in the Rustler Formation is found in Phillips' 1987 PhD dissertation, cited extensively by Hill (1999). This work focused on the Mescalero Caliche, the uppermost layer of lithified strata at and near the WIPP site. Phillips implied that the impermeability of such a layer has been an erroneous cornerstone of the hydrological modeling at WIPP, although he did not cite the references. In fact, the three-dimensional basin-scale modeling of the WIPP hydrologic system performed by Corbet and Knupp (1996; see also Corbet, 2000), which provides the conceptual underpinning of all recent WIPP hydrologic studies and models, does not include the Mescalero Caliche at all.

Inhomogeneities are common in the Mescaleo caliche and in caliches in general. Caliches, also known as pedogenic calcretes (i.e., calcareous hardgrounds formed by soil-producing processes) commonly develop pipe-like features as they age due to rooting of plants and other deposition/dissolution processes that form these layers (e.g., Bachman and Machette, 1977). Gile, Hawley, and Grossman (1981) document similar pipes from calcretes in the Las Cruces, NM area.

Phillips (1987, page 6) asserts that some of the depressions found in the hummocky upper caliche surface at the WIPP site formed due to "collapse or subsidence of caliche into voids left by dissolution of underlying soluble rocks", and by "dissolution and breaching of caliche by infiltrating rainwater". Phillips documented broken, solution-pitted, and displaced layers of caliche in hand-augered test holes as deep as 21 feet. He did not present direct evidence that there are solution caverns in the deeper strata that may have caused the disruption of the caliche layer, but rather used the observations from the caliche layers to infer this conclusion indirectly, and then supported his conclusions with peripheral evidence from geophysics and groundwater studies.

Phillips has related depressions in the land surface to depressions in a datum surface at depth, but the significance of this relationship is not clear, and the hypothesis of origin as collapse over solution voids in the Rustler Formation has not been proven. The depth of investigation was a few tens of ft (trenching and auguring), the surface depressions are a few feet deep, and measured offsets of the datum are a few tens of feet. Moreover, the significance and reliability of Phillips' datum as a structural horizon are ambiguous at best: he used as a datum a horizon defined by the first intersection by the auger of either caliche or sandstone. A combination datum such as this does not represent either a structural or a time horizon. Moreover, caliche deposition commonly follows the contours of the topography on which it forms, thus it cannot be determined whether depressions in the land surface caused depressions in the datum or whether both were later offset by a lowering of the strata and land surface together.

More importantly, several hundreds of feet of insoluble Santa Rosa and Dewey Lake sandstones and siltstones separate Phillips' supposed caliche sinkholes near the surface from any potential Rustler caverns at depth into which the caliche might have been displaced. Connection between the depressions and the Rustler Formation across these intervening layers, and voids in the underlying Rustler, are entirely speculative.

Phillips proposed an absence of perched water tables in these formations and used that to support the concept of hydraulic conductivity vertically between the surface, across the sandstones, and into the Rustler, via his hypothetical sink hole collapse structures. However, other publications have noted or suggested that perched water tables do in fact exist in the Dewey Lake strata (e.g., Morgan and Sayre, 1942; Holt and Powers, 1990a; Powers, 1997: Mercer et al., 1998). Although larger-scale breccia pipes penetrate these clastic units in several places (i.e., Powers, 1996), speculations regarding small-scale penetration of these sandstone units and karst-type conduit connection across them that might allow meteoric recharge down into the underlying Rustler at the WIPP site are unsupported.

The implication from Phillips' interpretation that holes in the layer of Mescalero caliche allow significant recharge of meteoric waters to the underlying formations is an unproven, over-interpretation of the data. Phillips' text contains numerous similarly speculative and unsupported assertions at a smaller scale, and phrases such as "it could be that", "appear to be", and "is probably due to" are common, whereas definitive statements relating data to a defensible interpretation ("this proves that") are rare. Moreover, the conclusion that the caliche layer is not an impermeable layer is irrelevant, as numerous studies (discussed below) have used the percolation/infiltration of rainfall through the formations a primary source of recharge of groundwater into the Rustler Formation.

3.2.3.2 Chains of Depressions

Phillips suggests that an alignment (a "chain": 1987, pages 74, 82, 122) of three depressions near WIPP-33 (Figure 7, Figure 8) might be indicative of the solution that can occur along linear fault trends in some geologic settings. The three depressions of the chain extend across a distance of 1500 ft, with the center of the middle one off-line by 100 ft. These depressions are shallow, the deepest being about eight feet deep and a few hundred feet wide (Figure 9). One of the depressions analyzed by Phillips is only two feet deep, and it is not clear that this is significant relative to the surrounding topography.

Hill (1999, p. 53) suggests that "the presence of the four WIPP-33 sinkholes trending eastward suggests that these cave passages may head eastward in the direction of the WIPP site." These depressions have not been proven to be sinkholes, and "cave passages" have not been proven to underlie them, thus this is a speculative, over-interpretation of the data. In fact, only three of the depressions are aligned (the fourth and deepest, the WIPP-33 depression, is offset from the linear trend to form an "L"): this is a mis-statement of the geometry of the depressions, and misleading. Phillips' and Hill's suggestion that this alignment of depressions could indicate a fault-line trend that leads karst conduits eastward is unsupported by data.

3.2.3.3 "Barrows' Bathtub"

Much discussion has revolved around an ambiguous topographic depression in the southwest-central part of the WIPP area, informally called "Barrow's Bathtub" (Phillips, 1987). This depression has been suggested to be an example of a doline/karst depression (Phillips, 1987, page 163), a wind-formed "blowout" (Bachman, 1985), or the remnants of an artificial excavation into the caliche, dug for road metal, (Phillips, 1987, page 163, cited as a personal communication from Hawley).

The depression was probably first brought up for public discussion during the field trip described in Chaturvedi and Channell (1985; Appendix C, Notes for the Karst Hydrology Field Trip by Larry Barrows, page 3 [the location is given as being in section 30 of T. 22 S., R. 31 E., whereas most others have placed it in section 29]). In these Notes, Barrows briefly states that this "dimple," eight ft deep by 100 ft across, would be "an appropriate location to discuss the lack of surface runoff, character of the rainfall, and implications of the water balance," but he does not specifically label this depression as evidence for karst dissolution in the subsurface.

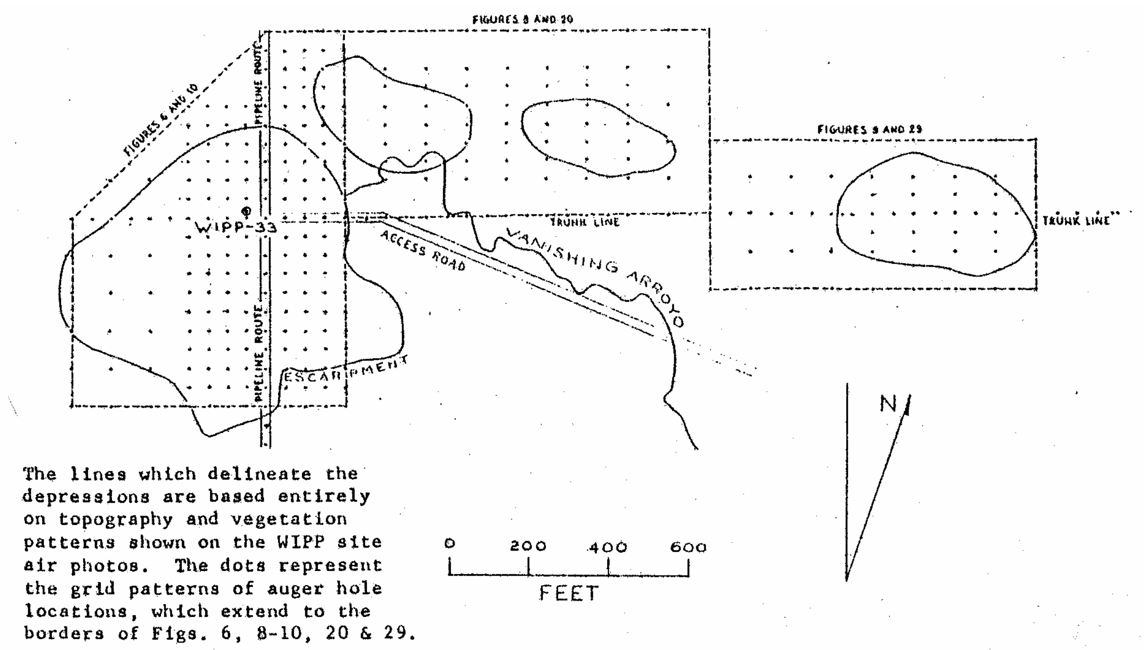


Figure 7. "Chain of sinkholes" associated with drillhole WIPP-33, and the proposed feeder stream, as mapped by Phillips (1987), his Figure 5/page 75.

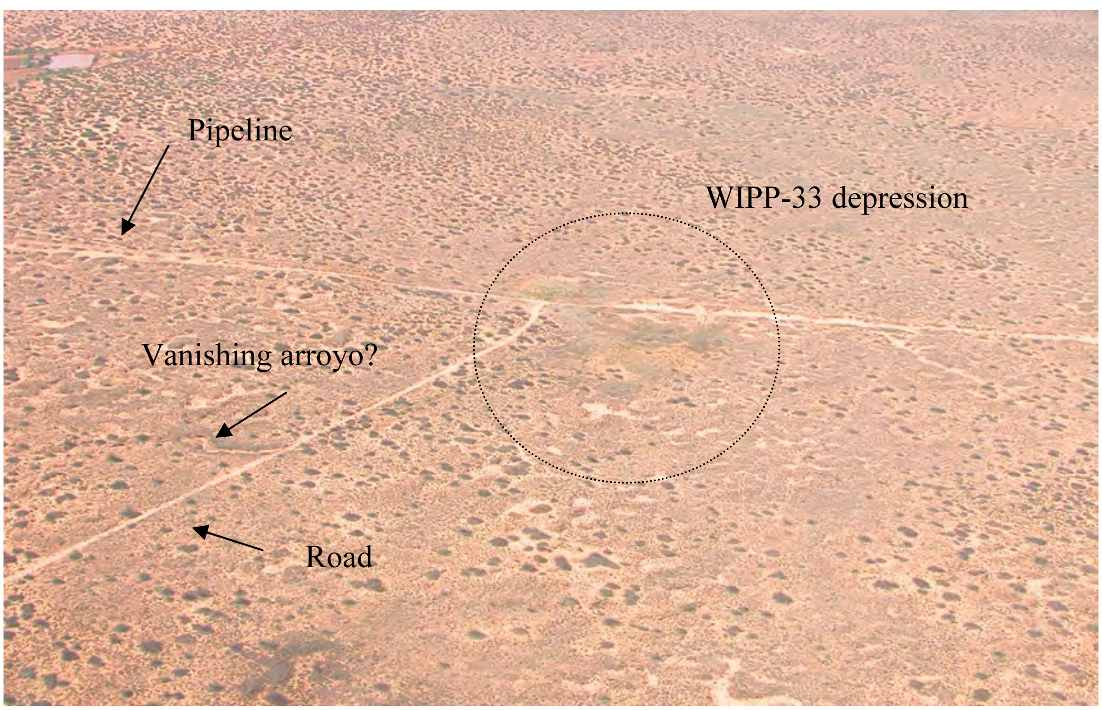


Figure 8. Low-angle aerial photograph of the area mapped in Figure 7, looking south-west. Drillhole WIPP-33 is located at the junction of the east-west road and the pipeline. Note the absence of well-defined drainages entering the area, and compare to Figure 11. Most of Phillips' vanishing arroyo is not apparent.

Figure 9. The WIPP-33 depression at ground level, looking west. Post (center of photo) marks the drillhole location, person to the right of it on the far side of the hollow for scale.

Others, notably Phillips (1987), have used this depression as evidence for a doline and for internal drainage into a karst system. Phillips (1987, pages 163-181) augured and trenched this depression, noting that the underlying caliche profile is poorly indurated, and that its surface mimics the overlying topography. Caliche is not present in the central parts of the depression, where the subsurface "structure" is floored by the Gatuña Formation. Phillips interprets this to indicate removal of the caliche and thus formation of the depression by dissolution. He suggests (page 165) that the "impregnation" of the underlying Gatuña sandstones with carbonate is "direct evidence of rainwater infiltration," though he does not indicate why the same waters that dissolved the carbonates of the caliche zone should have precipitated carbonate in the sandstone. In fact, carbonate is the most common cementing material in sandstone worldwide, and is not indicative of any particular process. A mechanism by which dissolution might have continued from the caliche and through the insoluble sandstone is not offered. Barrow's contour map of the sandstone surface with one-foot contour intervals (Phillips, 1987, Figure 45, page 186) shows a sandstone surface that is essentially flat and level.

Phillips (page 171) compared aerial photographs taken in 1958 with those from 1983 and suggested that they show an enlargement and increased angularity of the Barrows' Bathtub depression. Although he inferred from this that the depression is a doline, changes in outline and size are not exclusive evidence for any particular mode of formation: excavation operations would produce the same effects. He also offered an absence of surrounding dunes as evidence that this was not a wind-formed blowout (which was Bachman's [1985, page 21] interpretation), even though the area is located within a large, stabilized dune field (e.g., Chugg et al., 1971).

3.2.3.4 WIPP-33

Phillips (1987) and Barrows (1982) have provided the primary discussions cited by Hill (1999) in suggesting that one or more of the hollows noted above accommodate disappearing streams or "dolines." Although these and Hill's reports imply that such features are common at the WIPP site, in fact only the one supposedly feeding the WIPP-33 depression has been mapped, and this example is ambiguous, being much smaller and less well defined than the dolines found in Nash Draw.

This feature, inferred to be the course of a shallow, short, captured stream, terminates within the WIPP-33 surface hollow described above. It has been used as evidence to suggest that the land surface at and near WIPP is one of disrupted drainage, where numerous streams have been captured by the inferred system of karst-related subsurface conduits. Phillips (1987) suggests that the vanishing arroyo terminates in the eight-ft deep WIPP-33 depression, and he has mapped it at small scale (Phillips, 1987, Fig. 5). The valley of this arroyo does not show in the two-ft topographic contour lines of his Figures 6, 8, and 9, and the map of the arroyo (Figure 7) shows it entering one depression, then implausibly flowing uphill to cross the shallow divide into the next hollow where WIPP-33 is located.

An explanation is not provided for why the stream should pass through and beyond the first depression, which Phillips (1987, page 114) asserts is also "probably an alluvial doline, formed by subsidence or collapse of sandstone and caliche into voids in the Rustler". No other dolines have been mapped near WIPP, although several are obvious within Nash Draw a few miles to the west, where much larger and more definitive stream systems have been abruptly diverted into obvious sinkholes.

The poorly constrained rate of disappearance of water from these depressions has been offered as evidence that they are dolines. Data on rates of soil percolation would indicate whether ponded rainwater would be able to soak into the sandy surficial deposits within the observed time frames or whether capture by inferred subsurface drainage would be necessary to account for the rate of water disappearance from the hollows, but no such data have been offered. Rather, Phillips, citing anecdotal evidence, suggests that because the WIPP-33 depression was filled with five feet of water for "a matter of days" (Phillips, 1987, p. 86), disappearance of the water is evidence that it had to sink into an underground system. A more plausible interpretation of the same observation would be that because the sandy hollow held water at all, there is probably no drain outlet into a subterranean plumbing system at the bottom of the depression, and that the water seeped slowly into the surrounding sandy deposits.

Phillips (p. 125) writes that "Surface drainage is almost undeveloped east of the Pecos River…" and suggests that this is because the drainage has been captured by an underground system. This would as easily be explained by drainage disruption during migration of numerous sand dunes into the area, now partially stabilized (Figure 10), and the related low level of annual precipitation which does not contribute enough water to the surface drainage system to clear dune sand from the drainages. The evidence for sand dunes is unequivocal (Figure 10) (Chugg et al., 1977), whereas the evidence for karst is nebulous. Poor development of drainage on the one-degree structural dip of the local bedding would be expected regardless. In addition, there are no defined catchment areas on the low-relief topography to funnel drainage along specific paths, so the minimal rainfall in the area may not require a developed drainage system. In contrast, surface drainage that disappears into several obvious sinkholes in nearby Nash Daw is well defined up to the point where it is captured and enters the subsurface (Figure 11), and the difference between these undisputed systems and the inferred doline systems nearer to the WIPP site is striking.

The absence of well-developed drainage patterns in the hummocky topography at WIPP is not a good argument for the presence of dolines east of Livingston Ridge. These arguments do not account for the stabilized sand dune field that covers the area, limited rainfall, and evapotranspiration that more readily explain the poorly developed modern surface drainage. Cavernous porosity in the upper Rustler at WIPP-33 is present, as discussed in section 3.3.3, but a relationship between surface drainage at WIPP-33 and upper Rustler porosity still needs to be established, and the general lack of integrated drainage is not evidence of ubiquitous karst at depth as implied.

Figure 10. Low-angle aerial photograph of stabilized and active sand dunes in the area immediately northwest of the WIPP site.

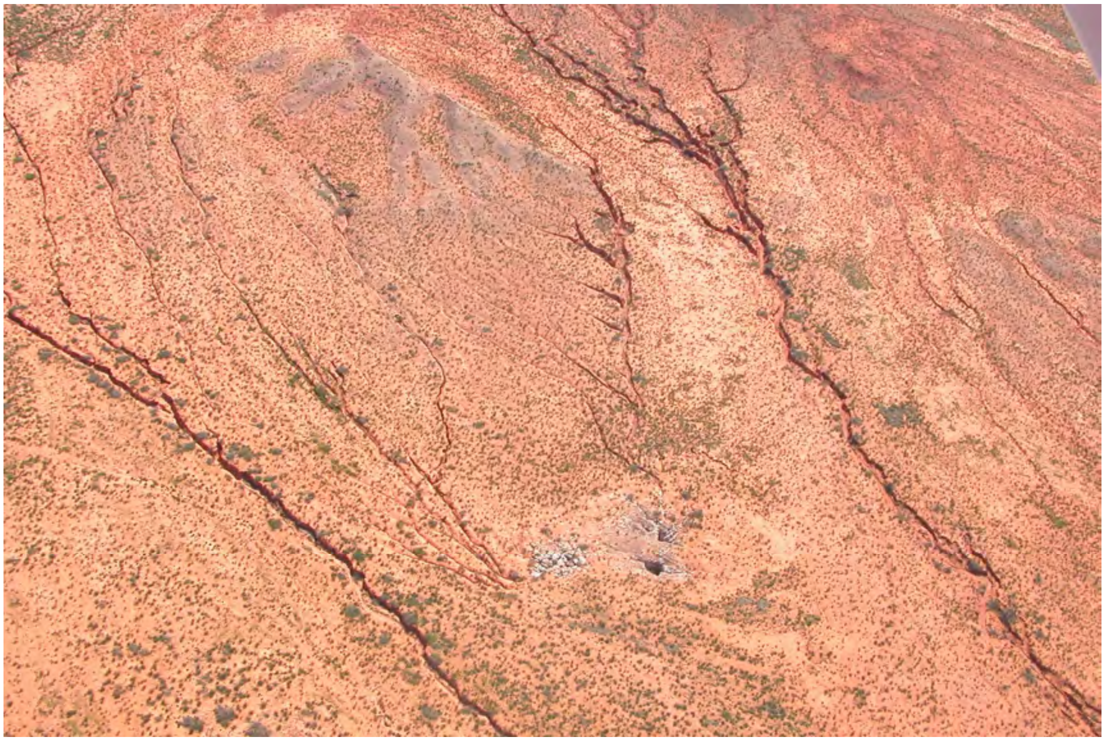


Figure 11. Low-angle aerial photograph of diverted drainage, vanishing streams, and the open sinkholes that capture them, in the Forty-niner Member of the Rustler Formation exposed in Nash Draw, for comparison with Figure 8.

3.3 Geologic Evidence for Karst in the Subsurface At and Near WIPP

Evidence for Rustler karst development in the subsurface at and near the WIPP site is not definitive like that seen in outcrop in Nash Draw. Hill (1999) has cited all of the possible circumstantial evidence to build the case for subsurface karst at the WIPP site. However, most of this evidence is indirect, few of the data have unique interpretations, and some of the evidence is inconsistent with other evidence. Geophysical, geochemical, and hydrological evidence will be discussed later, but the geologic evidence offered by Hill for karst development in the Rustler Formation, in the subsurface underneath and in the vicinity of the WIPP site, consists of:

1. Cores from the Rustler Formation that contain layers that have been interpreted as solution breccias and as "insoluble residue."
2. Basin-scale stratigraphic thinning of the Rustler, and stratigraphic intervals that contain halite in some areas but that do not in other areas, the latter extrapolated to indicate that the halite has been removed by dissolution.
3. Meter-scale bit-drops, encountered in the WIPP-33 borehole, that are inferred to be into karst-related caves.

3.3.1 Cores Containing "Insoluble Residue" and Disrupted Strata (Solution Breccia)

3.3.1.1 Background

Loaded Terminology: The words in the phrases "insoluble residue" and "solution residue", and the phrases themselves, have been widely used to describe certain units of the Rustler Formation, but the connotations and implications of these phrases are not in fact universally appropriate or applicable. Siliceous clay, silt, and sand are largely insoluble, especially relative to evaporite minerals, but the fact of insolubility alone is not diagnostic of the genesis of beds composed of these materials. The word "residue" has an automatic genetic implication, but the mere presence of a layer of clay, quartz, or feldspar does not automatically imply, and certainly does not prove, that the layer composed of these materials originated as a residue from dissolution of a bed of evaporite strata that contained them. Moreover, it is simpler to form such beds by primary deposition than through a multi-stage processes involving deposition and secondary dissolution, and by Occam's razor the simpler of the two processes should be applied in the absence of evidence for the other.

Dissolution that produced a presumed residue can also be read to mean that the dissolution took place either soon after deposition, or at depth within the stratigraphic column eons later. Both are valid processes, but the mere description of a rock unit as a residue, even if it is a valid interpretation, does not address the timing of dissolution. Evidence such as the presence of truncated bottom-growth halite or gypsum crystals, and/or of the up-turned bedding that rims desiccation cracks, along a dissolution horizon (i.e., Powers and Holt, 2000) is necessary to support interpretations of the timing of dissolution. "Residue" should not be applied to units where the origin cannot be definitively determined by means of accepted sedimentological or geochemical evidence, and if a unit is in fact a residue, that by itself does not automatically imply timing of dissolution or that it is a result of karst-formation processes. Valid interpretations of dissolution and of the timing of that dissolution require support from detailed sedimentological studies.

