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# ASSESSMENT OF THE GEOLOGICAL EVIDENCE FOR KARST IN THE RUSTLER FORMATION AT THE WIPP SITE

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**Abstract.—**This paper assesses the geological evidence that has been offered for the presence of karst in the subsurface at the Waste Isolation Pilot Plant (WIPP) site. Most of this evidence has been used uncritically and out of context, and does not form a mutually supporting, scientifically defensible framework. Plausible evidence for subsurface dissolution is limited to the water-bearing Magenta Member in drillhole WIPP-33. The remaining evidence is more readily interpreted as primary sedimentary features. Thinning and thickening of Rustler strata, and lateral lithologic variations from halite to mudstone, are primary depositional patterns related to lateral sedimentary facies changes across the WIPP site rather than evidence for post-depositional dissolution. Some of the evidence offered in support of dissolution is inherited from early interpretations made prior to the knowledge of modern evaporite depositional environments, and prior to the existence of definitive exposures of the rock in the WIPP shafts which show undissolved, primary depositional features. Holes drilled to investigate the subsurface strata at the sites of proposed sinkholes do not support karsting of the Rustler Formation. Extrapolation of the known karst features in Nash Draw eastward to the WIPP site is unwarranted.

## INTRODUCTION

The Rustler Formation overlies the nuclear waste repository excavated in the Salado Formation at the Waste Isolation Pilot Plant (WIPP) site in southeastern New Mexico. Among others, Hill (C. A. Hill, unpubl. report for Sandia National Laboratories, 1999; 2003) has proposed that karsted layers may be present within the Rustler Formation, which has implications for waste containment. The evidence for karst development in the Rustler Formation is assessed in this paper, using the published data but separating descriptions from interpretations. An attempt has been made here to assess whether interpretations of karst in the Rustler Formation at WIPP are proven, probable, plausible, merely possible, or even untenable. This paper is the distillation of a more comprehensive report (Lorenz, 2006).

The gently dipping Late Permian strata at the WIPP site in southeastern New Mexico (Fig. 1) have been truncated by erosion, with successively older units exposed at the surface to the west. The Rustler Formation is exposed at Nash Draw, west of the WIPP site, where exposure has led to dissolution and erosion of the local evaporitic strata. East of Nash Draw and across the WIPP site, erosion has beveled but has not completely removed the clastic strata of the overlying Dewey Lake and Triassic Santa Rosa Formations.

## GEOLOGIC EVIDENCE AND THE CONCEPT OF KARST AT WIPP

The lateral variability within the evaporitic to muddy Forty-niner, Tamarisk, and Los Medaños Members of the Rustler Formation (Fig. 2) contrasts with the lateral homogeneity of the intervening, dolomitic Culebra and Magenta Members of the formation. Thinning and lateral heterogeneity are some of the lines of evidence that have been used to suggest that karst is present in the Rustler Formation in the subsurface at the WIPP site.

Hill (C.A. Hill, unpubl. report for Sandia National Laboratories, 1999, p. 3-5; 2003, p. 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

These are not "characteristics" in a strict sense of the term, and they are not definitive. The fact that a feature can form in any position relative to the water table, points 1 and 3, does not help to define it. "Widespread," point 5, is a subjective term. Obscuration, points 2 and 4, is key for Hill, leading to the argument that a lack of specific evidence for karst at WIPP supports the possibility that it is present.

### Geologic Evidence for Karst at the Surface

A variety of unrelated local, surficial features have suggested to several authors, as summarized by Hill (C.A. Hill, unpubl. report for Sandia National Laboratories, 1999, 2003), that karst may be developed in the subsurface at and near the WIPP site. In

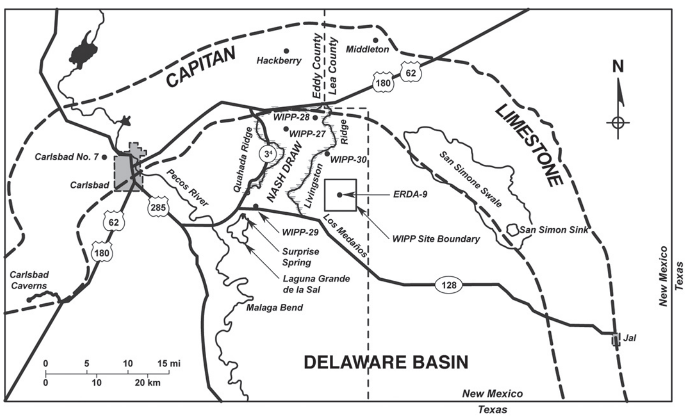


FIGURE 1. Location map for the WIPP site, southeastern New Mexico (from Siegel et al., 1991).