Many of the studies that have tried to understand evaporite deposition, diagenesis, and reworking in modern environments in detail have only been undertaken in the last several decades (see Powers and Holt, 2000), thus earlier studies of the WIPP-area evaporite deposits, and the early geologists who received their education even earlier, commonly misapplied the term "residue". However, "residue", "dissolution residue" and "insoluble residue" have become entrenched in the literature on the Salado and Rustler Formations. They have been applied indiscriminately, sometimes in lieu of a primary lithologic description, to many massive-looking clay-rich and/or silty beds for which no diagnostic sedimentary structures were obvious and therefore no depositional environment was apparent. Until recently, the phrase "insoluble residue" was used as a generalized descriptive term at the WIPP site for massive siltstones, but the genetic implications of this phrase have been largely unsupported.

Since most Rustler outcrops are badly weathered and disrupted, and since cores of fresh Rustler rock offer only small samples of the formation, it was only with the excavation of the WIPP air intake, exhaust, and waste-handling shafts that fresh, clean exposures of the evaporitic Rustler facies could be examined and studied in the kind of detail and with the kind of understanding that the recent studies of modern, evaporitic, depositional environments have made possible (see Powers and Holt, 1990). Therefore, the Rustler literature must be read carefully to determine whether or not there are data to support the specific interpretations implied by the labels with which the different lithologies have commonly been described.

The term "insoluble residue" and its variations seem to have first been applied to the thick, massive to chaotic, clayey unit that separates the top of the Salado Formation from the base of the Rustler Formation in the Nash Draw area. This unit is one of the more significant water or brine-producing horizons in the area (Mercer, 1983), and is generally accepted to be a remnant left-over from the in situ dissolution of tens to a few hundreds of feet of clayey halite. Jones (1973, p. 20) described this unit as being

> "composed of clay with crudely interlayered seams of broken and shattered gypsum and fine-grained sandstone…. The gypsum is clearly the hydrated remnant of anhydrite and polyhalite seams, for it commonly contains ragged and embayed masses of anhydrite and polyhalite, and, also grades laterally into anhydrite and polyhalite. The clay, gypsum, and sandstone unit….thins eastward by grading into and intertonguing with rock salt and the other precursory rocks from which it originated."

Few subsequent descriptions of units described as "dissolution residues" contain as much detail or data in support of the genetic interpretation implied by the term. Jones' description is a standard to which all supposed residues can be compared, and in fact the published descriptions of the characteristics of many clayey and silty layers called "dissolution residues" are insufficient to prove that they are the insoluble remnants of dissolved evaporitic strata rather than primary deposits of non-soluble minerals. Interestingly, the application of the term drifted over the years to where it was considered to include beds composed entirely of massive siltstone as well as the originally clayey layers.

Finally, disrupted and brecciated bedding has been widely cited at the WIPP site as evidence of collapse and brecciation related to post-depositional dissolution of soluble, evaporitic strata. While this is a known process, it is not the only process that produces disrupted strata, thus dissolution is not a unique interpretation for brecciated strata. Disruption of strata also occurs in modern evaporitic depositional environments as a synsedimentary product of the normal depositional and diagenetic processes (Figure 12), and genetic interpretations of cores showing disrupted layers in the Rustler Formation should be integrated, using mutually supporting lines of sedimentological evidence such as the character, extent, and context of the disrupted units, not merely their presence.

3.3.1.2 The Ferrall and Gibbons Report

An example of the misuse of the term "insoluble residue," and probably the reference most commonly cited in support of insoluble residues as evidence for subsurface dissolution near the WIPP site, is the Ferrall and Gibbons (1980) description of cores from the Rustler Formation from WIPP-19 and related boreholes. Hill (1999, p. 50-52) has drawn heavily on the Ferrall and Gibbons descriptions of some units in this core as insoluble residues. She suggests, simply because many of these "residues" occupy approximately the same stratigraphic position as anhydrite beds in other holes, that "where these residues/breccias exist, corresponding anhydrite rock has been removed." This ignores the well established geological principle of lateral, depositional facies equivalencies and lithologic variation, reverting to a

Figure 12. Salt ridges at Bristol Dry Lake, California. The salt ridges and associated cracking and disruption of bedding are formed by synsedimentary expansion and contraction of layers during deposition. Photo by John Karachewski.

simplistic concept of layer-cake stratigraphy. However, the point to be made here is that Ferrall and Gibbons were indiscriminate in their application of the term "residue," and as such their interpretive descriptions are not a valid basis for underpinning theories of karst at the WIPP site.

Ferrall and Gibbons (1980, page 3) recognized six rock types in the Rustler cores: "anhydrite, gypsum, halite, solution residue, dolomite, and siltstone". Of these six, only "solution residue" is not a purely objective lithologic descriptor. This term not only omits an indication of the lithologic composition (other than by implying that its mineralogy is of low solubility), but it also implies an interpretation of the genetic origin of the strata, an interpretation that is inferred by unstated analogy to other similar lithologies but which is left unsupported during the description of the core. Ferrall and Gibbons' characterization of their solution residues in general is a "siltstone/claystone, exhibiting a wide range of cementation", but numerous units in the cores are described only as non-definitive "solution residues".

Nothing in the Ferrall and Gibbons (1980) report resembles Jones' (1973) description of a residue or otherwise justifies an interpretation that the so-labeled layers composed of insoluble minerals originated as leftover, insoluble material from a thick evaporitic layer. There are no descriptions of remnants of red, embayed and altered anhydrite or gypsum beds that could be the hydration products of polyhalite and that would support an interpreted origin as a dissolution residue. There is no facies analysis that illustrates gradation laterally into equivalent, undissolved halites. The most common bedding type described by Ferrall and Gibbons in these units is structureless or massive bedding, which is a common primary sedimentary texture in evaporitic environments. It is not equivalent to the brecciated and disrupted bedding, showing the bedded remnants of out-of-position layers, that can be, but is not always, caused by post-depositional dissolution.

The few places where Ferrall and Gibbons provided somewhat better descriptions of these "residue" strata, they described them as massive or "chaotic" siltstones cemented with halite, with the halite often in crystalline form. The only potential evidence for solution offered in any of the descriptions of the units labeled as residues is the presence of local, seemingly exotic blocks and clasts of gypsum or anhydrite, but such blocks can also be incorporated into the strata during disruption of bedding on evaporite depositional surfaces during the normal course of deposition in such environments (e.g., Handford, 1982; Lowenstein, 1988; Powers and Holt, 2000). For example, gypsum and halite commonly grow displacively in the immediate subsurface in poorly consolidated silts and muds in evaporitic environments. This disrupts and even destroys bedding and other evidence of the currents that originally deposited the silt and mud. Teepee structures and desiccation cracks (Figure 12) can also disrupt primary bedding, often to depths of several meters, in halite, carbonate, and gypsum deposits, forming large, steeply dipping structures at the depositional surface. When these structures are buried and then cored, the strata can look like it was brecciated by post-depositional dissolution. Thus, disrupted bedding is not by itself unique evidence for dissolution since it can form in syndepositional settings.

Small-diameter cores rarely sample sufficient volumes of the strata to determine the origin of disrupted strata, and citing disrupted strata out of context does not prove an origin from dissolution. Regardless, none of the descriptions of the halite-cemented, silty units in these cores resemble Jones' benchmark description of the residual claystone found at the top of the Salado Formation in outcrop. In fact, Ferrall and Gibbons commonly put quotation marks around the term "solution residue", suggesting that they were uncomfortable with the term. They specifically state (1980, page 22) that they applied the term to several units that they do not consider to be residues only because the units "have been leached and are residues in other boreholes," although no evidence or discussion was provided to support that inference.

Halite, especially in crystalline form, should be rare to absent in a true residue since a residue forms by the removal of halite, one of the more soluble evaporite minerals. However, halite cement and even crystalline halite are present in all the siltstone units that Ferrall and Gibbons (1980, pages 12, 22) labeled as residues. Moreover, clay is the most common insoluble material incorporated into halite beds, not silt (typical Salado halites contain up to three percent insoluble material, 75% of which is clay: Gard, 1968). A true insoluble residue should be composed primarily of clay, not silt and halite.

An alternative interpretation for these silty units can be constructed from their positions within simple, repeated vertical sequences or cycles of facies described from the cores, although such successions were not recognized by Ferrall and Gibbons. Lithologically, a sequence starts with a bedded siltstone or shale, transitions up into the mislabeled "residue" of halitic siltstone, and finally grades upward into an evaporite, either halite or anhydrite. The sequences were sometimes truncated, but a simple model of deposition in a shallow-water environment that became progressively more saline would account for both this succession of lithologies and the observed characteristics in each facies, and is similar to the depositional sequences reconstructed by Lowenstein (1988) for repetitive cycles of successive lithologies in the Salado Formation.

Ferrall and Gibbons (1980) describe few specific characteristics of the material considered to be dissolution residues, and what they do describe bears little resemblance to Jones' (1973) description of the clay residuum at the top of the Salado Formation. In contrast, primary depositional origin of these units is strongly supported by the recognition of primary sedimentary structures and of truncated halite crystals and other diagnostic depositional features by Powers and Holt (2000), and Holt and Powers (1984, 1986, 1990b) in laterally equivalent strata. This recognition was made possible only by large, fresh, and detailed exposures of the Rustler strata in the WIPP shafts.

Ferrall and Gibbons (1980, page 17) specifically noted that there had not been much gypsification in the anhydrite matrix rock adjacent to several specifically noted but poorly described "leached voids parallel to bedding." They were therefore forced into the improbable speculation that any gypsified rock was immediately removed by the same waters that had rehydrated the anhydrite. No description of these voids was provided, nor any justification for inferring that they represent leached zones.

To summarize, the evidence that many beds in the Rustler Formation at the WIPP site consist of residual insoluble material left over from the post-depositional dissolution of halites is based indirectly on early, inconclusive descriptions of Rustler cores, encumbered by an inherited, non-specific terminology. The insoluble residue interpretation is not a unique interpretation of the available data, and in fact the data can be more readily explained by simpler models of primary deposition that are more consistent with recent observations from modern evaporite depositional environments (Holt and Powers, 1988; Powers and Holt, 2000).

3.3.1.3 Modern Sedimentological Studies

Lowenstein: Tim Lowenstein, a widely recognized evaporite sedimentologist familiar with modern depositional environments and modern sedimentary interpretation techniques (many of which he helped develop), was asked by the State of New Mexico to undertake a study specifically to address the question of whether or not there is evidence of post-burial alteration of the Rustler Formation. Although Lowenstein (1987) recognized and described many primary sedimentary features in his study of cores from five of the holes across the WIPP site, he did not reach a definitive conclusion, noting that "…identification of evaporite dissolution and the amounts of dissolution is interpretative…" (page 34), and writing further that the individual geological features present in the cores are "not unequivocal" (page 32) in being diagnostic of "late-stage alteration."

Lowenstein (1987), in using the term "late-stage alteration" for what evidence he did find for diagenesis and dissolution, did not specify whether he believed that these processes took place shortly after deposition or much later, after burial. Thus, he left open the question of whether such dissolution could have been synsedimentary as advocated by Powers and Holt (2000), or the result of much more recent, intrastratal karsting processes as implied by Hill (1999, 2003). In fact, Lowenstein's descriptions of truncated halite crystals at syndepositional flooding surfaces (1987, page 16) support synsedimentary dissolution. His descriptions of dissolution zones immediately above and below the Magenta and Culebra Dolomite Members (1987, page 35) suggest that more recent dissolution is also present locally, but the Magenta and Culebra are recognized to be water-bearing, and local dissolution in the adjacent beds is to be expected whether or not the rest of the Rustler units have been modified by karst channels. Regardless, the term "insoluble residue" is notably absent from Lowenstein's report.

Powers and Holt: Powers and Holt (2000), building on the new, unparalleled exposures of the Rustler Formation revealed by excavation of the large-diameter shafts at the WIPP site (Holt and Powers, 1984, 1986, 1990b), documented definitive, primary sedimentary textures that have always been obscured or even destroyed by weathering in outcrop. This new data source was significant enough to support a scientific paper (Powers and Holt, 2000) that was published in an international, peer-reviewed, scientific journal. The authors were able to combine the new features with knowledge of the recent detailed studies of modern evaporitic depositional environments to develop a scientifically supported, plausible reconstruction of Rustler deposition, and relate it to the present-day distribution of the Rustler lithologies. All of the structures exposed and documented in the WIPP shafts fit conveniently into a model of shallow, evaporite salt pans and saline mud flats, with vertical repetitions of lithologies fitting cycles of fresh water incursion and subsequent evaporation, and lateral lithologic variations meshing with geologically sound concepts of lateral facies variations.

The definitive absence of karst features in the Rustler Formation in the WIPP shafts was obscured by an early, out of context observation of a large, unfilled fracture in a halitic siltstone (not in an anhydrite as implied by Hill) of the Los Medaños Member of the Rustler Formation. A photograph of this fracture (Figure 13) was offered as evidence for large, open fractures in the subsurface, and has been used by various proponents of karst (e.g., Snow, 2002, page 7/his Figure 4) to imply that there was karst development in the Rustler Formation in the WIPP shaft (page 39, and Plate 1/page 80, Chaturvedi and Channell, 1985). However, at the time of initial excavation, the fracture was filled with halite and was not a karst conduit; the halite was leached from the fracture during and after excavation of the initial hole. When the shaft was later enlarged by conventional mining (without water), fractures in this zone were found to be filled with halite in their *in situ* condition (Holt and Powers, 1984, Figure 9, fracture notes).

3.3.2 Stratigraphic Thinning of the Rustler Formation and "Missing" Halite

Hill (1999), drawing on a theory advocated by Snyder (1985) and Snyder and Gard (1982), suggests that thinning of the Rustler Formation in the vicinity of the WIPP site must be related to dissolution since the thinning trend continues westward to where the Rustler has been markedly and demonstrably thinned by dissolution in Nash Draw. Although dissolution is an obvious process

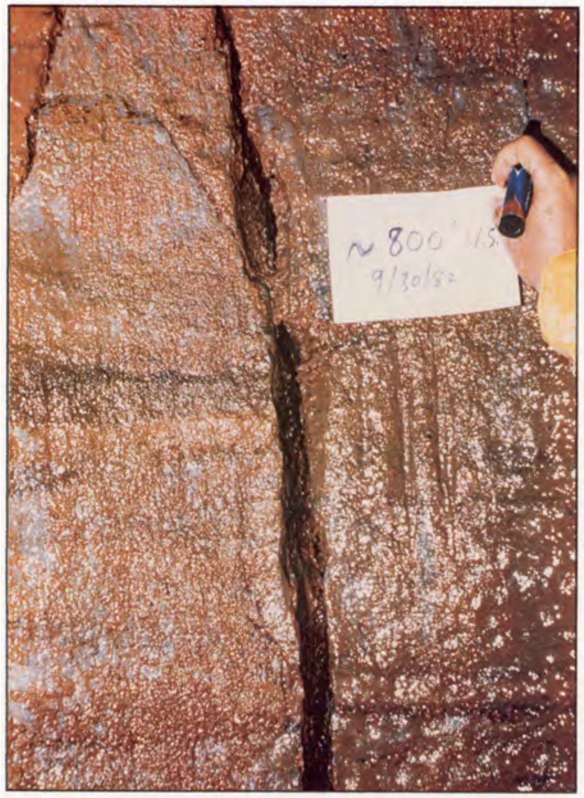


Plate 1. An open fracture in the unnamed lower member of the Rustler Formation.

Figure 13. Fracture in the Los Medaños Member of the Rustler Formation in one of the shafts at the WIPP site. The halite that filled the fracture *in situ* has been dissolved out by the relatively fresh water that flowed out of the overlying Culebra Member and flowed down the shaft walls during and after excavation, making it appear to have been an open fracture in the subsurface. Original figure and caption from Chaturvedi and Channell (1985). The notation "V.S." refers to the "ventilation shaft" that was subsequently enlarged and equipped to be the waste-handling shaft.

at Nash Draw, it is not the only process capable of causing marked thinning of the Rustler Formation. The questions are: 1) to what degree, if any, has Nash-Draw-type dissolution caused the thinning and absence of halite in the Rustler Formation at the WIPP site, 2) are there other equally or perhaps more plausible processes to explain this and which process does the data support, and 3) if there are several overlapping processes that have caused thinning, how much and where between Nash Draw and the WIPP site do they overlap?

3.3.2.1 Cross Section Evidence

The Rustler Formation has been exhumed and exposed to weathering west of Livingston Ridge for at least a half-million years (Bachman 1985). During that time it has been reduced in thickness by dissolution of the more soluble beds in the formation. Various authors (e.g., Snyder and Gard, 1982; Snyder 1985; Chaturvedi and Channell, 1985) have suggested that this process of thinning by dissolution continues eastward into the subsurface, encroaching on the WIPP site. These authors suggest that more halite, progressively deeper in the Rustler section, has been dissolved westward, the closer one gets to Nash Draw (Figure 14, Figure 15).

Although dissolution of sulfate beds is the primary factor controlling thinning of the Rustler Formation in outcrop near its western, erosionally truncated edge in Nash Draw, the Rustler Formation also thickens and thins numerous times in the subsurface across the basin where it has *not* been subjected to dissolution (Holt and Powers, 1988; Mercer, 1983). This subsurface thinning is due to lateral depositional facies changes and due to local variations in subsidence that accommodated the deposition of thicker or thinner evaporite beds (Figure 16, Figure 17). A large area such as the Permain basin doesn't subside uniformly, and slightly deeper parts of the basin accommodated deposition of thicker halites, whereas topographic highs allowed deposition of only thin halite beds or none at all. Thus the different halite beds in the Rustler Formation thicken, thin, and even vanish due to lateral facies changes in areas of the basin where the formation has never been exposed to weathering and dissolution. Thinning by itself is not primary evidence for dissolution as suggested by Snyder and Gard (1982).

The total thickness of the Rustler Formation decreases by nearly 50%, from more than 500 ft to less than 300 ft, east and southeast of the WIPP site where it has never been close to the surface (Holt and Powers, 1988, their Figure 4.15). The cumulative thickness of the several halite beds in the Tamarisk Member of the Rustler Formation diminishes from over a hundred feet thick to zero both east and west of a depocenter thickening located about ten miles southeast of the WIPP site (e.g., Holt and Powers, 1988, their Figure 4.5). The same pattern is present in the salt deposits of the Los Medaños Member, the Forty-niner Member, and in a small halite within the upper anhydrite of the Rustler (Holt and Powers, 1988), suggesting that this depocenter was an area of localized, relatively higher subsidence throughout late Permian time.

Therefore, thinning of the Rustler Formation, with or without accompanying thinning of the component halite beds, is not definitive proof, in and of itself, that the beds have been thinned due to dissolution of halite, since thinning and the absence of halite also occur where the Rustler Formation is deeply buried and protected from weathering, erosion, and dissolution. This does not negate thinning due to dissolution in Rustler strata west of WIPP, but rather suggests that such thinning does not prove dissolution since thinning can result from several different, or even from several combined causes.

It is also telling that the supposed dissolution front as reconstructed is thinly tapering, thinning by several hundred feet over four or five miles. In contrast, the dissolution front is abrupt in other basins where salt dissolution fronts have been definitively documented (e.g., Neal et al., 1998; Gustavson et al., 1980). Similar or even greater amounts of thinning in these basins takes place over half a mile or less, and steep surface ridges occur where the overlying bedding has been draped over the dissolution fronts. In the Holbrook basin of Arizona, the subsurface margin of the encroaching salt dissolution front is marked at the surface by a topographic scarp with up to a hundred feet of relief, by an abrupt change in the dip of bedding, and locally by clusters of sinkholes (Neal and Lorenz, 1998). Similar features are present in other basins (i.e., Gustavson et al., 1980). Powers et al. (2003) have recently suggested that the Salado salt-dissolution front is marked by the bedding roll-over at the Livingston Ridge escarpment on the eastern edge of Nash Draw (Figure 18). Nothing equivalent to this surface demarcation of a salt-dissolution front is present at the WIPP site.

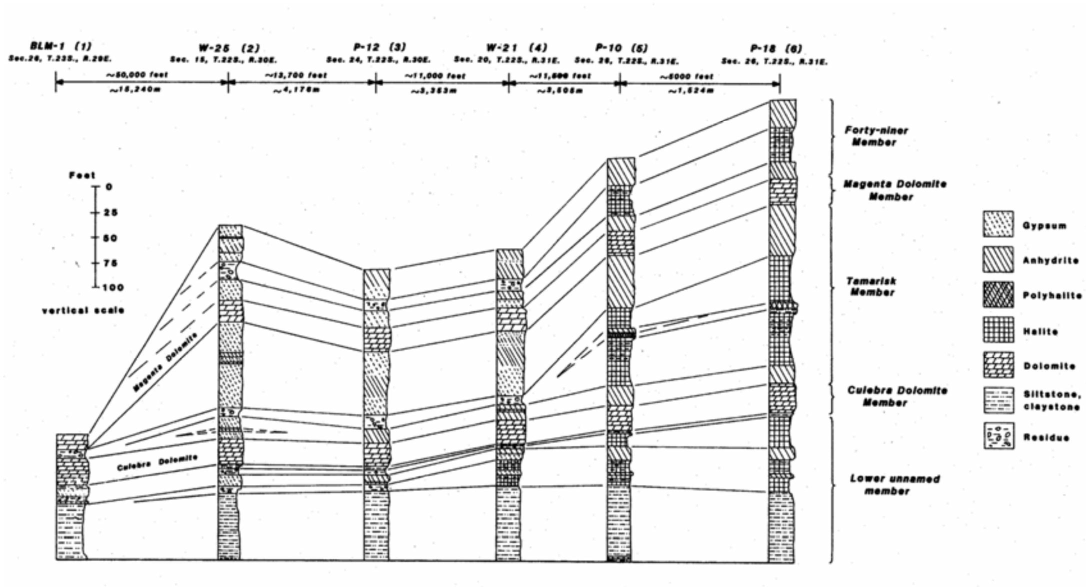


Figure 14. Cross section showing the westward thinning of halite beds in the Rustler Formation, including the polyhalite in the Tamarisk Member, inferred by Snyder to indicate progressive westward dissolution of the halites but more plausibly interpreted as lateral facies changes and variations in depositional topography. (From Snyder, 1985; his Figure 2). See also the regional cross sections in Holt and Powers (1988).

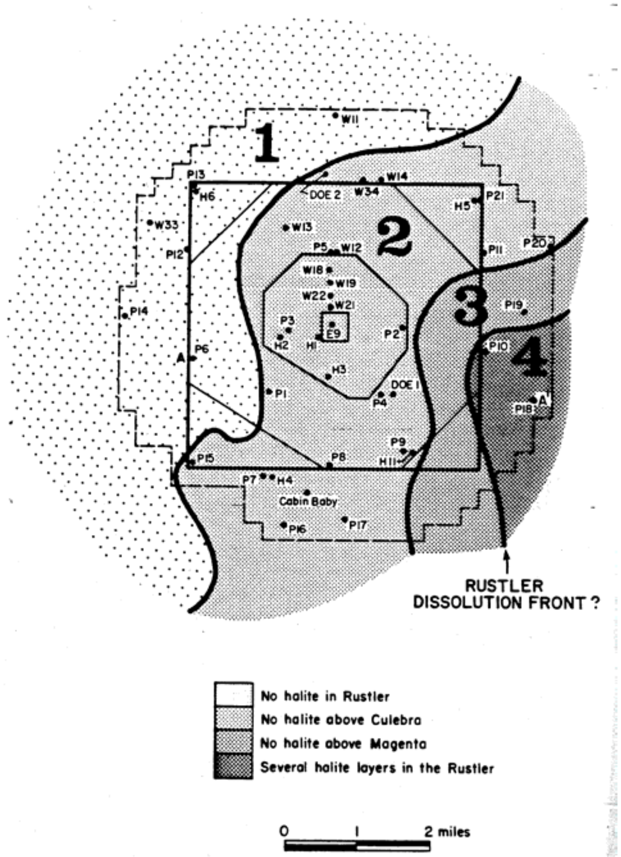


Figure 15. Proposed levels of halite dissolution (from Snyder, 1985)

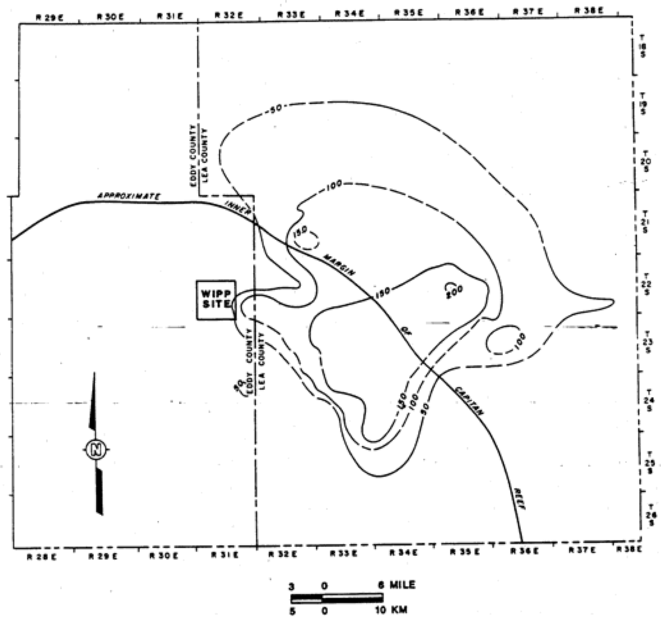


Figure 16. Isopach map of the Mudstone/Halite-3 interval of the Tamarisk Member of the Rustler Formation, showing thinning in all directions, including westward across the WIPP site, and indicating that thinning is a function of deposition rather than dissolution (from Powers and Holt (1990), their Figure 26/page 102).

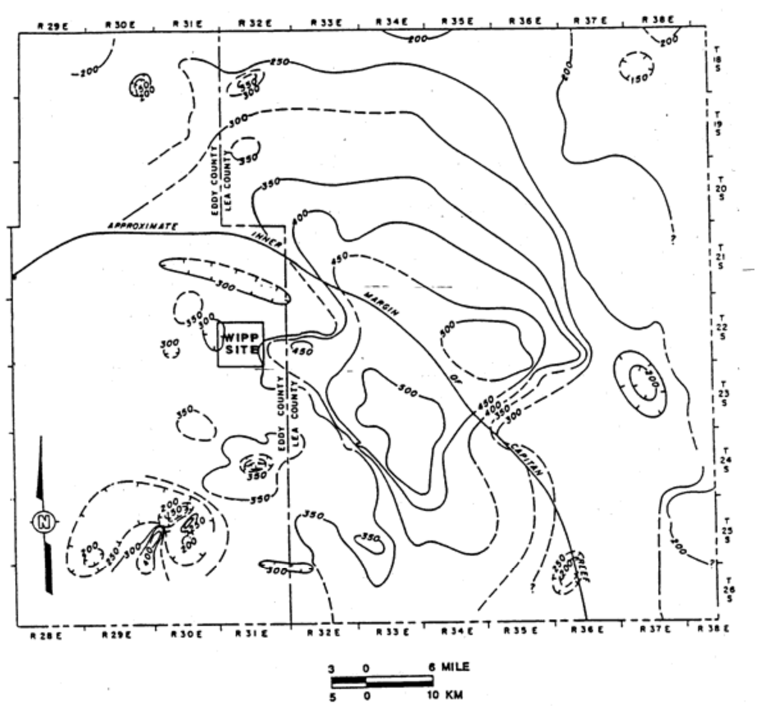


Figure 17. Isopach map of the total Rustler Formation, showing the depositional hollow east of the WIPP site that controlled thickening and thinning throughout Rustler deposition (from Powers and Holt, 1990, their Figure 25/page 101).

Figure 18. Fractured sandstones of the Dewey Lake Formation draped over probable edge of the salt-dissolution wedge at the northern edge of Nash Draw. View is to the northwest.

3.3.2.2 Volume Constraints

Volumetrically, the total thicknesses of beds labeled as insoluble residues in Rustler cores can not reasonably have been derived from the available volume of halite and its probable percentage of insoluble material (Powers and Holt, 2000), arguing strongly against an origin of so many clay and silt beds as dissolution residues. A quick estimation points out the implausibility of such a theory. The cumulative thickness of the massive silty beds labeled as "residues" by Ferrall and Gibbons (1980) in WIPP-19 is over 50 ft. If the silt and clay content of an average halite is as much as three percent (average values in halites in the Salado Formation range from 1-3%: Gard, 1968), a 50 ft residue would require the dissolution of a cumulative thickness of some 1500 ft of halite. This is unreasonable considering that the total thickness of the Rustler Formation, including the non-halite lithologies, is only 300-500 ft. Moreover, the thicknesses of the clay beds do not increase where they have supposedly been added to by residues from dissolved halite (Powers and Holt, 1995).

To look at it another way, the Forty-niner mudstone is about 20-25 ft thick at the WIPP shafts. At its thickest, the stratigraphically equivalent halite in drillholes to the east and southeast is about 40-45 ft thick, and nearly pure. Forty feet of nearly pure halite cannot have been the source of a 20-ft thick dissolution residue.

3.3.2.3 The Tamarisk Polyhalite Marker Bed and the Concept of Depositional Facies

A prominent polyhalite bed is present in the middle of the thicker salt beds in the Tamarisk Member east and southeast of the WIPP site. Polyhalite is less soluble than halite and remnants would be expected to be included in the residual material remaining after dissolution of this halite bed, as it is in recognized Salado residues. For example, Reddy (1961) described remnants of polyhalite in residues of the Salado Formation at the top of salt domes south of Carlsbad as distinctive, brick-red to orange gypsum alteration products. However, no embayed or red, gypsiferous polyhalite remnants have been reported from the units labeled as residual material in any of the Rustler cores examined by Ferrall and Gibbons (1980), or in any of the units found in the shafts.

Chaturvedi and Channell (1985, page 26) cite a personal communication from Snyder, who apparently correlated the Tamarisk polyhalite bed in drillhole P-18 with a clay unit in drillhole P-6, and suggested that the clay is the remnant residue from the polyhalite bed. Polyhalite is commonly formed as an alteration product from an anhydrite bed, thus anhydrite and polyhalite can be lateral diagenetic facies equivalents, but the model runs into problems in that 1) it is relatively difficult to totally dissolve polyhalite, and 2) it is even more difficult to leave behind a thick clay residue as remnant from a virtually clay-free lithology.

Arguments that dissolution must have occurred in the Rustler Formation wherever claystone and mudstone are found in the same stratigraphic position as halites use antiquated depositional concepts which acknowledge only superimposed, laterally extensive geologic layers. Such layer-cake models of stratigraphy were superseded early in the development of geological sciences by the well-supported models of lateral depositional-facies equivalents. For example, rivers, beaches, and lagoons can all be depositing different types of sediment in laterally- and time-equivalent environments, resulting in laterally equivalent deposits of gravel, sand and mud. The resulting facies assemblage does not consist of a layer of river gravel overlying a layer of beach sand overlying a layer of lagoonal muds unless the environments migrate laterally over one another with time. In the same way, relatively pure halite can be the lateral depositional equivalent to mudstone, as found in the Rustler Formation across the WIPP site and in modern depositional environments.

The fundamental geologic principle of laterally-equivalent facies has been ignored by proponents of insoluble residues at the WIPP site, leading to statements such as "…wells... where halite is completely missing from the Rustler or is found only below the Culebra, encounter several layers of clastics (mudstone, siltstone, and breccia in clay matrix) at different horizons in the formation. These layers are at the same stratigraphic locations as the halite layers of the wells in Region 4 and may have therefore resulted from dissolution of salt." (Chaturvedi and Channell, 1985, page 28). In essence, the finding of different types of rock at the same stratigraphic horizon is not a gross anomaly that can only be explained by special geological circumstances; rather it is a common and well-understood geologic occurrence.

In the Rustler Formation, most of the observed distribution of halites, polyhalites, anhydrites, mudstones and siltstones resulted from the deposition of laterally equivalent types of rock in laterally equivalent environments: saline mud flats, saline evaporation pans, and deeper saline ponds (Powers and Holt, 2000; Holt and Powers, 1984; 1986; 1990b). This type of pattern is the normal mode of deposition in modern evaporitic environments (e.g., Handford, 1982).

The more uniformly thick and more widespread Rustler units such as the Magenta and Culebra dolomites were the products of deeper waters which produced much more laterally extensive depositional environments, but they too have laterally equivalent facies of different lithologic composition. Because of the different depositional environments, the Magenta and Culebra facies vary on a scale of up to a hundred of miles rather than on the scale of miles to a few tens of miles as seen for the associated evaporitic deposits, and cannot be used as analogs to interpret the distribution of evaporitic facies.

In the vicinity of Nash Draw, the dissolution of halite and related evaporites has been superimposed onto the primary depositional patterns of lithologic distribution, and the relative importance of the two processes can be difficult to separate in the area between Nash Draw and the WIPP site.

3.3.2.4 Evidence from the Shafts

The absence of halite can be interpreted to mean either that it was never deposited or that it was deposited and then removed. The evidence to support an interpretation of dissolution is definitive at Nash Draw (e.g., caves, Figure 19; breccias; drastically thinned section), but becomes ambiguous in the subsurface to the east. The data presented by Powers and Holt (2000) and Holt and Powers (1988) strongly support non-deposition where the Rustler Formation thins without having been exposed in outcrop, and this interpretation is compatible with known depositional thickness and facies variations from modern environments.

Thinning due to dissolution overlaps with depositional thinning in the area immediately east of Nash Draw, and the relative effects of each are difficult to determine in the absence of good outcrop. However, excavation of the large-diameter air-intake, exhaust, and waste-handling shafts at the center of the WIPP site have provided data that definitively support an interpretation of halite non-deposition and syndepositional dissolution in the vicinity of the WIPP site, negating interpretations of post-depositional removal by dissolution and karst processes.

Figure 19. Dissolution cavern in Rustler strata exposed in Nash Draw. The cavern could be either a sinkhole or a spring depending on the water level.

These shafts were excavated in a position that is ideal for comparing the hypotheses of dissolution vs. non-deposition in the vicinity of the WIPP site, since isopachs of the Rustler Formation (Holt and Powers, 1988) show that it is dramatically thinner in the area of the shafts and there should be good evidence for dissolution if dissolution caused that thinning. At 309 ft thick in the shafts, the Rustler Formation is 176 ft (36%) thinner than the measured 485 ft Rustler thickness in a well located five miles east (see the isopach maps in Holt and Powers, 1988), part of an overall westward thinning trend. Moreover, the shafts are located in the zone where Snyder (1985) specifically suggested that halite was removed by subsurface dissolution from both the middle (Tamarisk) and upper (Forty-niner) Members of the Rustler Formation. Although dissolution was invoked by Snyder as the mechanism that caused both thinning of the formation and the absence of halite, the evidence he presented for that interpretation is circular in that it consisted only of 1) the fact that the Rustler Formation thins westward, 2) that it contains little halite in the western locations, and 3) the inference that much of the anhydrite has been converted to gypsum. (This inference was supported only by data from hole WIPP-25, which is located in Nash Draw where undisputed dissolution and water infiltration has occurred).

If the interpretation that broad, subsurface dissolution of the Rustler Formation has occurred miles east of Nash Draw is valid, then good evidence to support it should have been found in the large, fresh exposures of the Rustler created when the shafts were excavated, since these exposures were cut in an area of thinning. They were cleaner and more extensive than any previous data from either outcrop or cores, and thus showed important sedimentary details that have been previously obscured. However, the characteristics of the Rustler Formation found in the shafts document a normal, primary depositional sequence, with little or no evidence for recent dissolution and alteration. These characteristics (see the lithology logs from Holt and Powers, 1984; 1986; 1990b) include the following:

1. Definitive primary sedimentary structures found in siltstone and clay units that had previously been interpreted as dissolution residues
2. An absence of dissolution-indicator breccias and disrupted bedding in the Tamarisk and Forty-niner Members, the two members, according to Snyder's (1985) model where dissolution should have been most prominent
3. The overwhelming dominance of anhydrite in the Tamarisk and Forty-niner Members, unconverted to gypsum as would be expected if there had been sufficient water to remove significant thicknesses of halite. The only gypsum present is immediately adjacent to the Magenta Member, an acknowledged if poorly productive water-bearing unit. No conversion of anhydrite to gypsum was reported even in the anhydrites immediately adjacent to the more transmissive Culebra.
4. Normal dolomite lithologies in the Culebra and Magenta Members, devoid of large vugs and karst-type caverns.
5. The total thickness of bedded salt, present only in the lowest, Los Medaños Member of the formation, of only five feet, with the thickest individual bed being only three feet thick. Since these halite beds thicken to the east and southeast, "thinned" halite beds

in this, an acknowledged undissolved member, support the contention that the geometric thinning of the formation as a whole is the result of primary depositional processes rather than secondary dissolution and the removal of material.

6. There is no evidence of the ten-foot thick polyhalite bed that marks the middle of the halitic zones in the Tamarisk Member further to the east and southeast. Remnants of this unit might be expected in a dissolution residue, similar to the way they mark the residue between the Salado and Rustler formations described by Jones (1973). The absence of such a prominent, thick, marginally soluble unit from the shaft exposures strongly supports the interpretation that it and associated halites were never deposited in this area.
7. A sedimentary channel was found in the air intake shaft, eroded into the A-2 anhydrite and filled with siltstone and conglomerate. This feature indicates primary depositional processes.

As noted above, the halite filling cracks in the lower Rustler Formation in the original ventilation shaft (now the Waste Shaft) was dissolved back from the face of the initial, small-diameter pilot shaft by drilling fluids and by water dripping down the face of the shaft from the Culebra. A photo of this feature (Chaturvedi and Channell, 1985, Plate 1) was considered to be evidence of post-depositional dissolution or karst (Figure 13). When the shaft was enlarged, using conventional mining without water, the same fractures were found to be filled with halite. This fracture and the erroneous interpretation continue to be mistakenly offered as evidence for subsurface dissolution at the WIPP site.

3.3.3 Voids, Gypsum, and Problems Encountered in Drilling at WIPP-33

3.3.3.1 Bit Drops, Limited Core Recovery, and Lost Circulation

Perhaps the best and least ambiguous evidence for some degree of subsurface karst development comes from the records of the WIPP-33 drillhole at the northwestern edge of the WIPP site. Four, meter-scale bit-drops were encountered while drilling the WIPP-33 hole, and these have been cited as evidence for widespread subsurface conduits related to karst in the Rustler Formation east of Nash Draw (e.g., Hill, 1999; Phillips, 1987; Barrows, 1982). Although even Bachman (1981) wrote incautiously that the Rustler Formation in WIPP-33 was “found to be cavernous throughout,” examination of the drilling records for this hole (Sandia National Laboratories and the U.S. Geological Survey, 1981), shows that the bit drops occurred only while coring the Forty-niner and Magenta Members. The recorded drops were of 9.5 ft, 6 ft, 2 ft, and 5 ft. The evidence in the records of this drillhole for an additional, seven-foot “cavity” near the bottom of the Dewey Lake section as suggested by Philips (1987, p. 16, 50) consist of notations of “lost circulation” and rapid drilling rates on the imprecise drilling-time log (the geolograph from the drill rig floor).

Nine cores were cut in the Forty-niner/Magenta interval, with recovery ranging from zero to 46 percent and averaging 27 percent. Five cores were also cut through the Culebra Dolomite, and although no bit drops were recorded, recovery averaged only 57%. In contrast, the five cores cut across the Salado-Rustler contact averaged 87% recovery. The data report for the hole

(Sandia National Laboratories and the U.S. Geological Survey, 1981) also documents difficult drilling, with notations of lost circulation zones, and drilling ahead without mud and cuttings returns to the surface at numerous depths. The record briefly mentions but does not describe or explain "lost dolomite" in the Magenta interval, and anhydrite that has been hydrated to gypsum and perhaps dissolved entirely. The lithologic log indicates that most of the sulfate in this hole occurs as gypsum rather than anhydrite, suggesting access by water to much of the formation.

3.3.3.2 Normal Stratigraphic Section

The stratigraphic tops in this hole are found at normal depths, bedding is horizontal as expected, and the breccia blocks in the cores (in the A-3/H-3 interval) are small, suggesting that disruption is not great and that there has been no large-scale collapse or other disruption of bedding. A video camera lowered into the hole to assess the possibility of cavernous porosity was unable to see through the drilling fluid to the side of the drillhole. The caliper log that was run in the hole after drilling encountered areas where the hole was somewhat larger than the diameter of the drill bit, but these zones (or perhaps the actual enlargement, it is difficult to tell from the report) were "not extensive."

3.3.3.3 Discussion and Interpretations

In situ void space is a plausible and even probable explanation for the observations from drillhole WIPP-33, but it is not unique, and the sizes of the voids are debatable. Poor recovery of core is also common where the material is broken by fractures or faults, and drilling operations through evaporites can even create local solution cavities if the mud is not properly maintained at full saturation while drilling.

The void horizons in WIPP-33 are located where dissolution associated with the acknowledged water-bearing Magenta would be expected, i.e., strata-bound and adjacent to a known source of water. The daily drilling reports document intervals of lost circulation and no returns elsewhere in the Rustler section, but the exact horizons of lost circulation cannot be determined accurately from the daily drilling reports since an interval that leaks drilling fluid into the formation may continue to leak or start to leak again after the hole is much deeper, making it seem as if the hole has encountered a new zone of lost circulation as it is being drilled when it is only the previous zone accepting fluids again.

The data from this hole provide direct evidence for subsurface void space, but they are not quantitative. Although the data from this hole provide the best evidence for subsurface voids, it is an isolated data point and the bit-drop evidence comes from only limited stratigraphic levels in the hole, related to a water-bearing unit where dissolution would be expected. There are no data for similar voids in the nearby holes, voids that might form an interconnected subsurface network as would be expected in a developed karst system.

The vuggy porosity encountered in the WIPP-33 hole, while allowing drilling fluids to seep out and making drilling difficult, was not so large or well developed that it allowed drilling fluid to completely drain away, which would have made drilling with fluids impossible. The lost circulation was in fact controlled by the use of standard oilfield lost-circulation material (the "LCM" noted in the drilling reports), typical LCM consisting of relatively small bits of things like cotton hulls and/or walnut shells that can be pumped down the hole. Material of this size would be incapable of preventing lost circulation by bridging voids where the voids are much more than centimeters to a few tens of centimeters in scale, and this is not the scale of cavernous porosity typical of a karst system.

Hill (1999, p. 52) suggests that WIPP-33 penetrated "an unusually thick (44 ft)" layer of surficial fill material. The significance she attaches to this observation is not clear: if the thick fill represents a hollow created by a stratigraphic section downdropped over a solution void, that would also create an obvious offset of the subsurface stratigraphy, but the stratigraphy is normal in this hole. It is unlikely that the thick alluvial fill resulted from local, near-surface dissolution of the insoluble sandstones and siltstones. Hill diagrams a funnel-shaped zone of disruption, a shallow depression of unspecified origin and filled with surficial material, with a localized conduit leading into deeper karsted strata at the bottom (see Figure 6), but she does not adequately explain how the funnel might have formed. In contrast, the known sinkholes in nearby Nash Draw consist of obvious cave openings and diverted drainage, but are not associated with marked depressions of the bedrock surface or with thicker units of surficial fill material.

3.4 Summary: Assessment of the Potential for Karst at WIPP Based on Geologic Evidence

Bit drops, caliper logs, video images, and lost circulation zones provide evidence of a high degree of porosity within the Magenta and parts of the Forty-niner Members at WIPP-33. Nevertheless, geologic data do not support either the presence of cavernous porosity or the extrapolation of these characteristics across the WIPP site. The data commonly cited in support of subsurface karst development at the WIPP site consist of questionable labels that have improperly and incorrectly assigned an origin to certain lithologies in core descriptions, and a thinning of the Rustler Formation that can be explained more plausibly by facies changes since 1) the supposed missing material would have had to have been improbably thick, 2) because it does not contain the required volume or clayey types of insoluble material common in recognized residues, and 3) because the characteristics of these deposits are more plausibly explained by vertical sedimentary facies transitions. The hummocky surface topography at the WIPP site is real, but it does not imply karst-related pirating of drainage by subsurface conduits.

4.0 POSSIBILITY OF KARST-TYPE, MULTI-ORDERED CONDUITS, AND CONDUIT FLOW

4.1 Introduction

Hill (2003, pages 201-203) has laid out the theoretical arguments that:

- Since there is a big karst feature (Nash Draw), stream theory suggests that there must be a series of successively smaller conduit-type karst features that feed it, and that therefore these smaller features must be present but have not yet been found at the WIPP site.
- Since boreholes are such a small sampling of the subsurface strata, the fact that karst-type features have not been recognized in wells, cores, and logs does not preclude the possibility that they are present and effective.
- Since most fluid flow in strata containing karst-related conduits will occur through wide-open subsurface conduits, it will bypass the relict, relatively immobile water in the less permeable but volumetrically more important pore and fracture systems. Therefore, most water samples taken from wells drilled into a karsted system should be from the more pervasive bypassed matrix water system, and might have an isotopic signature different from the waters in the conduits so that age dates from the water samples will be unrepresentative of the conduit system.

Hill does not present direct evidence to support the application of these arguments to the Rustler Formation, merely stating that "The following principles and process of karst might be applicable to the WIPP Site" (1999, page 201). Coming to grips with such an approach to science is like debating random speculation.

The stream-theory argument requires that Nash Draw be part of an equilibrated, fractal system, and, if valid, would only be of significance if that system extends outward from Nash Draw and encroaches eastward as far as the WIPP site. The argument about unrepresentative water sampling would be valid only if conduit flow is in fact a reality, and only if insignificant interaction between matrix waters and conduit waters occurs. The vague argument (that an intrastratal karst system should be present at or near WIPP but is unrecognized due to the low probability of sampling it) can be addressed by considering the geometry of the targets relative to the geometry of the sampling mechanisms (primarily wellbores). It is also addressed definitively by data collected during hydraulic pumping tests, which interrogate large volumes of rock.