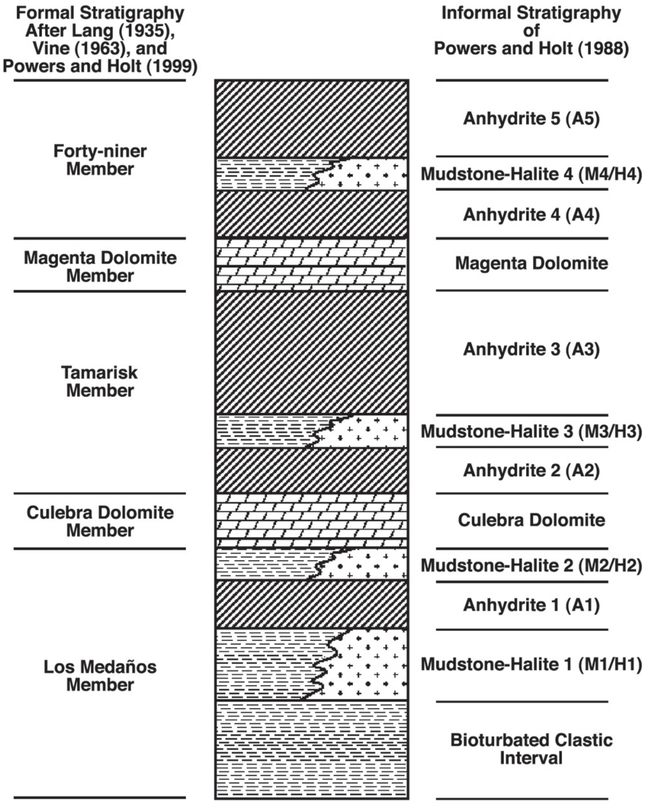


FIGURE 2. Stratigraphic nomenclature and schematic lithology of the members of the Rustler Formation.

extrapolating the widely recognized karst sinkholes, caves, and collapse features that are present at Nash Draw eastward to the WIPP site. Hill (C.A. Hill, unpubl. report to Sandia National Laboratories, 1999) suggests that 1) local 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), enters one of these topographic depressions where surface drainage is captured by the inferred subsurface karst conduit system.

## Nash Draw

The surface depression of Nash Draw is about 20 miles long and 5-12 miles wide. It lies several miles west of the WIPP site (Fig. 1) and is generally agreed to have been caused by the removal of evaporites by weathering, dissolution, and erosion from the partially exposed Rustler Formation and from the upper parts of the underlying Salado Formation (Bachman, 1981, 1985, 1990; Mercer, 1983). Recognizable karst features in and immediately around Nash Draw include caves, sinkholes, fractured and brecciated strata, and saline springs. 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 beds that were originally interbedded with the halite and anhydrite/gypsum units.

Bachman (1985) determined that Nash Draw began to form when erosion by westward-flowing streams unroofed the soluble evaporitic units of the Rustler Formation 500,000-600,000 years ago. The process is still active but at a much slower rate (Bachman, 1981). 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 just because the soluble strata are there and because globally such strata often have karst features superimposed onto them (Phillips, 1987), 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.

## Topographic Depressions East of Nash Draw

Hill (C.A. Hill, unpubl. report for Sandia National Laboratories, 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 should thus have been disrupted. However, wells drilled in these depressions to sample and test for karst have encountered neither vertically displaced strata nor extensive breccias. Hill (C.A. Hill, unpubl. report for Sandia National Laboratories, 1999: her fig. 8, p. 18 and fig. 17, p. 41) draws a hypothetical, funnel-shaped dissolution structure to explain why the wells could have missed evidence for karst, and suggests that karst is likely in the subsurface since the wells must have missed the evidence. A funnel-shaped geometry is incompatible with the cylindrical shape common to most sink-hole collapse features, and the funnel shape, widest at the top, is unlikely at WIPP since this is the level of the low-solubility sandstone, siltstone, and shale layers that overlie the Rustler Formation.