Hill (1999, 2003) presents the three arguments as theory but then draws conclusions as if these theories were a proven reality at the WIPP site. The three theories are discussed below.

4.2 Nash Draw as the Largest of a System of Ever-Smaller Karst Features

An ordered system, where small channels feed increasingly larger but fewer channels in stream systems, is a common pattern developed on homogeneous media and under homogeneous conditions. The karst system studied by Sares (1984), and cited by proponents of karst as an example of what they would expect to see in the subsurface at WIPP, is developed west of the Pecos River on widely exposed and relatively homogeneous anhydrites of the Castile Formation.

This formation has been subjected to relatively uniform conditions of weathering and erosion over a wide area and for a long period of time, and a pattern of ordered stream channels has developed on it. In contrast, the Nash Draw-Rustler system is not a homogeneous medium, and different parts of the system have been developed under vastly different conditions. The Rustler Formation is composed of heterogeneous lithologies, including sandstones, claystones, dolomites, anhydrites, and halites, each variable resistance to erosion and dissolution. Moreover, significant differences exist between the outcrop conditions at Nash Draw, supposedly the largest element of the system, and the subsurface conditions to the east where the rest of the system supposedly is developed, but where the Rustler Formation is buried and thus protected from surficial erosion and weathering processes.

Bachman's field relationships (1985, page 24) indicate that much of Nash Draw formed as "The Gatuña stream system eroded into the evaporites of the Rustler Formation, and collapse sinks began to form near the end of Gatuña time…. As a result of following the strike of the Rustler Formation for a time, Gatuña drainage contributed to coalescing these sinks" (Figure 20). Present-day Nash Draw is therefore analogous to an oversize valley/underfit stream in previously glaciated terrain, wherein the size of the valley is relict from previous conditions and not directly related to the drainage system found there today. More importantly, the Pleistocene surface drainage over the outcropping Rustler Formation cut directly into that formation and thus played a significant part in enlarging Nash Draw to its present size: there is nothing comparable in the subsurface to the east, and no reason to believe smaller branches of a system exist there.

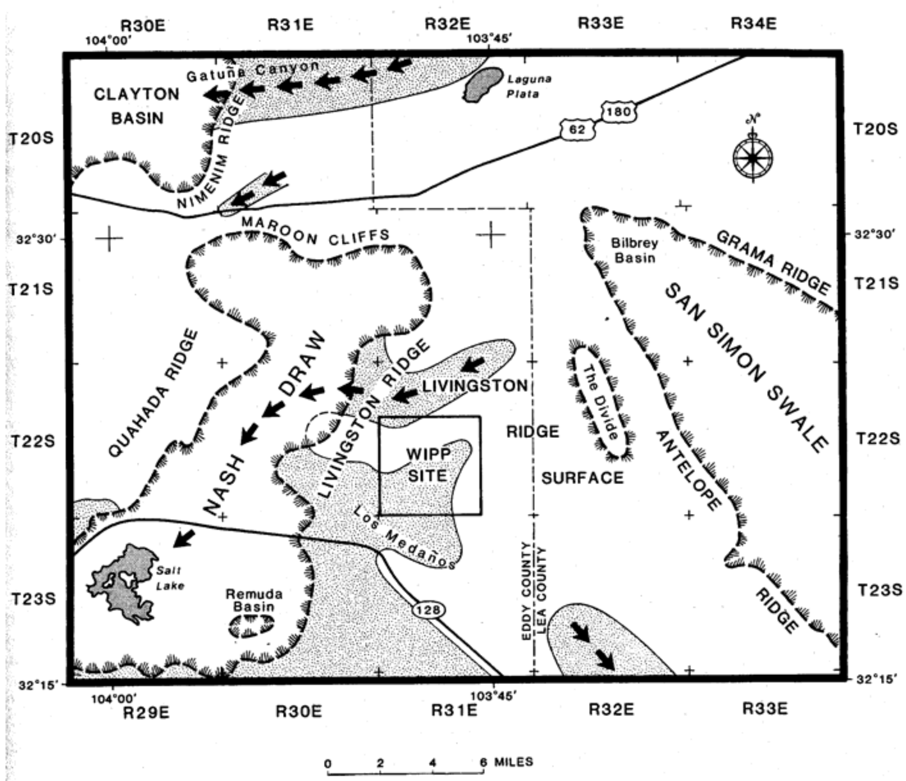


Figure 20. Generalized Pleistocene Gatuña stream system, as reconstructed by Bachman (1985).

Thus the medium and the conditions across the Rustler Formation were not, and are not, homogeneous as would be required for the development of ordered, dendritic drainage patterns, and theories of ordered sets of stream channel sizes are not applicable. The presence of a large Pleistocene stream, developed under conditions of more precipitation than at present, was responsible for dissolving out much of Nash Draw as a large, unique, and localized feature. Nash Draw should not be modeled as the largest of a system of pervasive and successively smaller upstream conduits.

4.3 Assessing Possible Conduit Flow with Pumping Tests

4.3.1 The Value of Hydraulic Testing, and Distinguishing Karst Flow from Fracture Flow

If conduit flow exists in the Rustler Formation at the WIPP site, it should be evident in the data from the numerous hydrologic pumping tests done in the formation at and near the site. Such tests can sample the hydrologic response and flow capacity of a large volume of strata between several widely spaced wells at once, thus the data are representative of significant volumes of strata. This offsets concerns that sample sizes have been too small to truly assess the potential for karst at the WIPP site.

Flow dominated by fracture systems (which have low storativity and high transmissivity and which therefore give relatively rapid inter-well response times, and, commonly, good regional interconnection), has a distinctly different response when tested hydraulically compared to flow within karst-related conduit systems (which have high storativity, dampening the inter-well response, but which should have limited regional interconnectivity).

4.3.2 Fracture Flow

The pumping and slug tests carried out in the Culebra at and near the WIPP site have shown both single- and double-porosity hydraulic behavior (Beauheim, 1987b; Beauheim and Ruskauff, 1998). Double-porosity behavior typically indicates a combination of matrix and fracture porosity in the tested medium, with the matrix providing most of the storage capacity and the fractures providing most of the transmissivity. Beauheim and Ruskauff (1998) have noted that the Culebra behaves as a double-porosity medium in those regions where open natural fractures are thought to dominate hydraulic responses, and as a single-porosity medium where fractures are thought to be fewer, smaller, and more commonly plugged with gypsum.

Hydraulic testing of the Culebra has indicated horizontal directional-flow anisotropies of up to 1.6:1 measured in pumping tests, and up to 7:1 measured in tracer tests (Haggerty et al., 1997; Meigs et al., 1997a,b). This type of behavior is typical of flow within preferentially oriented fracture systems (e.g., Lorenz et al., 2002). The measured axis of flow anisotropy at the WIPP site is not consistent among the various tests, suggesting local variability in the dominant subsurface fracture orientations or in the *in situ* stress conditions.

Testing has also indicated the presence of local hydraulic boundaries within the Culebra Member. “No-flow” boundaries are interpreted as representing decreasing transmissivity, while “constant-pressure” boundaries are interpreted as representing increasing transmissivity. This indicates that the Culebra Member is not homogeneous. None of these tests indicate the presence of karst conduits.

Outside of Nash Draw, the Magenta has not been found to be transmissive enough to sustain the minimum one-gallon-per-minute flow rate required to perform a pumping test. As a result, only slug tests have been performed in the Magenta, and these tests have uniformly indicated low transmissivity and single-porosity (i.e., unfractured and unkarsted) conditions (Beauheim, 1987b; Beauheim et al., 1991; Beauheim and Ruskauff, 1998).

Transmissivities measured in the Rustler Formation vary by five to six orders of magnitude. However, even the highest transmissivities measured (Beauheim and Holt, 1990; Beauheim, 1987c) do not indicate or support open-conduit flow.

4.3.3 Pumping Tests

A pumping test was carried out in well WIPP-13, where the Culebra was pumped in the test well for 36 days, and responses to that test were measured in the Culebra in surrounding observation wells (Beauheim, 1987c). Measurable responses were observed in all wells within two miles of WIPP-13, as well as in several other wells up to four miles distant. The closest wells to the northeast (DOE-2) and northwest (H-6) responded in one and eight hours, respectively, indicating a relatively high-permeability but low-storage connection. These results indicate good interconnectivity within the Culebra, arguing for a pervasive and interconnected, but low-volume, natural-fracture system rather than a system of high-volume karst conduits.

If the pressure transient had propagated to a highly conductive karst conduit, drawdown responses would have diminished and tapered off with time as the large-volume conduit supplied water to the pumping well. Instead, pressures in all wells dropped gradually and evenly over the course of the test, indicating both that there is no large reservoir of fluid in the system and that the fractures were fluid-filled.

No response was observed in the Magenta where it was monitored in H-6, indicating no vertical communication between the Culebra and the Magenta.

A more recent (2005), 19-day pumping test at WIPP-11 also suggests that there is a well-connected, fairly high transmissivity region among wells in the north-central and northwestern parts of the WIPP site. The apparent storativity of the Culebra is still low, i.e., the Culebra is dominated by fracture flow and not conduit flow. Earlier interference testing had shown the existence of two areas at the WIPP site characterized by relatively high conductivity (fractures, not conduit flow). In the northwestern area of WIPP, H-6, DOE-2, WIPP-13, WIPP-30, WQSP-1, and WQSP-2 (see Figure 5b) all appear to be well connected at the level of the Culebra Member (Beauheim, 1986, 1987c; Beauheim and Ruskauff, 1998). In the southeastern part of the WIPP site, H-3, H-11, H-15, H-19, WQSP-4, DOE-1, and, to a lesser extent, H-17 and P-17 appear to be well connected based on pumping tests conducted at H-3, H-11, and H-19 (Beauheim, 1987a, 1989; Beauheim and Ruskauff, 1998). An interconnected natural fracture system provides potentially high flow rates locally, but has very little volume so the porosity and storage capacity are low, as seen in these tests. The results are not compatible with the properties of a high-volume karst-conduit system.

These test results reflect a pervasive fracture network rather than discrete channels because all wells within an inter-connected region respond when any one of them is pumped, and because all wells newly drilled within the connected areas also show the connections (e.g., H-19, WQSP-1, WQSP-2, and WQSP-4). Rapid responses to even low pumping rates (3-30 gallons per minute) indicate good connectivity but low storativity; karst conduits would show high storativity signatures.

Pumping tests at H-3, H-11, H-19, P-14, WQSP-4, and WIPP-13 all showed decreasing transmissivity ("no-flow" boundaries) as the pumping-induced pressure transient propagated farther and farther from the pumping well, while surrounding observation wells were drawing down (Beauheim, 1987a; 1987c; 1989; Beauheim and Ruskauff, 1998). Of all the wells tested near the WIPP site, only the H-6 wells (and WIPP-13 at very long times) show transmissivity increasing (similar to a constant-pressure boundary effect) as the pressure transient propagates (Beauheim and Ruskauff, 1998).

Large, highly conductive karst channels would also have appeared as constant-pressure boundaries in the pumping-test responses, but the channels would have prevented the responses that were observed in wells located beyond the hypothetical channels. For example, the H-6 wells respond strongly to pumping at WIPP-13, and well D-268 responded to pumping of well P-14 (Beauheim and Ruskauff, 1998) despite Snow's suggestion (1998) that a large karst channel, presumably capable of capturing flow or at least dampening the hydraulic response, exists between them.

4.3.4 Lack of Culebra-Magenta Interconnections

The parallel water-level behavior of the Magenta and Culebra observed at wells such as WIPP-25, WIPP-27, and H-6 (Figure 21) leads to a question of how well interconnected the Magenta and Culebra might be. For H-6, the lack of interconnection is shown in Figure 21 by the clear lack of a Culebra response to the five pumping episodes in the Magenta at H-6c, evident in the first four years of data on the plot. Equally important, no drawdown has been measured in any wells completed in the Magenta during testing of the Culebra (Figure 22).

This indicates that the two members are hydraulically isolated from each other even in wells drilled into the acknowledged karsted terrain of Nash Draw (e.g., WIPP-25), where the vertical separation of the two units is at a minimum and where the potential for fracturing and vertical communication is the greatest.

4.3.5 Potentiometric Heads

The measured patterns of the Culebra and Magenta potentiometric surfaces (Figures 23 and 24) suggest that the water-bearing units of the Rustler Formation are poorly interconnected hydrologically to each other. The potentiometric heads in both the Magenta and Culebra generally slope in different directions, strongly suggesting that the two units are hydraulically isolated from each other. A karst system would create good hydraulic connections between the units, and the potentiometric heads would be in equilibrium, probably parallel, and possibly even equivalent

Strong deflections of the Magenta potentiometric heads in the vicinity of drillhole WIPP-33 near the northwest corner of the WIPP site may indicate a local development of higher-volume porosities in this member of the Rustler Formation, but it is the only such indication. Few Magenta data points exist southwest of the WIPP, and the contours in this area are not well constrained.

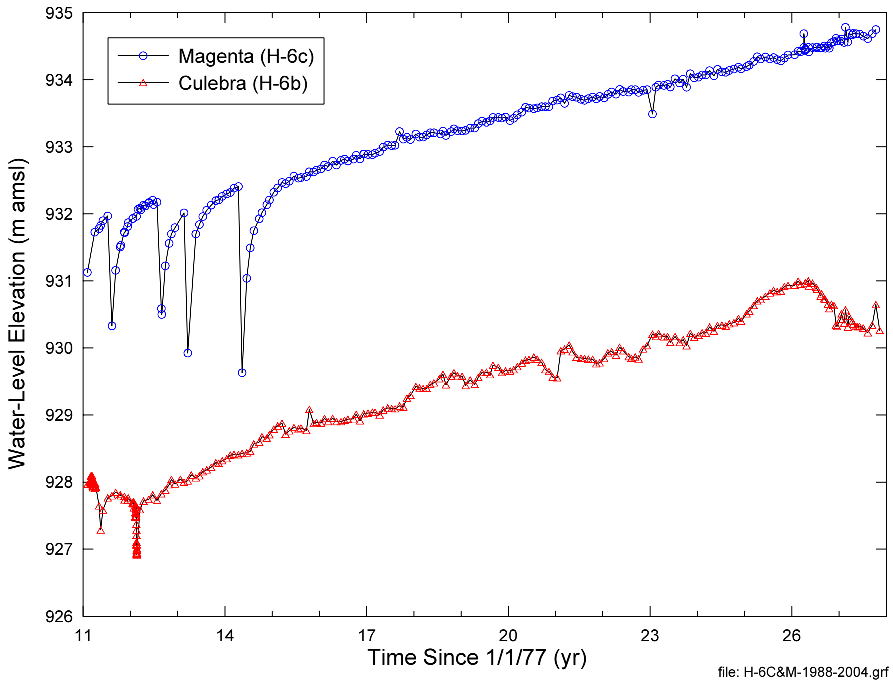


Figure 21. H-6 Magenta and Culebra hydrographs, 1988-2004. Magenta and Culebra water levels are monitored in wells separated by only 100 ft on the H-6 pad. The figure shows that water levels are generally rising in both units, although the Culebra shows more minor fluctuations than the Magenta. It also shows no response in the Culebra to pumping in the Magenta during the years 1988-1991.

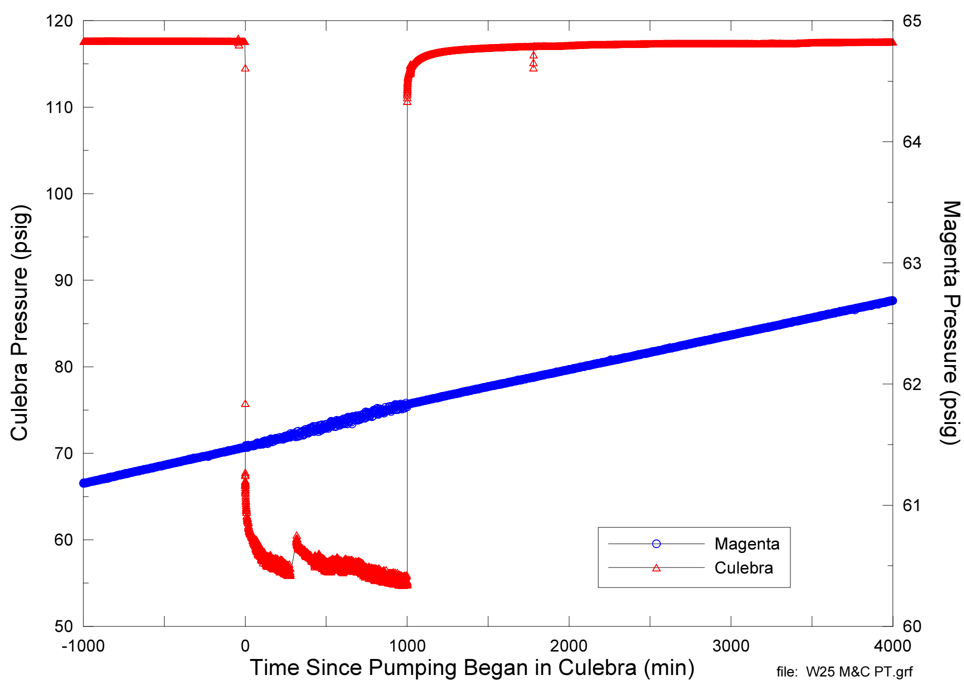
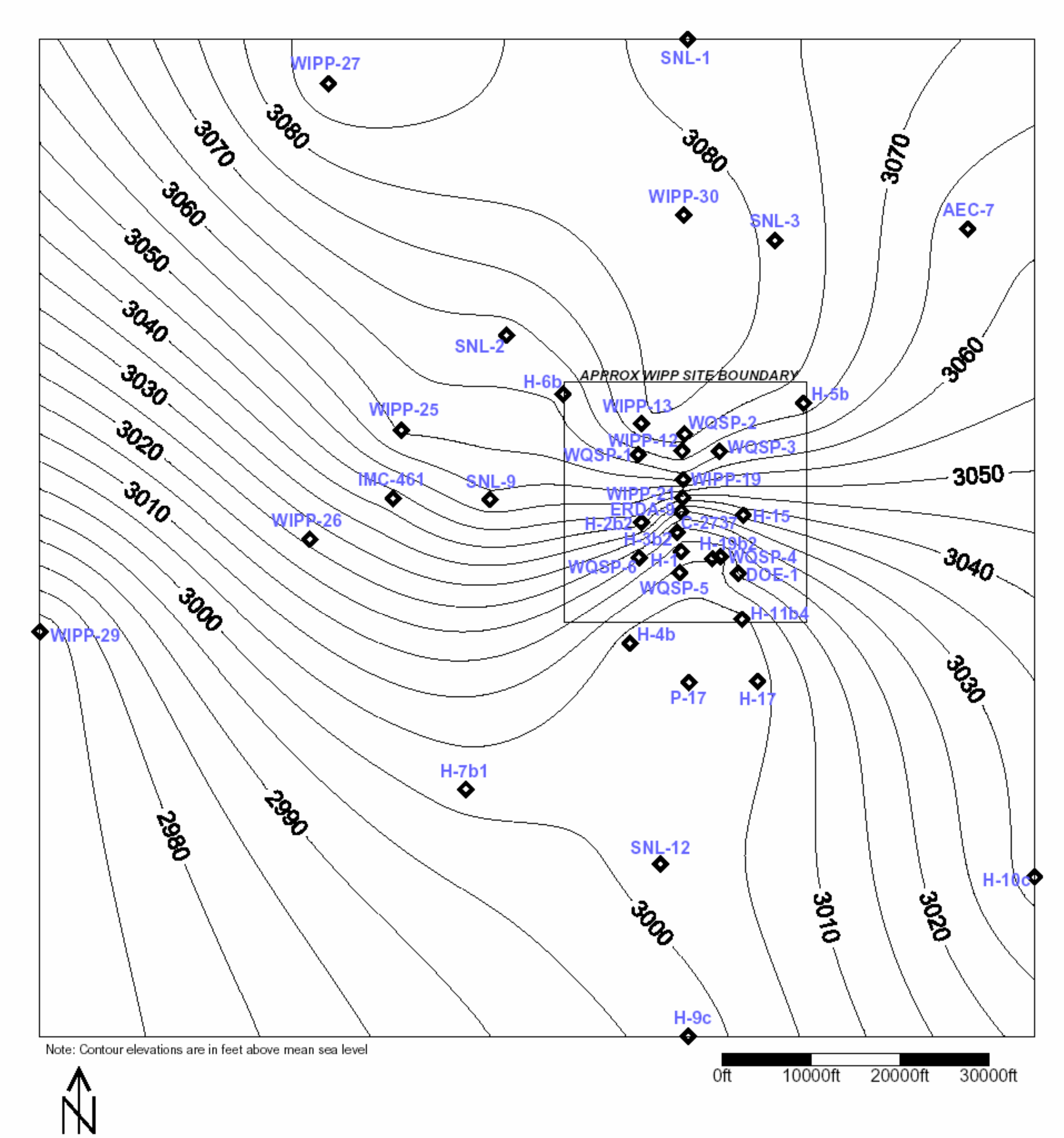
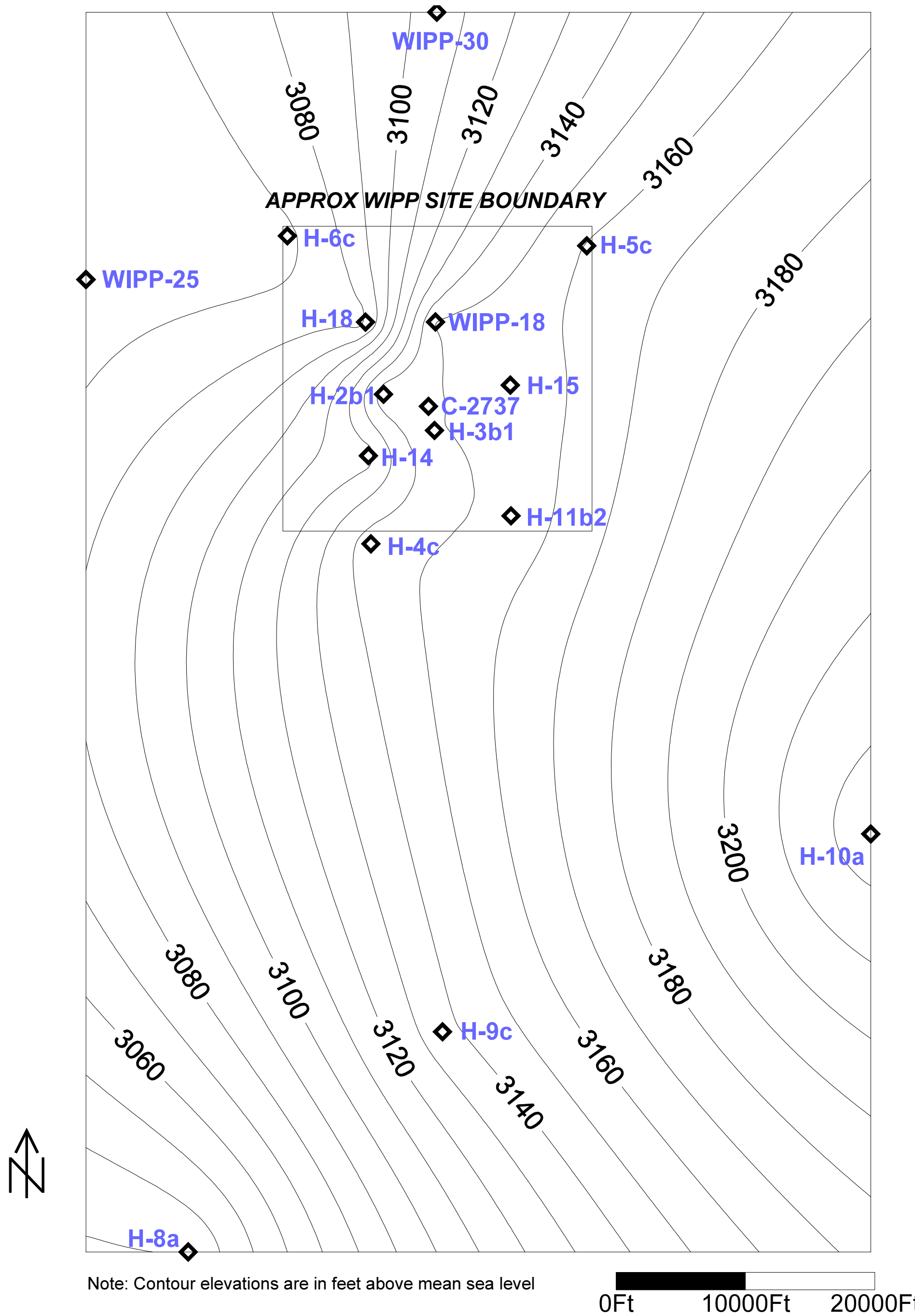


Figure 22. WIPP-25 Magenta and Culebra pressures during Culebra pumping test conducted in 2004.



Potentiometric Surface, Adjusted to Equivalent Freshwater Heads, of the Culebra Dolomite Member of the Rustler Formation near the WIPP Site, March-April 2004

Figure 23. Potentiometric heads of the Culebra Dolomite Member of the Rustler Formation. From Johnson (2005a).



Potentiometric Surface, Adjusted to Equivalent Freshwater Heads, of the Magenta Dolomite Member of the Rustler Formation near the WIPP Site, 2004

Figure 24. Potentiometric heads of the Magenta Member of the Rustler Formation. The H-14 and H-18 heads were affected (lowered) by equipment problems. From Johnson (2005b).

4.4 Conduit Flow, Bypassed "Fossil" Water, and Diffusion

4.4.1 Old and Young Water in the Same Unit

In trying to integrate Lambert and Harvey's (1987) finding (that isotopic analyses indicate water samples from the Rustler Formation are 12,000-16,000 years old), with karst theory (where waters should be capable of coursing rapidly through large Rustler conduits), Hill (1999, p. 54-55; 2003, page 206) has suggested a compound porosity system. She cites Chapman's (1986; 1988) interpretations to support a theory that there could be two separate isotopic compositions of water in the subsurface: old, fossil water and younger, recently recharged water. The argument is that water with a relatively old isotopic composition fills and is trapped in matrix porosity in the blocks between conduits, and that this is the water most frequently sampled since the matrix blocks are larger than conduits and they therefore have the highest probability of being intersected by a wellbore, explaining the data that indicate old water fills the system. Different water with a young but unsampled isotopic signature supposedly fills karst conduits between the matrix blocks but is rarely sampled because there are few such conduits, and therefore the Rustler water-sample data showing isotopic indications of most-recent recharge 12,000-16,000 years ago should not negate the possible presence of a rapidly and recently recharged subsurface karst system.

Chapman's (1988, p. 46) assertion that "The salinity differences and uranium isotopic data suggest that either the Culebra contains discrete, rapid flow paths interspersed with areas of slower groundwater movement and/or that young fresh water leaks into the aquifer," seems to have been the inspiration for this theory. However, Chapman also suggests (same page) that "Extreme salinity variations…may be due to leakage of concentrated brines in the Rustler from underlying evaporite units." Chapman prefers the first interpretation, but the sample area includes Nash Draw and the area south of route NM 128 where local points of fresh water influx are known. Moreover, although the locations of Chapman's "rapid flow paths" are unspecified, Chapman suggests that they are broad in scale, extending for miles in length, and thus they do not mesh well with Hill's concept of conduits (anything larger than a centimeter). Nor do they fit with or support the proposed locations or sizes of Snow's (1998) four hypothetical conduit channels. Chapman's concepts do not support Hill's concept of conduit flow and bypassed water.

Chapman (1986) also suggests that the stable isotope data from Rustler water samples are similar to "verifiably young" groundwater samples elsewhere in NM. No one has reviewed or explained the reasons for the differences between this and Lambert and Harvey's (1987) findings of older, matrix waters, although authors more often cite Lambert's work.

4.4.2 No Evidence for Conduit Flow; Consideration of Diffusion

Hill's argument for two water systems at depth is negated by the hydraulic tracer and pumping tests, which inherently sample large volumes of rock and which did not produce evidence for the presence of conduits. In addition, whether a well directly intersects fractures or somehow misses them, pumping the well will preferentially pull water from the most permeable part of the system (the fractures). Hence, water in fractures is always, not rarely, sampled. As the pressure in the fractures decreases due to pumping, water flows from the matrix into the fractures. This water comes from the portion of the matrix that is closest to the fractures, and therefore closest to chemical/isotopic equilibrium with the water in the fractures. Therefore, the isotopic signature of the water would be much more characteristic of the fractures than of any hypothetical older water in the matrix. Furthermore, diffusion would have equilibrated water chemistries between the fractures and matrix over the many years that fractures (or conduits) have existed.

4.4.3 Conclusion

Based on pumping and tracer tests, the concept of two subsurface water populations with widely divergent isotopic and age characteristics is untenable. Thus the inference derived from this concept, that the ages calculated from the isotopic signatures of sampled Rustler waters support the potential for karst at WIPP, is invalid.

5.0 PROBABILITY AND ISSUES OF LIMITED WELL-BORE SAMPLING

5.1 Introduction

Hill (1999) suggests that it is still possible that karst features are present and as yet unsampled in the Rustler Formation at the WIPP site, even though only one of the numerous wells drilled near the site (exclusive of Nash Draw) encountered evidence for karst, because wellbores sample such small areas of a formation. She also suggests that wells drilled in the center of topographic depressions to test them for an origin due to subsurface karst have missed relatively small (dimensions not estimated) karst conduits leading from the surface depression to a more extensive subsurface karst system.

5.2 Probability of Intersecting Fractures with a Drillhole

Aside from the hydraulic testing described above, a wellbore is, in fact, a small sampling of a formation. The 8¾-inch diameter wellbores typical of oilfield operations have a cross-section of less than half a square foot. A wellbore, therefore, is an inefficient way to sample and characterize widely scattered or vertical, two-dimensional features such as vertical fractures. The probability of intersecting vertical fracture planes with a vertical wellbore is low unless the fracture spacing is very small, i.e., the probability of intersecting vertical fractures with an eight-inch well is only 50% when the average fracture spacing is only 16 inches (Figure 25), and the probability of intersecting a fracture decreases exponentially as fracture spacing increases (Lorenz, 1992).

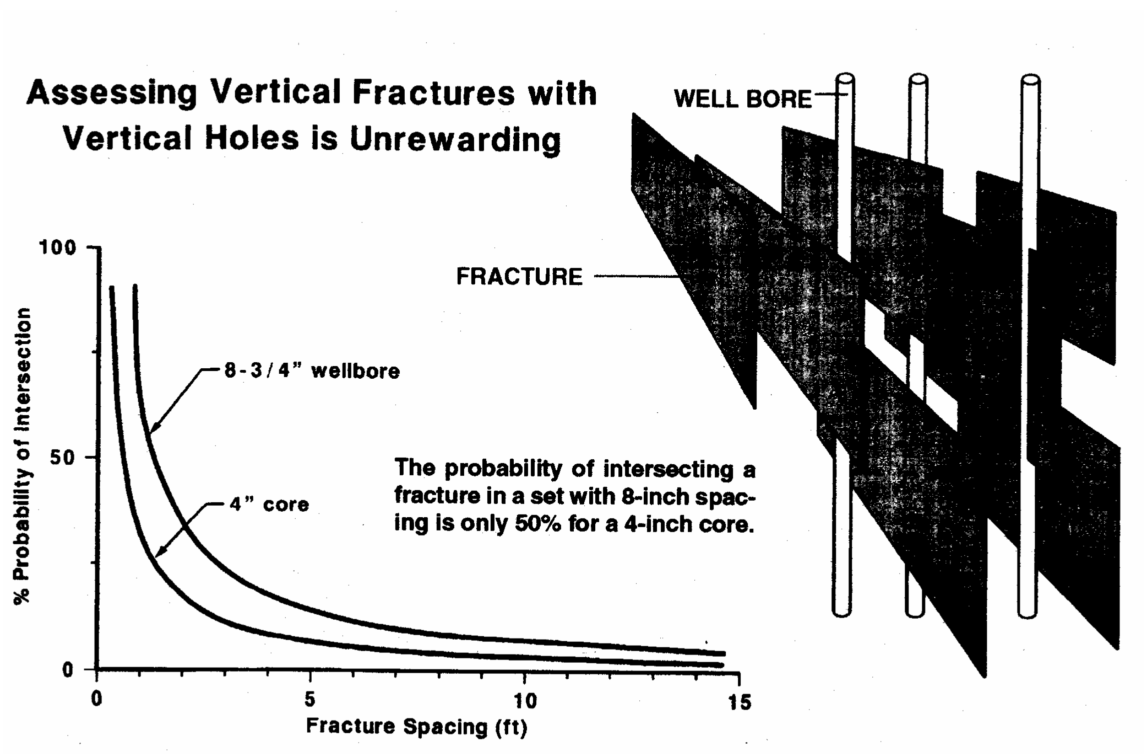


Figure 25. The probability of intersecting fractures with a vertical drillhole is low unless the fractures are not vertical (from Lorenz, 1992).

5.3 Probability of Intersecting Karst with a Drillhole

However, karst conduits such as postulated by Hill are neither vertical nor two-dimensional. Although they may initiate by dissolution along two-dimensional fractures, by the time they have widened into conduits that are large enough to significantly affect fluid flow within a formation they are three-dimensional features (see Figure 4). Hill (1999) defines a conduit as anything over one cm in diameter, but does not provide examples or descriptions of actual conduits. The addition of the third dimension significantly increases both the ability to conduct fluids and the probability of intersection by a drillhole.

More significantly, the documented fractures in the Rustler Formation have a variety of orientations, ranging from vertical to inclined to horizontal. The probability that a well will intersect two-dimensional fractures, or the karst-related conduits developed along them, increases as a sine function as the fracture dip decreases from vertical. There is a high probability of intersecting horizontal fractures with vertical wells.

Since so many of the documented natural fractures in the Culebra and other members of the Rustler Formation are inclined to horizontal, and since potential karst dissolution features should be initiated and preferentially developed along fractures, vertical wellbores do in fact adequately sample the formation for potential karst. The samples are small, but the potential targets, if present, would be big. The absence of karst evidence in wells at the WIPP site, with the possible exception of WIPP-33, is a valid indication that karst has not been developed in the Rustler Formation at this site.

5.4 Data from the WIPP Shafts

The absence of karst is strongly corroborated by the significantly larger-scale, direct sampling of the Rustler Formation afforded by the air intake, waste, and exhaust shafts, excavated in the central part of the WIPP site to support the subsurface facilities and operations. These shafts had unfinished diameters of 20.25 ft, 20.0 ft, and 15.0 ft respectively, and all geological features in the penetrated formations, including the Rustler Formation, were carefully mapped during excavation (e.g., Holt and Powers, 1984, 1986, and 1990b).

The three shafts have a combined plan-view area of 812 square ft, as much area as would have been sampled by nearly two-thousand standard, oilfield, 8¾ inch-diameter wells. The Rustler Formation penetrated by the three shafts is 309 ft thick, thus over 53,000 square feet of Rustler wall rock were exposed in the three shafts for examination and detailed mapping. No evidence of karst was found in the well-exposed rock in the three shafts, excavated at three separate, although closely spaced, locations.

5.5 Volume of Caves

Hill (1999, page 21) makes the theoretical argument that the void space of caves in many karst terrains constitute only 1-2% of the total rock volume, and that therefore the evidence of "caves" (bit drops) encountered while drilling only one of 60 (1.7%) wells in the WIPP area (WIPP-33) is consistent with the presence of similar, karst-related void space percentages at WIPP. While the assignation of a limiting, maximum percentage to what is a spectrum of phenomena seems to be an unwarranted restriction, the absence of dissolution in Rustler strata in the large, clean, high-volume shafts is perhaps the most telling evidence against this hypothesis.

5.6 Drilling in the Centers of Depressions

Hill (1999) argues that holes WIPP-33 and WIPP-14, drilled to investigate the possibility that local topographic depressions indicate an underlying karst system, have merely missed the subsurface evidence for karst. This is a nebulous argument for which no rebuttal can ever be satisfactory to the arguer, since no matter how many holes are drilled, any and all holes that drill through an unkarsted sequence of the Rustler Formation can be alleged to have been merely drilled in the wrong location.

However, the holes drilled to assess these depressions and their associated gravity anomalies were located near the centers of the surface topographic depressions (see Figure 9), and the location of WIPP-14 was based on the surface features and gravity data that had been interpreted by Barrows et al. (1983) and reviewed by Barrows (Sandia National Laboratories and D'appolonia Consulting Engineers, 1982, Appendix A).

It is unclear whether Hill suggests that the surface depressions are caused by an actual karst collapse as the underlying Rustler strata became brecciated and displaced during dissolution beneath the entire area of the surface depression, as seen in the local breccia pipes, or whether Hill infers that the depressions result from large-scale dissolution or subsidence of the sandstone layers near the surface. Regardless, neither theory is supported by the data. If it is the former case, then the collapse that formed the surficial depressions should have resulted in relatively large breccia chimneys, or at least measurable downward displacement of the stratigraphic layers, either of which would have a large enough signature to be intersected by the wells drilled to test these structures. The wells drilled into these surface depressions/gravity anomalies have encountered neither displaced strata nor extensive, definitively post-depositional breccias. Moreover, near-surface solution is untenable since the Triassic and Permian siliceous sandstones, siltstones, and claystones that underlie the thin recent deposits are highly resistant to dissolution.

An alternative interpretation is that shallow stream channels, formed during the Pleistocene and partially filled with Gatuña deposits, have been choked by migrating sand dunes. The upper 97 ft of WIPP-14 core is consistent with Gatuña channel fill, and on trend with a Gatuña paleovalley mapped by Bachman (1985, his Figure 20). More recently, Powers and Richardson (2004a) have shown that thick Gatuña deposits are present in the SNL-3 drillhole along this same trend. Wind-driven sculpting of the surface (including the "blowouts" of Bachman, 1981) is a widely recognized process in this part of New Mexico that has continued to modify the area.

6.0 NEGATIVE GRAVITY ANOMALIES AND RELATED GEOPHYSICAL MEASUREMENTS

6.1 Introduction

Numerous remote-sensing techniques have been applied to the WIPP site in an effort to characterize the subsurface strata. Each technique seems to have produced local anomalous signal responses, suggesting that there might be local anomalies in the subsurface, but there is little overlap between the resistivity anomalies (Elliott Geophysical, 1976,1977), gravity anomalies (Barrows et al., 1983), seismic anomalies (Barrows et al., 1983), topographic anomalies (Phillips, 1987), groundwater flow anomalies (Mercer, 1983, Crawley, 1988), potentiometric head anomalies (Beauheim and Ruskauff, 1998), groundwater geochemistry anomalies (Mercer, 1983), and electromagnetic anomalies (Cline and Blohm, 1987), and these do not coincide with the positions of the large Rustler karst conduits postulated by Snow (1998). A plausible case could be built for subsurface anomalies if indications of the anomalies from one or more of the different techniques overlapped in location, depth or size, but the different techniques have provided scattered and inconsistent indications.

The failure of the different techniques to suggest the same locations for subsurface anomalies highlights the difficulty and latitude in interpreting these techniques. The sensors have presumably responded to one or more real, physical features in the earth, but there is rarely a unique or even well-supported interpretation of that response. Recognition of this fact led to drilling and coring of test holes in order to physically investigate the shallow strata under several of the anomalies, and, in turn-about, to claims that these holes did not confirm or deny the remote-sensing signatures.

Most of the discussion has revolved around the WIPP gravity survey (Barrows et al., 1983). Hill (1999, p. 37-40; 2003, p. 205) cites the Barrows 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 himself. Barrows' discussions are convoluted and sometimes contradictory, and his interpretations are not definitive.

For example, there are discrepancies in Barrows' discussions of the comparison of density logs between holes and how or whether they indicate karst in the Rustler Formation. Barrows et al. (1983) note that the WIPP-34 velocity survey logged through the Dewey Lake Formation has slower overall travel times than the WIPP-13 velocity survey (their Figure 3.1-3, discussions on page 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.

He then portrays 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. He extrapolates this to an interpretation of mass removal by karst processes in the vicinity of WIPP-14.

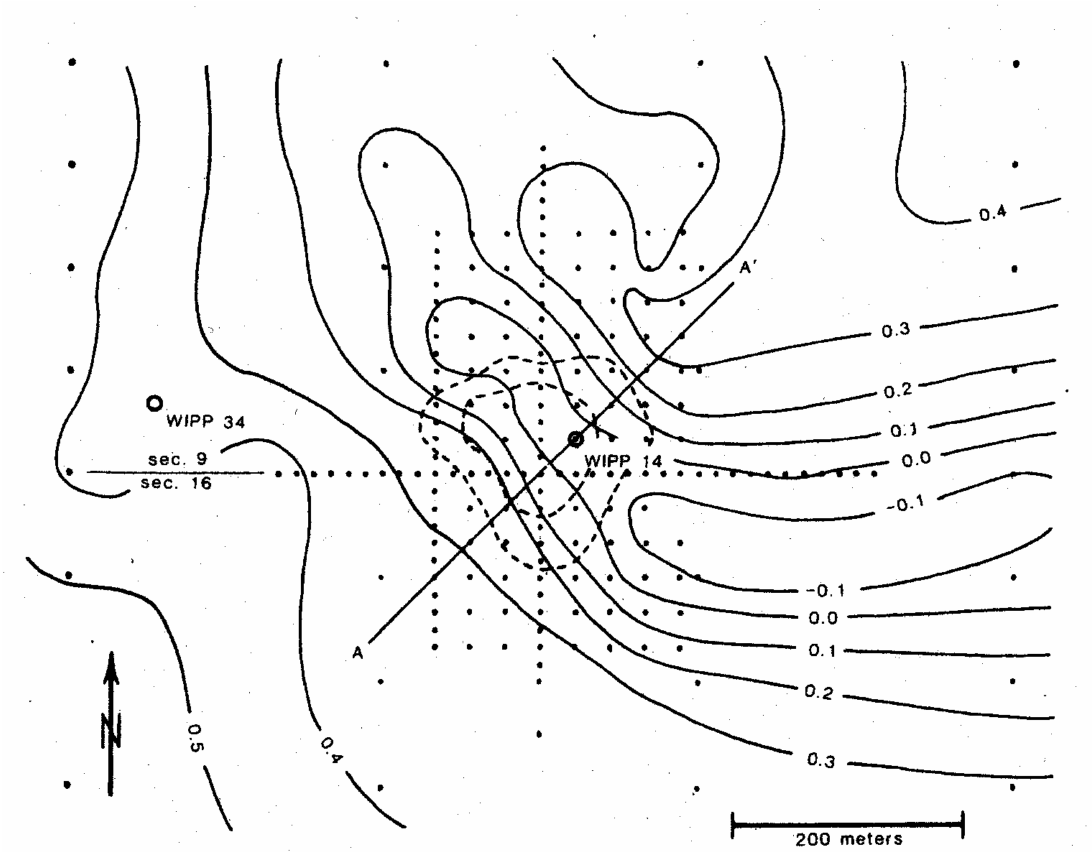


Figure 26. Superposition of the WIPP-14 gravity anomaly and topographic contours. (From Barrows and Fett, 1985; their Figure 4/page 828). Topographic contour (dashed lines) not specified by the authors but probably about five feet. Gravity contours 0.1 mGal.

6.2 The WIPP-14 Gravity Anomaly

The gravity anomaly explored by the WIPP-14 drillhole is an elongate, narrow pattern on the order of 5000 ft long along a curved axis, and 1000 ft across (Figure 26). The overlying topographic depression is much smaller, about ten ft deep and 700 ft across, and located about 600 ft northwest of the center of the gravity anomaly.

Barrows et al. (1983) calculate 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 (Sandia National Laboratories and U.S. Geological Survey, 1981). This does not correlate to the two zones (300-400 ft, and 650-750 ft) where Barrows' calculated the presence of mass deficiencies from the density logs, or with the concept of karst development being in the Rustler Formation. Barrows does not address these discrepancies or the questions of why and how dissolution of insoluble sandstones, siltstones, and shales of the Dewey Lake Formation might have occurred in the karst model he builds. The question of why karst should have formed in the Dewey Lake Formation rather than in the more soluble, underlying

Rustler Formation is left unasked and unanswered.

The core and geophysical logs from WIPP-14 document a normal stratigraphic succession, although there is an anomalously thick alluvial fill found at the top of this hole. This fill most closely resembles the sandstone and conglomerate of the Gatuña Formation, strongly suggesting that the fill is the remnant of a local tributary channel that fed the thick Gatuña fluvial deposits (see Figure 20) mapped by Bachman (1985) just to the north. This thick interval of relatively porous rock explains the local gravity anomaly more easily than karst in the Dewey Lake or Rustler Formations. Elongation of the gravity anomaly is consistent with this interpretation as a fluvial channel.

Barrows also noted that seismic data at the WIPP site above the Castile Formation "are considered too unreliable to map" (1982, page 16), yet later in the report (page 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 use of "unreliable" data is not sound practice. Although the shallow reflectors do in fact appear to be depressed, suggesting near-surface, lower-velocity sediments, this is consistent with and more easily explained by Bachman's Gatuña-filled paleovalley.

6.3 The WIPP-33 Gravity Anomaly

The gravity anomaly at WIPP-33 is outside the main WIPP area 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-D 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, page 50), so it is probably roughly circular and perhaps 1500 ft across. The overlying topographic depression is about eight feet deep and 200 ft in diameter, reasonably well centered on the gravity anomaly. Barrows 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.