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 is found in Phillips' 1987 PhD dissertation, cited extensively by Hill (C.A. Hill, unpubl. report for Sandia National Laboratories, 1999). This work focused on the Mescalero Caliche, the uppermost layer of lithified strata at the WIPP site. Inhomogeneities are common in this unit and in caliches in general. Caliches are calcareous hardgrounds formed by soil-producing processes, and commonly develop pipe-like features as they age due to rooting by plants and to other deposition/dissolution processes that form these layers (e.g., Bachman and Machette, 1977).

Phillips (1987) suggests that some of the depressions found in the caliche surface at the WIPP site formed due to collapse or subsidence into voids left by dissolution of underlying soluble rocks. Phillips documented broken, solution-pitted, and displaced layers of caliche in hand-augered test holes as deep as seven meters. He did not present evidence that there are solution caverns in the deeper Rustler strata, but rather inferred this from his study of the caliche. However, the mechanical significance of his documented relationship between surface topography and the underlying rock is not clear. His hypothesis of solution voids in the deeper Rustler Formation remains hypothetical because the depth of investigation was less than ten meters (trenching and auguring); the depth of the proposed karsted horizon is nearly 100 m and separated from the studied caliche layer by thick sandstones of the Santa Rosa and Dewey Lake Formations. The significance and reliability of Phillips' subsurface datum (a horizon defined by the first intersection by the auger of either caliche or sandstone) are ambiguous at best, since a combination datum such as this does not represent either a structural or a time horizon.

Phillips suggests that an alignment (a "chain": 1987, p. 74, 82, 122) of three depressions near WIPP-33 might be indicative of the solution that can occur along linear fault trends. These depressions are shallow, the deepest being about eight feet deep and a few hundred feet wide (Fig. 3). One of the depressions is only two feet deep, and it is not clear that this is significant relative to the surrounding topography. Hill (C.A. Hill, unpubl. report for Sandia National Laboratories, 1999, p. 53) believes 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." This is an over-interpretation of the data, and in fact, only three of the depressions (not including the largest) are aligned.

Phillips (1987), Barrows (L.J. Barrows, unpubl. memo to W. D. Weart, 1982), and Barrows et al. (1983) have provided the primary discussions cited by Hill (C.A. Hill, unpubl. report to Sandia National Laboratories, 1999) in suggesting that these hollows accommodate disappearing streams or "dolines." Although Hill's reports imply that such features are common at the WIPP site, only the one supposedly feeding the WIPP-33 depression has been mapped. This example is much smaller and less well defined than the dolines found in Nash Draw. Phillips' map of the arroyo shows it entering one depression, then implausibly flowing uphill to cross the shallow divide into the nearby WIPP-33 hollow.

The poorly constrained rate of disappearance of water from these depressions after a storm has also been offered as evidence that they are dolines. Phillips, apparently using 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 subterranean, karst-related drain at the bottom, and that the water seeped slowly into the surrounding sandy deposits. In contrast, surface drainage that disappears into several obvious sinkholes in nearby Nash Draw is well defined (Fig. 4), and water there does not pond after storms.

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 is as easily explained by the flat-lying topography, by drainage disruption during migration of sand dunes into the area, now partially stabilized, and by the low level of annual precipitation which rarely contributes enough water to the surface drainage system to clear dune sand from shallow drainages.

**Geologic Evidence for Karst in the Subsurface**

Hill (C.A. Hill, unpubl. report for Sandia National Laboratories, 1999) cites theory and circumstantial evidence to build the case for subsurface karst at the WIPP site. However, most of this evidence is indirect, few of the actual data have unique interpretations, and some of the evidence is inconsistent with other evidence. The geologic evidence offered by Hill consists of:

1. Cores from the Rustler Formation that contain layers that have been interpreted by early workers as solution breccias and as "insoluble residues."
2. Basin-scale stratigraphic thinning of the Rustler, and stratigraphic intervals that contain halite in some areas but that