The text of the basic data report for WIPP-33 (Sandia National Laboratories and United States Geological Survey, 1981) notes that this well drilled through an "unusually thick" sequence of "surficial Holocene deposits" (44 ft according to the abstract, although this is difficult to corroborate in the accompanying Table 3 lithologic log). These deposits are described as filling a "small closed basin," although the interpretation that the surficial basin was closed at the time of deposition appears to be speculative, or at least not supported with direct sedimentological evidence in the basic data report.

Much has been made of this gravity anomaly because it coincides with a surface depression and because 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' 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 stratigraphic tops that were penetrated 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.

6.4 The WIPP-13 and H-3 Gravity Anomalies

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?)." The Rustler strata cored in both these holes show some disruption, possible indications of dissolution but more plausibly interpreted as syndepositional disruption since they are overlain by undisrupted strata with primary depositional structures. Although Holt and Powers (1988) infer 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 report two thin anhydrite beds and a polyhalite bed to the east in a stratigraphically equivalent halite bed. 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) describe 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, 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. Both holes encountered normal stratigraphic successions, and the cored breccias are too thin and too deep to have affected the gravity survey.

The WIPP-13 gravity anomaly is nearly circular, about 2000 ft across. With only -0.15 mgal of relief, it is relatively shallow. The H-3 gravity anomaly has similar relief according to the gravity map (Barrows et al., 1983, their Figure 2.1-4), although Hill reports it as a -0.45 mgal depression. It is also circular and shallow, about 3500 ft across. Neither anomaly is a "sharp" departure from the regional trends as suggested by Hill.

6.5 Assessment of the Gravity Anomaly Data

Hill and Barrows have used questionable correlations between large (thousands of feet across) irregular gravity anomalies and small (hundreds of feet in diameter), circular topographic features, to reach poorly supported but definitively stated conclusions. They have been selective in using the array of available data, presenting only those data that they feel support their concept of subsurface karst and ignoring other data. They have not attempted to explain topographic depressions that do not have associated gravity anomalies, nor have they integrated the other available remote sensing/geophysical data into their models and conclusions. Most of the anomalies considered by Hill are broad and shallow, not fitting a rigorous definition of the term "anomaly": only the WIPP-14 and possibly the WIPP-33 anomalies could be considered to be "sharp" departures form the regional gravity trends when compared to other anomalies across the area.

7.0 ABSENCE 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 soils 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 3) recharge of the subsurface Rustler units must be through surface runoff that flows primarily into sinkholes, and 4) that therefore there must be sinkholes and an associated subsurface karst system at the WIPP site.

This is an over-extended extrapolation from the original observation (no surface runoff), which of itself does not point exclusively to the presence of sinkholes. In fact, nothing on the surface in the vicinity of the WIPP site east of Livingston Ridge is similar in shape or scale to the obvious stream piracy by sinkholes seen in Nash Draw and elsewhere in southeastern New Mexico (see Figure 11). In comparison, the short "disappearing arroyo" near WIPP-33 (see Figure 8) does not actually reach the WIPP-33 enclosed surface expression. Hill (1999, p. 42) therefore falls back on an artificial and not wholly analogous example where water seeping from the Dewey Lake into the WIPP exhaust shaft "may be due to the focusing of water downward from the WIPP site parking lot (K. Larson, personal communication)." Water in fact is perched locally within the uppermost Dewey Lake Formation (Powers, 1997; Holt and Powers, 1990a) at the WIPP site. Hill's unproven implication is that the surface depressions at the WIPP-14 and WIPP-33 drillhole sites are locations similar to the parking lot in form and effect. The analogy fails since the former would be resultant features, whereas the parking lot catchment area is a causative feature.

Even if all 12 inches of rain came at once, potential runoff pathways across the site area are dammed by a blanket of stabilized and unstabilized sand dunes. Such sands are also capable of soaking up large volumes of rainwater (Geohydrology Associates, 1978), thus the 12 inches of rain per year need not have carved out an integrated drainage system on the low-relief topography. Discussions of evapotranspiration rates and the rapid infiltration of rainwater into sandy material that blankets the WIPP site are given below under Recharge and Discharge Issues. The surface-water runoff argument is poorly defined, circumstantial evidence.

8.0 RECHARGE AND DISCHARGE ISSUES

8.1 Introduction

Questions of recharge of the Rustler water-bearing units in the vicinity of the WIPP site, the locations of discharge from them, and the groundwater flow between, are somewhat open-ended since so few data are available. The location(s) and modes of recharge are largely theoretical, and few data concerning recharge and discharge points have been collected since Robinson and Lang (1938) first proposed that the waters in the Culebra and Magenta Members and/or in the brine aquifer collect in Nash Draw and discharge at the numerous springs at Malaga Bend on the Pecos River southwest of the WIPP site.

Malaga Bend is still widely accepted, *de facto*, as the probable discharge point for some Rustler groundwaters and the brine aquifer. Recharge locations are another story. Measurements of the potentiometric heads and of the chemistry of the waters found in the Rustler have been significantly improved during recent studies, yet the significance of these data is still under debate. The modeling of Corbet (1998) and Corbet and Knupp (1996) suggests that many of the observed patterns of groundwater geochemistry can most readily be explained by assuming that, over geologic time scales, there is a certain amount of vertical connectivity across formation boundaries as well as the widely accepted and more rapid lateral flow within members of the Rustler Formation.

Within these loose constraints, arguments have been made for flow through karst-related channels in the Rustler Formation at the WIPP site. Hill (1999; page 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.

In the following discussions, it is useful to note that the proponents of karst at the WIPP site make little or no distinction between the recharge potential and fluid-flow characteristics of the Rustler Formation where it crops out in Nash Draw and these characteristics where it is buried by insoluble younger strata east of Livingston Ridge. Although the formation is stratigraphically continuous laterally between these two domains, the data suggest that hydrologically the formation comprises two different, although connected, systems. Within Nash Draw, the data suggest that caves, sinks, fractured strata, and a thinner formation allow good hydrologic communication within the Culebra and Magenta Members of the Rustler Formation, rapid fluid flow, and, probably, recent local recharge. Eastward, however, where the formation is protected by overlying strata, it is not disrupted and therefore it has lower hydraulic conductivity. Nondiscrimination between data from the two domains, which show a difference of nearly two orders of magnitude in transmissivity values (Powers et al., 2003), obscures the important differences between them.

8.2 Correlations Between Malaga Bend and WIPP Site Precipitation

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 (1999, page 47) 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", and although she did not in fact do this herself, the reader is ultimately left with the impression that she considered that the data support the presence of karst in the Rustler at the WIPP site.

Ultimately, however, the poorly constrained behavior of groundwater in the area in and between the widely recognized dissolution/karst features at Nash Draw and the Malaga Bend springs is immaterial to the understanding of groundwater at the WIPP site to the east. Although climatically similar, the geology and the surface catchments are dissimilar.

8.3 Recharge

The following is a brief summary of groundwater recharge, flow, and discharge in the Rustler members at and near the WIPP site. Like the discharge points, recharge mechanisms and locations are typically assumed rather than documented. The water budget calculated by Geohydrology Associates (1978) suggests that in the WIPP site and Nash Draw areas, water inflow from precipitation and industry/oilfield brines exceeds outflow (evapotranspiration plus discharge at the Malaga Bend springs) by 3,327 acre-ft per year. This net increase appears to correspond in general to the observed increase in potentiometric heads in the Culebra across the area, although the exact source of recharge is debatable.

8.3.1 Localized Recharge

Specific potential recharge locations, where the Rustler Formation crops out or is near enough to the surface to be recharged by precipitation, are rarely specified by authors. The Forty-niner, Magenta, Tamarisk, and Culebra Members of the Rustler Formation all crop out in various areas in Nash Draw. Several sinkholes that capture overland drainage are obvious from the air within this area of closed drainage (e.g., Figure 11), but details of these sinkholes have not been published, although Bachman (1981) did map a number of them. Because Nash Draw is a closed-drainage depression, rain falling into it evaporates, gets collected in the brine ponds, or is funneled underground. Mercer (1983) suggested that the Rustler might also be recharged at Bear Grass Draw, about 30 miles northwest of the WIPP site, but did not present data to support this inference. Other authors have not offered opinions or evidence for locations where recharge of the Rustler Formation is occurring or could plausibly occur.

8.3.2 Irrigation and Industry Effluent

Theis et al. (1942, page 68-69) noted that water levels in Culebra water wells in Nash Draw south of Laguna Grande de la Sal rose during the summer in conjunction with irrigation, whereas water levels fell during this season in wells outside the areas of irrigation. They attributed this to direct recharge to the Culebra from irrigation operations. This correspondence between water levels and irrigation is observed only in the southwestern end of Nash Draw, where the Rustler Formation is exposed, the Culebra is near to the surface, and where dissolution-related disruption of Rustler bedding allows rapid communication between the surface and subsurface units. This model is not applicable to the WIPP site where the Rustler Formation is buried beneath insoluble sandstones.

Brine effluents from potash mill operations have been discharged to the surface for decades, and Geohydrology Associates (1978), treating the Culebra, the Rustler/Salado brine aquifer, the Santa Rosa Sandstone, and alluvium together as a single aquifer, suggested that as much as 40% of the recharge to the groundwaters in Nash Draw comes from the effluent of potash mills and oilfield brines, and that this discharge has significantly raised the potentiometric levels. However, recent drilling of the SNL-1 drillhole immediately south of a potash tailings pile just outside the northeastern arm of Nash Draw, and analysis of the underlying Culebra waters, suggests that there is no chemical signature from the tailings in the local groundwater (Powers and Richardson, 2004b).

Geohydrology Associates (1978) noted that the water chemistry from specific springs is dissimilar to that of industrial brines, and other studies have suggested that the difference in chemistry between the brines in the effluent ponds in Nash Draw and the brines discharging from the springs at Malaga Bend indicates little communication between discharge ponds and the local aquifers.

8.3.3 Infiltration of Precipitation

Geohydrology Associates (1978) suggested that 60% of the water inflow to local aquifers in Nash Draw and surrounding areas comes from the 12 inches of precipitation per year, infiltrating at about half an inch per year despite rates of potential evapotranspiration which can exceed precipitation by an order of magnitude during the summer (Sares, 1984). This infiltration rate is consistent with four earlier studies cited by Geohydrology Associates, but it is significantly higher than the 0.2-2 mm/yr infiltration rates calculated more recently by Campbell et al. (1996) for a much more restricted area on Livingston Ridge. Corbet (1998) and Corbet and Knupp (1996) have suggested that some of the lateral variations in geochemical signatures of the waters in the Culebra can be explained by local, long-term recharge from vertical infiltration. Moreover, their models suggest that most precipitation over the WIPP site enters the higher-permeability sandstones of the Dewey Lake and Santa Rosa Formations, and that only a limited vertical "leakage" of this water filters down into units of the Rustler Formation.

Theis et al. (1942) noted a sharp rise in the water levels in wells in the vicinity of Laguna Grande de la Sal 14 days after rainfall, suggesting rapid transfer of precipitation into the aquifers in that area of Nash Draw. However, influx of water into the more deeply buried Rustler strata east of Nash Draw is a different matter. Monitoring of the Dewey Lake water-table aquifer at wells

H-3d and WQSP-6A at the WIPP site has never shown a water level response to rainfall events. The observations of Theis et al. (1942) are probably related to karst flow into sinkholes at Nash Draw, whereas the absence of karst at the WIPP site prevents rapid, karst-related water-level responses to rainfall in that area.

8.4 In Situ Flow

The directions of flow in the Rustler units at the WIPP site have not been directly measured, but rather are inferred from measurements of the potentiometric heads in the different units using the assumption that water flows down pressure gradients. Flow directions, and rates, can also be inferred from isotopic data and variations in water chemistry. Because these parameters are not directly measured, there has been room for argument in how the primary parameters that were used to derive flow directions should be interpreted.

One interpretation is that the water-chemistry data thought to imply directions of flow different from those indicated by current potentiometric contours are the result of a reversal of flow direction since Pleistocene time due to changes in precipitation and recharge areas. The proponents of karst, however, suggest that the data are compatible with rapid present-day flow westward away from the WIPP site to nearby discharge areas. More recently, Corbet (1998) has suggested that waters with different chemistries may have different recharge areas, and that limited amounts of mixing of these waters may be occurring along flow paths.

8.4.1 Directions of Flow from Potentiometric Heads

Based on water levels measured in wells and corrected for water densities, the overall present-day flow is to the south in the Culebra, and westward in the Magenta (Mercer, 1983; Johnson, 2005a,b) (Figures 23 and 24). These trends have not changed significantly since the heads were measured by Robinson and Lang (1938). Crawley (1988) corroborated the inferred Culebra flow directions, and contributed several three-well pressure-difference calculations to confirm local flow towards the southeast in the southern part of the WIPP site.

8.4.2 Isotopes, Residence Time, and Flow Rates

Chapman (1986) suggested that the stable oxygen isotope composition of Rustler water is not different from modern meteoric ground water and that therefore the Rustler is presently being recharged through percolation. This would imply that water flows relatively rapidly through the Rustler Formation from recharge areas to point(s) of discharge, the rapid flow implying a possible subsurface karst system.

On the other hand, Lambert (1987) and Lambert and Harvey (1987) interpreted the isotopic composition of Rustler water samples to indicate that Rustler water was emplaced over 10,000 years ago, and that therefore waters in the Rustler members have moved slowly if at all since recharge during the Pleistocene.

Campbell et al. (1996) also studied oxygen isotopes, in the local soil profiles rather than from the Rustler, and reached a corroborating conclusion that there is the potential for only “a small amount of infiltration (.2- to 2 mm/yr) through the desert soil” down to recharge the Rustler, and that, therefore, "water in the Rustler Formation need not have been recharged in the past (>10,000 yrs) under different climatic conditions" (page 153). However, they complicated their interpretations by stating that, since their data did not support surficial infiltration as a mechanism, "If modern recharge is occurring to the Rustler Formation, it must be water which has been recharged from surface runoff through karst features or other direct conduits that minimize evaporation." The key word is the "if" that starts the quoted sentence: the Campbell study did not prove or disprove whether the Rustler members are actually being recharged at present, only that there is minimal potential for recharge. The inference relating to karst is speculation, and not based on their data or on subsurface water sampling, and Campbell et al. do not require nor state that recharge through karst is occurring at the WIPP site itself.

Siegel et al. (1991) report radiocarbon dates from Culebra waters that indicate ages of at least 10,000-16,000 years, supporting Lambert and Harvey's (1987) isotopic data and inferences of slow rates of groundwater movement within the Culebra. Siegel et al. also measured hydrogen ratios in gypsum and noted that the ratios are not consistent with the formation of gypsum by the hydration of anhydrite by meteoric waters, again supporting a model where groundwater does not move quickly through the Rustler Formation. Finally, they compared the strontium ratios in gypsum and carbonates in the Rustler, Dewey Lake, and surface rocks, and showed that the secondary sulfates and carbonates in the Rustler did not form in a hydrological regime connected to the surface.

These isotopic data and interpretations, except for the interpretations of the same data presented by Chapman, support a model of slow groundwater movement through the Rustler Formation.

8.4.3 Water Chemistry Domains and Flow Directions

Several geochemical domains are recognized in the water-bearing members of the Rustler Formation. In general, the salinities, densities, and Total Dissolved Solids (TDS) contents increase eastward, which suggests to some that the overall flow is in that direction on the grounds that waters that have been in an aquifer system longer have had more time to interact with the chemistry of the host strata and are therefore more highly mineralized. However, such an interpretation runs counter to the measured heads in the Culebra and Magenta (Figures 23 and 24), which suggest southerly and westerly flow, respectively.

Different authors have mapped and interpreted the groundwater chemistry domains of the Rustler Formation in slightly different ways. Ramey (1985) defined three geochemical zones (Figure 27):

- Zone A from the eastern WIPP site to the east, with NaCl-type water with high concentrations of K and Mg;
- Zone B south of the WIPP site, with $CaSO_4$ water and relatively low TDS; and
- Zone C over most of the WIPP site and to the north and west, with NaCl-type water with low concentrations of K and Mg.

Chapman (1988) recognized three broadly similar zones, although she differentiated Ramey's Zone A from his Zone C on the basis of Ca concentration (Figure 28).

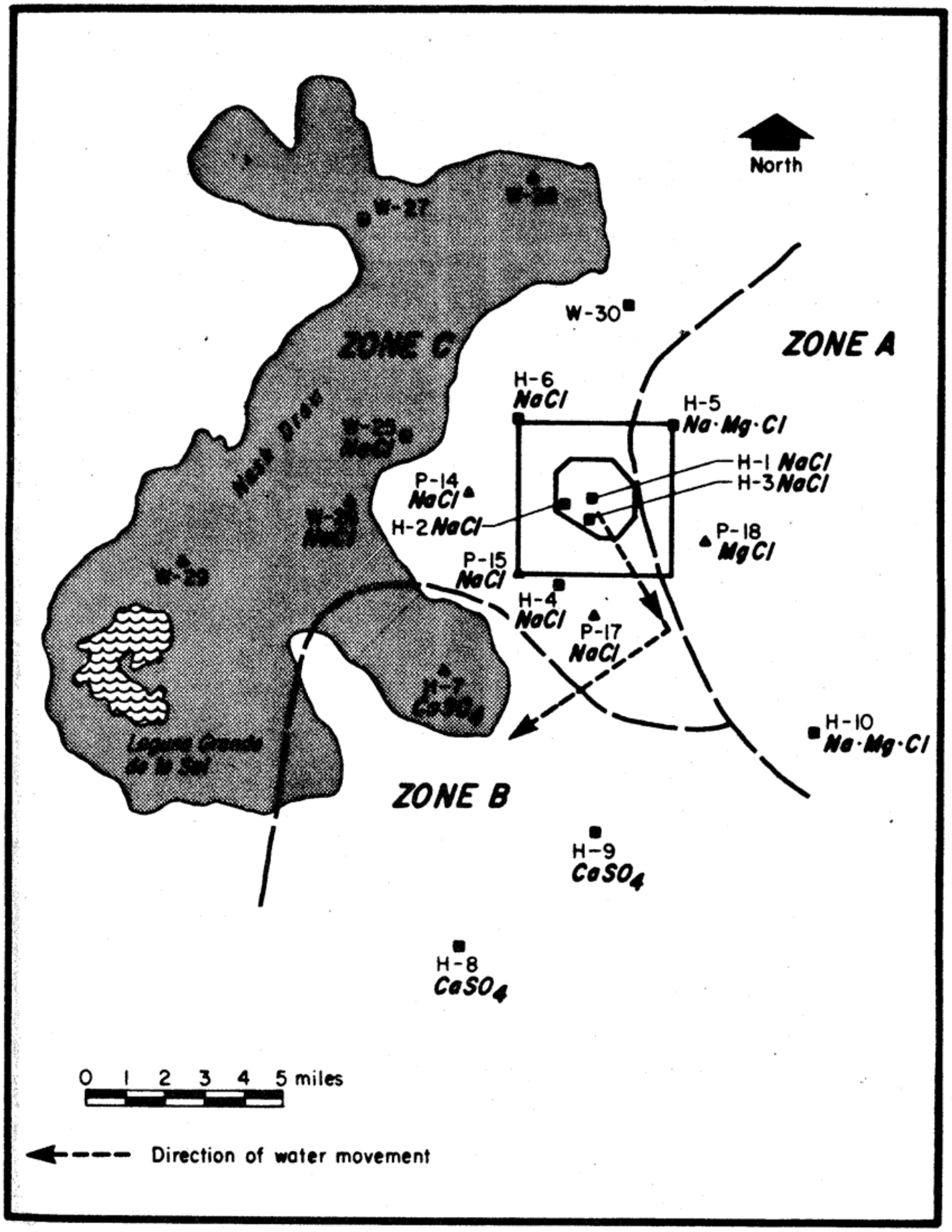


Figure 27. Geochemistry domains for Rustler formation waters as suggested by Ramey (1985). In most of the mapped area the samples were taken from the Culebra interval; in Nash Draw, however, the groundwaters are not confined to the Culebra reservoir and some mixing is likely.

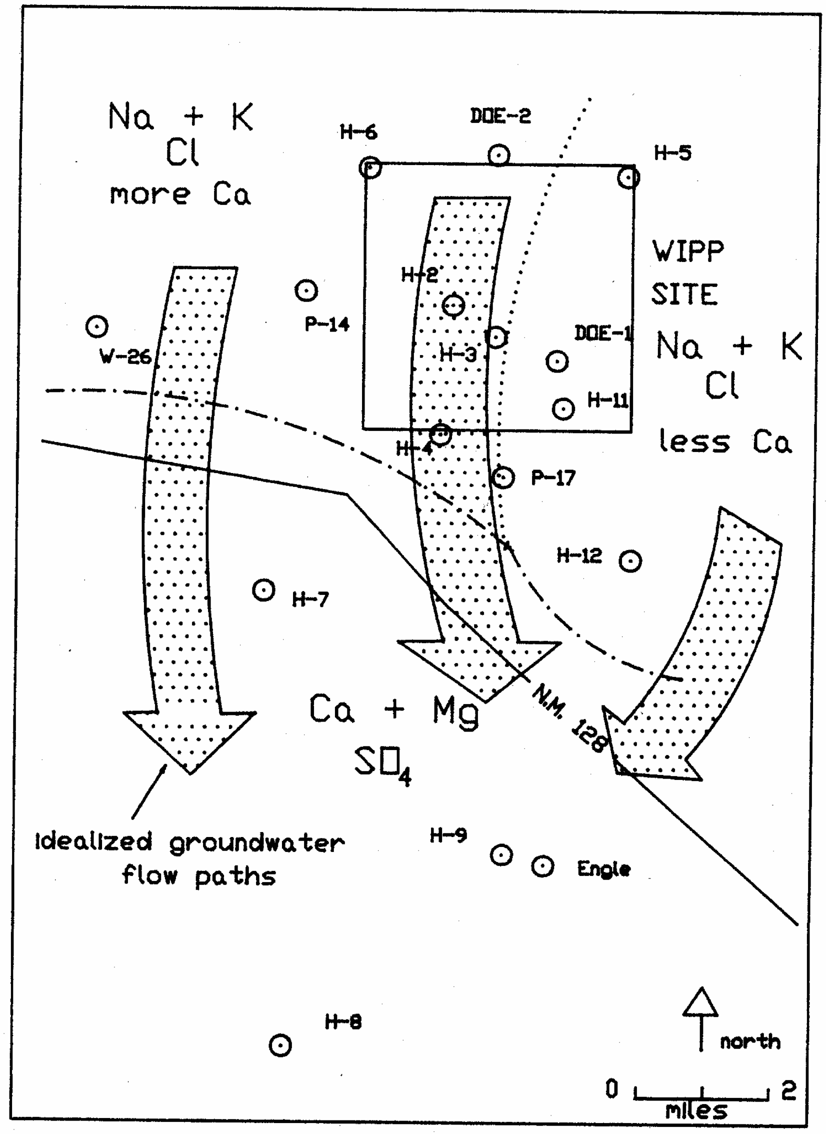


Figure 28. Geochemistry domains for Culebra waters as suggested by Chapman (1988) (including arrows indicating "idealized groundwater flow paths.")

Siegel et al. (1991) split off the western part of Nash Draw in mapping four recognizable water-chemistry facies in the Culebra (Figure 29):

- A: eastern half of WIPP, highly saline, TDS >100,000 mg/L, NaCl type water rich in Mg and Ca
- B: southwest of WIPP and south, relatively fresh water, TDS <10,000mg/L, $CaSO_4$ type water
- C: east half of Nash Draw and east to mid-point of WIPP, NaCl-dominated waters of variable compositions, TDS 10,000-80,000 mg/L (increasing eastward). This may be a mixing zone between facies A and facies B.
- D: west half of Nash Draw and westward: contaminated by potash mining effluent

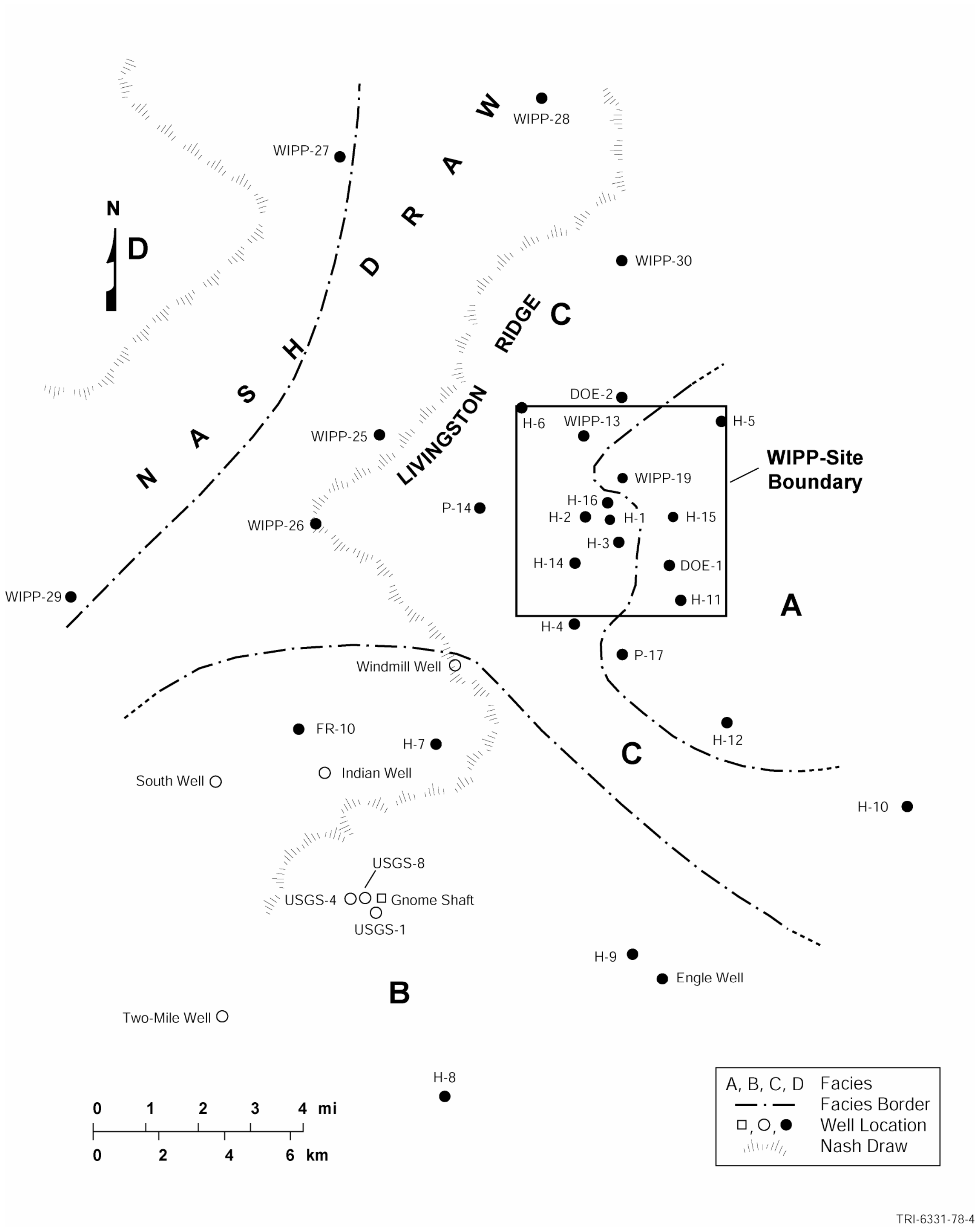


Figure 29. Geochemistry domains for Culebra waters as suggested by Siegel et al. (1991).

In a relatively uniform, confined aquifer, solute concentrations should generally increase in the downgradient direction. With such an assumption, the chemistry of the Culebra would suggest west to east flow. The present-day potentiometric heads, however, suggest flow in other directions. Heads measured in the Magenta suggest a westward potential flow (Figure 24), and heads in the Culebra suggest a generally southward potential flow (Figure 23). Moreover, eastward flow does not fit with discharge of any of the Rustler water-bearing units at the springs at Malaga Bend on the Pecos River to the south.

Various ideas have been offered to explain this dilemma. Chapman suggests that the southern area of low TDS and Ca-SO_4 waters corresponds to an area where salt is not present ("complete removal"). Local non-deposition of halite would explain the water chemistry equally well, but the basic idea, that formation waters are less saline where there is less interbedded formation halite, is plausible. Chapman also suggested that the "major hydrochemical facies change from Na-Cl to Ca-SO_4" is due to influx of a large quantity of low-TDS water", and suggests recharge through local, unspecified, gypsum caves.

Beauheim and Holt (1990, page 150) suggest that the water chemistry changes across the region are related to concurrent east to west changes in the Rustler lithology, as anhydrite changes to gypsum and ultimately gets dissolved westward at Nash Draw. The observation of greater mineralization of Rustler Formation waters eastward has been used to support an interpretation that flow through the formation, no matter in what direction, is slower in the eastern region, i.e., that long residence time has allowed greater rock-water interaction and resulted in greater mineralization of the water (e.g., Mercer, 1983). This inference of variable flow rates is indirectly supported by the regional differences in the potential for flow, as measured by generally lower transmissivities in eastern wells than in western wells. Mercer (1983) also inferred slower groundwater movement under the WIPP site, the boundary between fast and slow movement being at approximately the western edge of the site.

The discrepancy in flow directions inferred from the different data has also been suggested to be caused by a Pleistocene flow reversal: Ramey (1985) and Siegel et al. (1991) note that modern (potential) flow directions within the Culebra are not consistent with modern salinity distributions and that TDS decreases in the implied direction of flow, which is not typical of a steady-state system. They explain this by suggesting that the TDS distribution is a fossil one that has been overprinted by modern flow (head) vectors (Figure 30). Siegel et al. (1991) report eastward-increasing uranium isotope ratios suggestive of "recharge from a near-surface Pleistocene infiltration zone flowing from WNW", and suggest that these data imply a change in flow direction in the Culebra during the last 12,000-30,000 years.

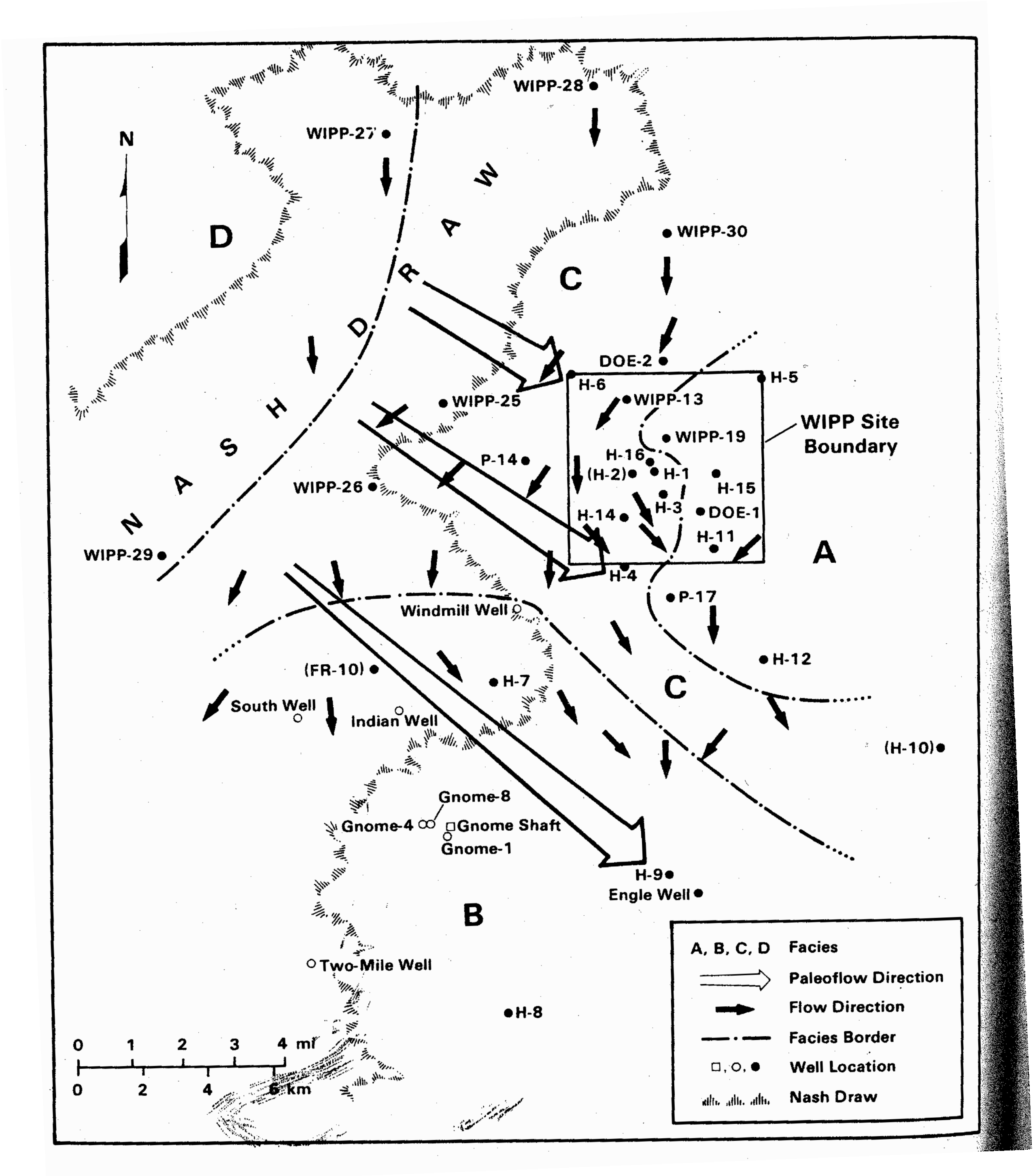


Figure 30. Suggested flow reversal in the Culebra from Pleistocene time (broad arrow outlines) to the present (smaller black arrows). (From Siegel et al., 1991, their Figure 1-34/page 1-96).

Corbet (1998) suggests that the different chemistry domains observed in the Culebra, as well as the apparent discrepancy between flow directions inferred from these domains and the flow directions inferred from the potentiometric heads, do not have to be explained by lateral, strata-bound migration of water through the formation. He suggests that the geochemistry domains can best be explained by considering that all members of the Rustler Formation are part of a single integrated groundwater system that is connected through vertical "leakage." More leakage occurs in areas where halite is absent from the Rustler, such as south and west of the WIPP site, than were halite is abundant in the Rustler, such as east of the WIPP site. Thus the chemistry domains are related to different amounts of vertical leakage through varying geochemical/host-rock environments rather than to lateral flow and varying residence times of the waters in the formation. This interpretation is consistent with the observed heads.

Regardless, the high salinities and mineralization in the Culebra at the WIPP site are not compatible with the rapid groundwater flow rates typical of karst conduits as suggested by Hill (1999). Hill also suggests that the variable chemistry of the Culebra waters described here suggests karst development, and this is addressed below.

8.5 Discharge

8.5.1 Malaga Bend Springs

There are conflicting interpretations of the few data available that indicate where the Rustler members discharge. One's perception of whether or not defining specific discharge locations is a problem depends on whether or not one believes the Rustler members are presently being recharged to a significant degree and if so, whether this recharge occurs at WIPP: if the Rustler is accepting water and passing it rapidly through a high-volume, high-conductivity karst type of groundwater system, then it needs discharge points where significant amounts of water can be eliminated from the system as fast as it is recharged. As pointed out by Lambert (1983), dissolution of a geologic system of evaporites cannot take place if no outlets for the dissolution brines exist. On the other hand, few discharge points for minor amounts of water would be consistent with a Rustler water system that is largely relict and relatively immobile under the WIPP site. To consider the system from the other end, if the identified discharge points are related only to groundwater flow in the karsted terrain at Nash Draw, then they are largely irrelevant to hydrology at the WIPP site.

To date, 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 (Figure 31), 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,

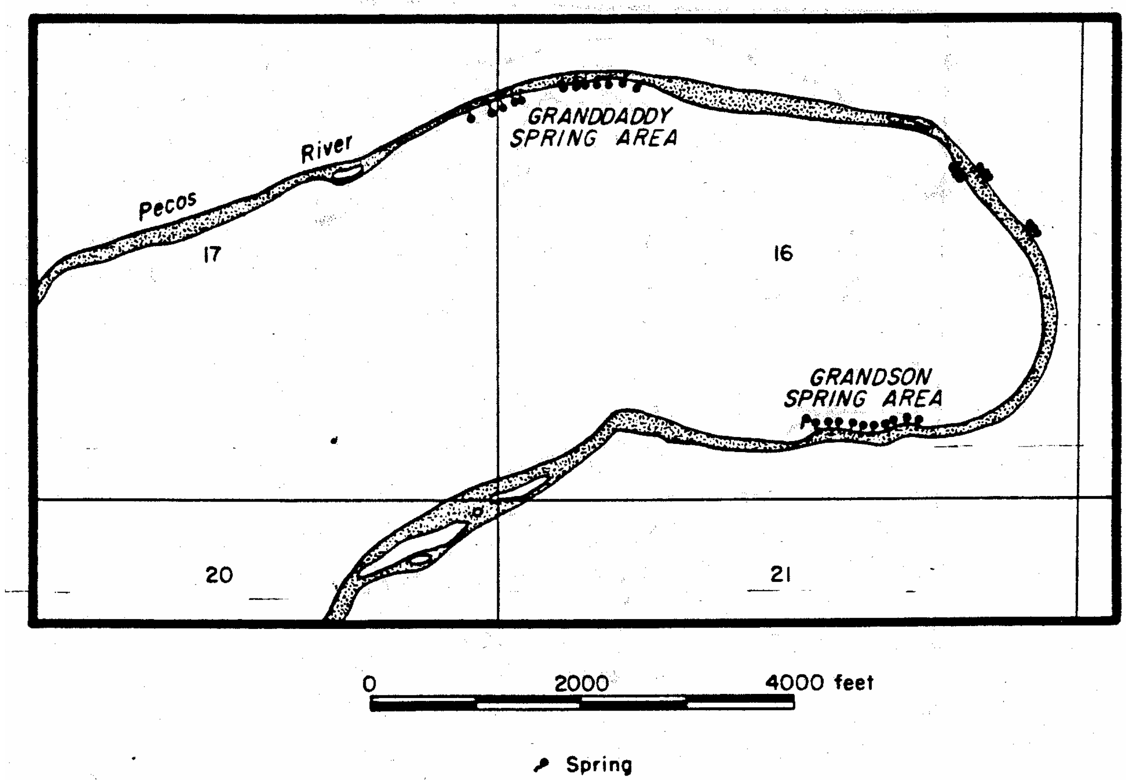


Figure 31. Map of the Malaga Bend Springs (from Chaturvedi and Channell, 1985, their Figure 16/page 44).

Magenta, brine aquifer, and alluvium as a single aquifer for their calculations, calculated that aquifer outflow at Malaga Bend Springs is only about one percent of the total of rainwater precipitated in the potential catchment area. The remaining 99% is lost to evapotranspiration.

8.5.2 Other Discharge Points

Lakes are commonly discharge points for groundwater, and Robinson and Lang (1938) noted that potentiometric head measurements suggest that Rustler ground waters flow towards Laguna Grande de la Sal, making it a possible discharge point. However, they also noted that the chemistry of the lake water is different from that of the local groundwater, and that it is improbable that the lake brine re-enters the Rustler Formation from the bottom of the lake.

Mercer (1983) suggested that Rustler discharge from the Nash Draw catchment might include Surprise Spring at the edge of, or sometimes submerged below, Laguna Grande de la Sal. Geohydrology Associates (1978) believed that two-thirds of the topographic hollows, including local lakes in their study area (centered on Nash Draw) are likely to be sites of groundwater discharge to the surface, as well as, or perhaps instead of, being sinkholes. Hill (2003) cites Snow (2002) as indicating that there may be a point-source karst-type discharge into Laguna Pequena, and Sares (1984) for other karst-type point source discharge locations further south in the Pecos River valley.

These discharge points are plausibly, even probably, sourced in the Rustler Formation, but no definitive data have been collected to indicate what parts of the Rustler are contributing to them. Karst and high hydraulic conductivities in the Nash Draw area contrast with the low hydraulic conductivity Rustler Formation characteristics measured at the WIPP site, and the simplest interpretation is that the discharged waters at Malaga Springs are derived primarily from Nash Draw. Although Hill (1999) suggests that Surprise Springs at the edge of Laguna Grande de la Sal within Nash Draw is a possible discharge point for the Nash Draw watershed including the WIPP site, the connection to WIPP is speculation.

8.5.3 Gypsite "Spring" Deposits

Bachman (1985) suggested that local beds of gypsite (re-sedimented gypsum sand) near WIPP-25 in the eastern part of Nash Draw are evidence that springs drained the upper Rustler Formation from below the WIPP site, discharging at the base of the nearby Livingston Ridge escarpment. Hill (1999, p. 53) took this piece of data and extended it to infer that gypsite springs indicate karst.

Whether or not gypsite springs indicate karst, on closer examination, the gypsite deposits reveal few definitive features that are diagnostic of their origin. Although they are associated with snail fossils (suggestive of damp conditions), and vertebrate bones (of unknown significance), they do not display the travertine-type bedding commonly formed around springs that produce highly mineralized water. Gypsite sand is currently forming in Nash Draw where the primary gypsum/anhydrite beds are exposed to weathering and erosion (Figure 32), but the local active springs are not forming and depositing gypsite.

Some of the gypsite deposits in the area display eolian crossbedding (Figure 33), suggesting that gypsite originated as weathered sands, reworked by winds and deposited as dunes. The gypsite deposits near WIPP-25 probably do not record the locations of spring discharge points for the Rustler, and as such are poor evidence for karst.

Figure 32. Gypsite derived from decomposing gypsum beds under present-day weathering conditions, Laguna Quatro area.

Figure 33. Large-scale, steep-angle crossbedding, typical of eolian sand dunes, in gypsite deposits in a road cut along route NM 128.

8.6 Assessment of Recharge and Discharge Data

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. This supports the hypothesis that water gets from the surface into and through the Rustler, and to the discharge points, but does 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.

9.0 SIGNIFICANCE OF LOCALLY EQUIVALENT CULEBRA AND MAGENTA HEADS

9.1 Introduction

The measured potentiometric heads of the Culebra and Magenta vary regionally, sloping irregularly but generally southward (Culebra, Figure 23) or westward (Magenta, Figure 24). Over most of the area, they are at different levels, showing that the members are individually confined and hydraulically unconnected to each other. The difference between the Culebra and Magenta heads diminishes from as much as 155 ft at the center of the WIPP site to a few feet in the WIPP-25 and WIPP-27 holes in Nash Draw.

Locally, in the vicinity of WIPP-25 in Nash Draw and west of the WIPP site, the measured heads of the waters in the two members are nearly equal. Hill (1999), apparently drawing on Snow's (1998) paper, 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, page 56). Hill then suggests that this implies the development of karst passageways at depth.

Chaturvedi and Channell (1985) have also suggested that there is vertical, karst-related, cross-stratigraphic hydraulic connection between the Magenta and Culebra west of the WIPP site, based on a gradual, westward merging of the potentiometric heads from the two units.

9.2 The Data

The uncertainty ranges on Magenta and Culebra heads do in fact overlap at H-6 and WIPP-25. However, this by itself does not prove that hydraulic connectivity exists between the two members. Implying that it does is an example of using isolated data points out of context. The plane of the Magenta potentiometric head slopes down to the west (Figure 24) and therefore must cross the southward-sloping Culebra regional trend (Figure 23) somewhere. 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 (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 (Figure 21) shows that the degree of actual hydraulic connection is at best low.

At H-6, Mercer (1983, page 61) notes significant differences in sodium chloride concentrations between the Magenta and Culebra in the adjacent test wells H-6a and H-6b: 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 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, 1987c). Lack of connection between Culebra and Magenta has also been repeatedly demonstrated during the WQSP water quality 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.

9.3 Misuses and Mis-citation of Data

Some of the arguments for karst based on hydraulic equivalence of heads in various wells have been muddled by careless use of the data. For example, Snow (1998, 2002), repeated by Hill (1999), cites data from wells H-6, WIPP-13, WIPP-33, and WIPP-25 as evidence of vertical hydraulic connections between the Magenta and Culebra across the Tamarisk anhydrite. However, such data were never obtained from two of these wells: the water levels in the Magenta have never been monitored at WIPP-13, and water levels have never been monitored in either the Culebra or Magenta at WIPP-33. Thus, there is no factual basis whatsoever for Snow's assertions regarding WIPP-13 and WIPP-33; the data from the other two wells have been addressed above.

Some of Snow's conceptual modeling is physically impossible and/or internally inconsistent. For example, if the hypothetical karst channels are located above the present water table as postulated, their effects will not be apparent, and their existence cannot be proven by pumping tests (which can only measure the flow in water-saturated zones) as asserted by Snow. The assertion that the hypothetical karst channels are presently dry also requires that they must be located above the present water table, which is in the siliciclastic Dewey Lake beds. This is inconsistent with the location of the strata that would be prone to karst dissolution, and with the assertions that karsting is located in the Rustler Formation which is below the water table.

9.4 Assessment of Equivalent Heads in the Two Rustler Members

The intersection of the potentiometric heads of the two Rustler members is a localized phenomenon, the inevitable intersection of two non-parallel surfaces, that has no regional significance. Water chemistry and the lack of interference during pumping tests both support hydraulic isolation of the Culebra from the Magenta, and argue strongly against the development of a subsurface karst system within the Rustler Formation at the WIPP site.

10.0 SPATIAL VARIABILITY IN THE CHEMISTRY OF CULEBRA FORMATION WATERS

10.1 Introduction

Hill (1999, p. 64) suggests that spatial and/or temporal changes in water chemistry and salinity are characteristic of groundwater in karst systems, 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. She 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 does not correlate the observed geochemical variations with specific possible point recharge locations, but rather uses only the generalized existence of variable groundwater geochemistry in the Rustler Formation at the WIPP site as evidence for karst. She does not analyze the characteristics of that variation in order to support the karst theory.

10.2 The Data

The variability in water chemistry of the Culebra can be defined in different ways, and the rate at which it changes laterally is an important characteristic for this discussion. Different divisions of the subsurface water chemistry in the Culebra have been previously illustrated in Figures 27 through 29. The three schemes of mapping variations in the water chemistry in the Culebra are basically compatible. The lines drawn on the maps by the authors to divide the geochemical domains are somewhat arbitrary since the chemical composition of the waters changes gradually, explaining variations in the mapped boundaries.

10.3 Scale of Variability

None of the water-chemistry data support the existence of localized pockets of chemical variability associated with large influxes of fresh water through karst sinkholes. The water chemistry varies gradually and on a broad scale (kilometers). No evidence is seen of significant water quality changes between wells tens or a few hundred meters apart, nor are anomalous "pockets" of relatively fresh water found that are surrounded by wells containing more saline water.

Hill cites Chapman (1988) as mapping regions of low salinity and facies changes from Na-Cl to Ca-SO_4 over the region of the H-1, H-2, and H-3 drillholes, but this is a gradual, not an abrupt change. Chapman draws a dotted line at about this location delineating two of the water facies domains (Figure 28); Ramey (1985) draws the boundary between his similar zone A and zone B geochemical water facies a mile or more to the east (Figure 27). The positions of the lines on the map are subjective delineations of broad geochemical domains; they are not indicators of abrupt changes in water chemistry.

In any case, the fact that water-chemistry varies does not necessarily prove the presence of karst at depth. Rather, the characteristics of that variation should be analyzed and compared to measured chemistry variations in known karst systems or to expected variation given modeled rates of fluid flux and the potential reactivity between water and the host rock.

10.4 Possible Causes for Water Chemistry Variability

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-SO_4" is due to the influx of a large quantity of low-TDS water, suggesting recharge through gypsum caves.

While the basic observations may be valid, they do not exclusively imply that therefore halite has been dissolved from the western parts of the study area, or that one can therefore assume that this implies the development of karst. Siegel et al. (1991) also suggested that "A likely explanation for the less saline waters south of the WIPP site is that at the time of influx of the present generation of Culebra ground water from the WNW, Rustler halite was absent adjacent to the Culebra in that area, and did not provide a source of NaCl."

In the absence of sedimentological data, the data showing a change from sodium-chloride to calcium-sulfate waters may be explained in several ways. Two of them are: 1) the removal of halite in the calcium-sulfate area, or 2) 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.

10.5 Assessment of the Significance of TDS Variability in the Culebra

Hill (1999, page 64) suggests that salinity variations are characteristic of karst, and uses the bald, broad fact of salinity variations across the region of the WIPP site, not the specific characteristics of that variation, as evidence for the probable subsurface development of intrastratal karst. Hill uses generalized concepts and theory to suggest that specific interpretations have been proven, an inversion of the more widely accepted scientific process and logic which use specific data to prove or to construct broader-scale interpretations.

The Culebra water chemistry data from drillholes at and surrounding the WIPP site have not been used rigorously to support an interpretation of karsted Rustler Formation in this area. There is variability in the geochemistry of Rustler formation waters, but the scale of that variability is not compatible with the scale or type of variability that would be expected in adjacent holes that sampled both fresh, karst-introduced meteoric waters and saline, long-residence waters. Hill's one example of local extreme variability turns out to be suspect, possibly contaminated data. The variability of formation waters found within the confines of Nash Draw is of a different, more highly variable scale, but both hydrologically and geologically, this is a significantly different area.

11.0 POTENTIAL FOR KARST AT WIPP-13

11.1 Introduction

The cores from several holes (WIPP-13, WIPP-14, and H-3) have been cited by Hill (1999, 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 (Sandia National Laboratories and the U.S. Geological Survey, 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. However, the drillhole penetrated a normal stratigraphic section with only localized, apparent brecciation of a thin sulfate bed within the Tamarisk mudstone unit.

Nevertheless, 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 mere presence of well-test variations, without investigating or analyzing their characteristics, to support an interpretation of karst in the Rustler Formation at this site, and she does not describe stratigraphic relationships or sedimentological characteristics from the core that would allow distinctions to be made between post-depositional, solution-related disruption and syndepositional disruption of bedding.

11.2 Drawdowns

As noted above, Hill (1999, p. 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.

Beauheim also reported several ambiguous responses to the WIPP-13 pumping test in observation well ERDA-9, a mile and a half to the southeast. These included: 1) drawdown was several hundred hours "late" in ERDA-9, suggesting that no high-flow pathway connects the two wells and not suggestive of a rapid-response karst network, although 2) recovery from the drawdown was rapid, possibly indicating rapid recharge from a separate, high-flow source, and 3) "drawdown in the middle of the recovery period (1700 hrs) appeared to be a response to a separate event." The Culebra fluids in the nearby exhaust shaft behaved similarly to those in ERDA-9, "as if a withdrawal of fluid from the Culebra at some location temporarily caused drawdown at the exhaust shaft".

The fact that there are variations indicates anomalies, but of itself does not specify what they are. It is the next level of assessment, i.e., the characteristics of those variations that should be considered before drawing conclusions. It is unclear what type of pressure response to pumping tests Hill and/or Snow would expect from their hypothetical karst channels. The response would be entirely different for fluid-filled or air-filled conduits below or above the water table, respectively, and neither Hill nor Snow are consistent in defining the location of the proposed conduits relative the water table. 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.

11.3 Breccia and Mixing in the Core

Hill (1999, page 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 (page 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^{o} in WIPP-13).” Hill does not indicate the extent of brecciation or the size of the breccia clasts, i.e., how extensive, and therefore how significant, this breccia might be, and infers more significance to this than warranted.

Holt and Powers (1988, page 8-16) describe this occurrence in WIPP-13, indicating that “Collapse, upward stoping, and mixing of clasts derived from various stratigraphic horizons occur in core from WIPP-13 where the deformation is not clearly attributable to Salado dissolution. The lowest deformed unit is A-2 [anhydrite 2] and… the source of at least part of the deformation is within or below A-2…” Hill suggests that this is “exactly” (just above the Culebra) where one would expect karst to form, and “exactly” what she would expect it to look like. This is correct in the sense that it is also exactly where localized, bed-boundary dissolution related merely to the presence of water in the Culebra has been observed; however, it does not imply a widespread karst system. This dissolution horizon is localized adjacent to the Culebra aquifer where it is not unexpected. It is present in other cores, and dissolution has not developed from this into a widespread karst system. The undeformed beds of the overlying strata show that “upward stoping” is of limited vertical/stratigraphic extent.

Holt and Powers (1988, page 8-16) describe a second deformation horizon higher in the section in the WIPP-13 core as “extreme deformation” of the Mudstone-3/ Anhydrite-3 contact (in the Tamarisk Member, between the Magenta and Culebra Members). Examination of the core shows this deformation to be a rearrangement of clasts, and of fracturing and movement of blocks at the base of the overlying anhydrite and within Mudstone-3/Halite-3 itself, but with no indication for the involvement of other stratigraphic zones. Exposures of this unit in the air intake shaft showed definitive evidence (truncated breccias overlain by laminated anhydrite) that the disruption of this unit is syndepositional.

11.4 Summary

The breccias found in the 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 wide-spread karst-type dissolution is not present in the Rustler Formation at the WIPP site.

12.0 POTENTIAL FOR KARST AT WIPP-14

12.1 Introduction

The WIPP-14 drillhole was purposefully 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. Controversy exists over the nature, or at least of the interpretation, of the rocks interrogated by this drillhole. 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. Some of the data have been misinterpreted or mis-used by the karst proponents.

12.2 The Data

12.2.1 Patterns

Phillips (1987, page 209) suggests that the WIPP-14 depression is one of "A chain of ten thickly vegetated topographic depressions…" that he suggests "…are probably related to deep-seated dissolution of the halite and gypsum in the Rustler Formation", and that five shallow, ephemeral "watercourses" drain into this zone. The watercourses supposedly related to this chain are not mapped by Phillips, and no depressions other than at the WIPP-14 site, no trends of vegetation, and no watercourses, were apparent during a low-level aerial reconnaissance over this area in March 2005.

The maps presented by Phillips in support of a correlation between the gravity anomaly and irregular patterns of both "calcareous dissolution residues" and "structural depressions in the [Mescalero] caliche" surface are self-fulfilling. Phillips' maps (his Figures 69 and 70, page 207) show only the patterns of residues and depressions that are within and near the general outline of the gravity contours. Demonstration of an absence of these residues and depressions in areas outside of the gravity contours would be plausible evidence for a correlation, but many of his patterns overlap the edges of, and extend beyond, the gravity zone, suggesting that the patterns are not limited to the depressions. No evidence is presented to demonstrate that the residues and depressions are exclusive to the area of the anomaly.

12.2.2 Normal Lithology

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.

12.2.3 Gypsum

Hill (1999, page 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. The presence of gypsum in these intervals is not unexpected since the Magenta and Culebra are water-bearing, and hydrated anhydrite 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. Gypsum occurs in varying amounts in most of the Rustler sulfate beds across the WIPP site, so the presence of gypsum is not a good indicator of karst.

12.2.4 Mass Deficiency

Hill (1999, page 38) notes that "Barrows et al. (1983) interpreted the mass deficiency (negative gravity anomaly) at WIPP-14 to be due to density variations caused by the hydration of anhydrite to gypsum in the Rustler Formation." Some layers of hydrated gypsum were penetrated in this hole, but without concurrent removal of some of the strata, for which there is no evidence, hydration would add mass to the system, resulting in increased thickness of the beds as well, and which is not observed.

Barrows et al. (1983, page 57 and their Figure 3.2.1-2) suggested that because the overall thickness of the Rustler Formation does not change between drillholes WIPP-34 and WIPP-14 even though some of the member units thicken and thin, the presumed dissolution of strata in WIPP-14 could have been compensated by a volume increase associated with the hydration of anhydrite to gypsum.

This idea was not thoroughly thought through: the mere fact of uniform thickness was offered as sufficient evidence, without exploring the ramifications. No calculations were presented to show whether the volumes of anhydrite in WIPP-34 are sufficient, when expanded by 38% as gypsum forms, to maintain formation thickness in WIPP-14, or that the thicknesses of the gypsum beds in the WIPP-14 hole would be equivalent to the anhydrite beds that could have been hydrated in WIPP-34. No notice was taken of the fact that whereas the Tamarisk Member is indeed thinner in WIPP-14, the underlying Los Medaños Member is *thicker* in WIPP-14, and that therefore the thinning of the Tamarisk could be related merely to diminished sedimentation accommodation space during deposition (i.e., a formation can only be as thick as the depth of the hole in which it is deposited).

Barrows et al. (1983) dismissed lateral facies changes as the possible cause for thickening and thinning of the evaporite facies of the Rustler Formation because the related and less soluble Magenta and Culebra are uniformly thick and "remarkably persistent" across the area, but this is specious geological reasoning. The dolomite layers were deposited in marine environments that are not sensitive to the subtle topography of the depositional surface the way shallow evaporitic salt pans are, and the Culebra and Magenta Members of the Rustler Formation can not be used as standards for the original lateral continuity of all facies.

Barrows et al. (1983 p. 56/Fig. 3.1-3) were also constrained by the gravity survey to model a shallow density change at WIPP-14. Nevertheless, they inferred from log data (comparing the sonic log from WIPP-14 to the "normal" sonic log from WIPP-34) that there should be mass deficiencies in WIPP-14 in the middle of the Dewey Lake Formation, at depths of 350-450 ft, and in the Forty-niner Member of the Rustler Formation at depths of 650-700 ft. The upper interval was continuously cored, the lower partially cored: no evidence of missing material was found in either cores or in the subsequently run geophysical logs.

The apparent mass deficiency calculated by Barrows et al. for the elongate gravity anomaly near the WIPP-14 drillhole can be accounted for by what appears to be a thick interval of the low-density Gatuña Formation in the core at the top of the WIPP-14 hole. This would be a tributary to the deep Gatuña drainage channel mapped by Bachman north of the WIPP site (see Figure 21). Similar thick Gatuña deposits have been encountered on trend with the paleo-valley during recent drilling at SNL-3 (Powers and Richardson, 2004a).

12.3 Misuse of Data

12.3.1 "Mud"

Five cuttings samples in an interval 81.4 ft thick at the top of the Los Medaños Member were recorded in the well records as consisting "mud, dark-reddish-brown (10R ¾)" in the WIPP-14 drillhole (Sandia National Laboratories and D'Appolonia Consulting Engineers, 1982, Table 3, page 31). Three of the five samples also contained anhydrite, gypsum, or siltstone fragments. This record was interpreted as a mud-filled cavern by Phillips (1987), even though the geophysical logs for this interval show an entirely normal signature, including the 10-ft-thick, A-1 anhydrite bed, and a complete stratigraphic sequence that is identical to that found in drillholes nearby.

The designation "10R ¾" refers to a specific reddish-brown color on the Munsell geologic color chart. It is a common color for the Rustler mudstones and shales (see other logged "mudstones" from this hole), and it is easily distinguished from grayish-brown drilling mud. It is most likely that the mudlogger did an unacceptable job of logging the cuttings, and omitted the "-stone" in recording them. No lost returns were noted during drilling, and the drilling parameters, i.e., weight on bit (12,000 lb), pumping pressure (400 psi), and bit rotation speed (100 RPM), were all normal while drilling through this "muddy" interval. There is no support for the alleged presence of an eight-ft diameter cave in the subsurface at WIPP-14.

12.3.2 "No Core"

The graphic image of the lithologic log for the WIPP-14 drillhole (Sandia National Laboratories and D'Appolonia Consulting Engineers, 1982, their Figure 5) labels an uncored 240-ft interval with the term "No Core". This notation was suggested to be evidence of cavernous zones by Snow (1998) based presumably on an interpretation that "No Core" meant that no core was recovered. The interval might have been more clearly labeled as "Not Cored," since, as indicated in the text, no core was cut in this interval. The WIPP-14 hole was not cored continuously, and the zones that the proponents of karst have suggested were zones of lost core are actually intervals that were drilled by conventional rotary drilling, as planned (Sandia National Laboratories and D'Appolonia Consulting Engineers, 1982). The consecutive core numbers (#99 above and #100 below the uncored interval) indicate the logistical rather than geological nature of this section.

12.3.3 Fractures

Some data from the WIPP-14 hole have been presented with invalid interpretations, for example: “Carbonate-filled fractures in the Santa Rosa sandstone beneath WIPP-14 are direct evidence of rainwater infiltration” (Phillips, 1987, page 25). Carbonate filling in fractures can be precipitated from carbonate-rich waters at any depth, and in fact calcite (calcium carbonate) is the most common type of fracture-filling material in geologic strata. Both fractures and carbonate fill have multiple possible origins (e.g., Lorenz et al., 1991). This is an example of the common practice of presenting bald data as tenuous proof of a concept, without an investigation or analysis of the precise meaning of the data being presented.

12.4 Assessment of Karst at WIPP-14

There is no evidence for karst development in the Rustler Formation in the WIPP-14 drillhole. Proponents of karst at this location have misinterpreted annotations in the lithologic log and have ignored critical complementary evidence such as the geophysical logs. The stratigraphic section penetrated by the drillhole has not been disrupted or displaced by karst-related dissolution features. The hydration of anhydrite beds to gypsum is not extensive, and the gypsum beds are found in positions that are consistent with normal hydration adjacent to the Culebra and Magenta water-bearing units. The ambiguous data that have been suggested as evidence of karst do not come from the same intervals of the hole and thus do not support a cross-referenced, integrated concept of karst development in this drillhole.

13.0 POTENTIAL FOR KARST AT H-3

Hill (1999, page 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, 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) suggest that "Features attributable to dissolution of halite and attendant collapse are found within the interval M-3/H-3" in this interval correspond to a highly transmissive zone in the Culebra in the southern part of the WIPP site.

14.0 SUMMARY

Analysis of the primary data suggests that the overwhelming majority of data support an interpretation of fractured but unkarsted strata in the Rustler Formation at and near the WIPP site. There are a few data anomalies of ambiguous significance, and some evidence for local dissolution at the Magenta horizon in the WIPP-33 drillhole, but extrapolation of the known karst features in Nash Draw eastward to the WIPP site, where conditions are and have been significantly different for half a million years, is unwarranted.

Examination of the early geologic studies indicates that although they were valid studies by competent geologists, the state of the science at the time was such that the early conclusions reached by these studies were incomplete. This planted the seeds for future misinterpretation. Interpretations of "insoluble residues" in the cores were based on undeveloped theory, faulty analogy, and severely limited exposures. These early interpretations, however, now constitute an inheritance that interferes with a valid interpretation of these strata in light of more detailed and accurate knowledge of sedimentary environments developed during the last few decades. More recent, better exposures of these strata have documented the presence of primary sedimentary structures, proving that they are primary deposits that have not been subjected to post-burial dissolution. Most of the observed disruption of bedding can be related to syndepositional desiccation and cracking, and to limited dissolution along bedding planes during the minor flooding events which initiated each cycle of deposition.

Topographic depressions near the WIPP site that have been cited as being the probable locations of sinkholes are few, and the data that have been cited to interpret these depressions as sinkholes have been taken out of context and have other, more scientifically valid and better supported interpretations. The characteristics of these few supposed sinkholes are not similar to the characteristics of unambiguous sinkholes, which pirate drainage systems in Nash Draw to the west.

The stratigraphic thinning commonly cited as evidence of dissolution of the Rustler Formation at the WIPP site is in fact related to dissolution only in the immediate vicinity of Nash Draw. This dissolution-related thinning overlaps with and obscures the depositional thinning and thickening that is common to the Rustler Formation across the Delaware Basin, and which was caused by the irregular Permian depositional topography.

Rustler halites were deposited in shallow depressions ("pans") on this depositional surface at the same time that muddy deposits were accumulating at the margins of the pans, and this lateral facies equivalency, a well documented and founding principle of stratigraphy, caused most of the sedimentary patterns that are mistakenly cited as evidence for post-depositional dissolution and removal of halite from the thinner parts of the Rustler Formation in the vicinity of the WIPP site. The larger extents of the dolomite layers are not evidence for the original extents of the halite layers since the dolomites were deposited in much deeper waters that were not affected by the low-relief topography of the depositional surface. It would be impossible to obtain the observed thicknesses of muddy and silty deposits that have been called "residues" by dissolving the limited available volume of muddy and silty halite. Moreover, the silty and muddy beds do not contain evidence of other insoluble remnants that are common in the thicker halite beds.

The concept that Nash Draw is the largest of a series of sequentially smaller karst-related conduits that should extend eastward under the WIPP site is fallacious. Nash Draw formed under exceptional circumstances, during rapid erosion of the Rustler evaporite deposits exposed at the surface by a local, large drainage system during Pleistocene time. There was no equivalent to this at the WIPP site, where the Rustler Formation was and is deeply buried, thus the homogeneous medium and uniform conditions required for the development of such an ordered system were not obtained.

The existing drillholes, though small in diameter, are sufficient to assess the probability of karst at the WIPP site, since the karst should have developed preferentially along the numerous horizontal fractures present in the Rustler Formation and since the probability of hitting a horizontal plane with a vertical drillhole is high. The large-diameter shafts excavated into the WIPP repository have provided a large subsurface sampling, at a location where significant dissolution was hypothesized to have occurred and which should have had a high probability of intersecting evidence for that dissolution. In fact, the shafts offer evidence only for primary deposition unaffected by later subsurface dissolution, and that evidence is definitive.

The general absence of dissolution, karsting, and related conduits is corroborated by the pumping tests which have interrogated large volumes of the Rustler Formation between drillholes. These tests have not revealed evidence for karst-related, channel or conduit flow. Rather, they suggest that the Culebra and Magenta Members have relatively low conductivity, but with local indications of low-volume/high conductivity flow that is probably influenced by natural fractures. Diffusion calculations indicate that it would be virtually impossible to have separate isotopic signatures for the water found in the fractures and the water found in the pores of the matrix rock between fractures, as suggested to explain the isotopic evidence for ancient formation waters by the proponents of karst.

The various geophysical techniques run in the vicinity of the WIPP site show a number of anomalies, but the anomalies do not overlap to portray consistent and mutually supporting patterns that could be definitively related to specific locations for karst-related void space at depth. The most prominent anomaly, the WIPP-14 gravity anomaly, is a curved, linear feature that may be due to the presence of thick, low-density deposits of a local Gatuña tributary system.

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.

Recharge, flow, and discharge of water in the Rustler Formation are largely theoretical. Few direct measurements or observations of this flow are available except for the brine discharge from springs at Malaga Bend on the Pecos River, and this discharge is probably from the brine aquifer at the Salado-

Rustler contact, and limited to drainage from Nash Draw. The springs do not support the existence of a karst system in the Rustler Formation at the WIPP site.

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.

The evidence for karst in drillholes WIPP-13, WIPP-14, H-3, and H-6 is spurious: many of the breccias in the core are due to synsedimentary disruption of bedding, and the more severe breccias are found where they are most likely to be related to localized dissolution, adjacent to the Magenta and Culebra water-bearing units. The significance of the few well-test variations is ambiguous, but the mere fact of variations does not prove the presence of karst as suggested; their characteristics must be analyzed.

The proponents of karst in the Rustler Formation at the WIPP site tend to mix data, to take data out of context, and to offer theory as fact and to continue to offer misconceptions in the face of evidence. They do not analyze the data or synthesize it into a mutually supporting framework. Hill commonly used the existence of an anomaly rather than the specific characteristics of that variation as evidence for the probable subsurface development of intra-stratal karst, and has used generalized concepts and theory to suggest that specific interpretations have been proven. This is an inversion of the standard and more widely accepted scientific process that uses specific data to prove or to construct broader-scale interpretations.

When the specific data cited by the proponents of karst at the WIPP site are examined, they are commonly non-unique in their possible interpretation. More plausible, less complex interpretations are usually possible. The data are cited randomly rather than being assembled into an interlocking and mutually supporting scientific case for the presence of karst in the subsurface Rustler Formation at the WIPP site.

The case for karst development in the Rustler Formation has not been advanced or proven. Rather, the data suggest that most of the subsurface evaporitic strata of the Rustler Formation at the WIPP site have not been subjected to dissolution since the time of deposition.

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