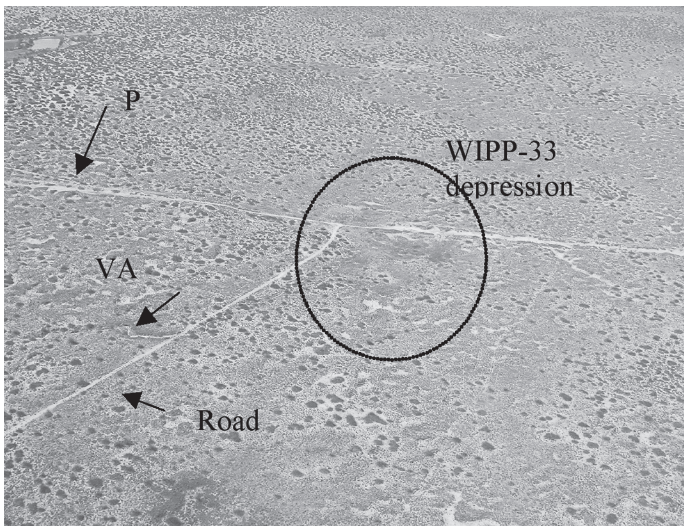


FIGURE 3. Low-angle aerial photograph, looking southwest. Drillhole WIPP-33 is located at the junction of the east-west road and the pipeline. Note the absence of well-defined drainages entering the area, and compare to Figure 4. P = pipeline; VA = Phillips' "vanishing arroyo."

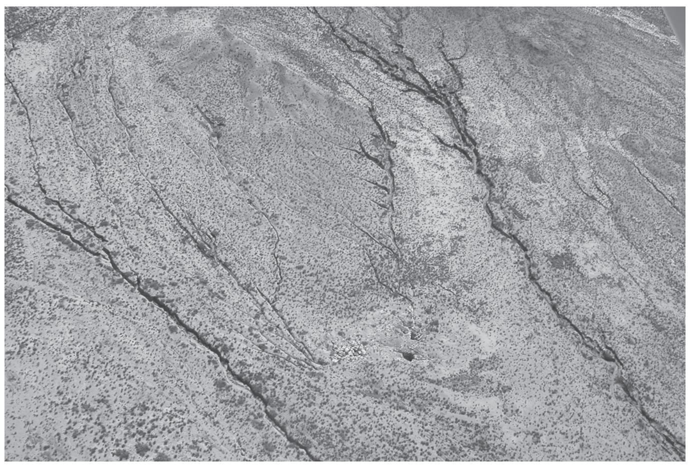

FIGURE 4. Low-angle aerial photograph of diverted drainage, vanishing streams, and the open sinkholes that capture them, in the Forty-niner Member of the Rustler Formation exposed in Nash Draw, for comparison with Figure 3.

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 caused by karst-related caves.

**Insoluble Residue and Disrupted Strata**

Several subtle but important problems are inherent in accepting the interpretations of many of the early geologic investigators at face value, as has been done by the proponents of karst in bolstering their arguments. Many of the early geologists (e.g., Vine, Jones, Gard) published their interpretations prior to the proliferation of studies of modern sedimentary depositional environments in the late 1960's and 1970's, and thus did not have the background to recognize and correctly interpret the definitive signatures present in the evaporites of Rustler cores and outcrops.

For example, Gard (1968), laboring under the prevailing theory that bedded halites were deposited in sub-aqueous marine environments, hypothesized a cumbersome and implausible system of repeated, localized, and temporary uplifts during Salado deposition in order to explain evidence he found for subaerial exposure (desiccation cracks and truncated bedding) in the Salado halites in the Gnome shafts. More recent studies (e.g., Smoot and Lowenstein, 1991; Harville and Fritz , 1986; Powers and Holt, 2000), have shown that, in fact, modern halite deposits and many of the thick Ochoan evaporites were deposited in irregularly exposed and flooded salt pans which were primarily subaerial and only marginal to marine environments, explaining Gard's data much more simply and plausibly.

Most of the early WIPP geology reports also used geological conventions that blurred the distinctions between basic data and interpretations. Rustler lithologies that are dominated by siliciclastics were called "dissolution residues," which is an unsupported, interpretive description that has become entrenched in the literature, causing confusion among later authors who have assumed that the interpretation is valid. In fact, the mere presence of a layer of insoluble clay, silt, or sand 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, although this interpretation is commonly cited uncritically by proponents of karst.

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, and which is generally accepted to be a remnant left-over from the *in situ* dissolution of approximately 100 meters 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 this much detail in support of the genetic interpretation implied by the term. Jones' description is a minimum standard to which all supposed residues should be compared.

An important example of the misuse of the term "insoluble residue" is the Ferrall and Gibbons (1980) description of cores from the Rustler Formation from WIPP-19 and related boreholes. Ferrall and Gibbons (1980, p. 3) recognized six rock types in the Rustler cores: "anhydrite, gypsum, halite, solution residue, dolomite, and siltstone." Only "solution residue" is not an objective lithologic descriptor. In fact, Ferrall and Gibbons commonly put quotation marks around the term "solution residue", suggesting that they were uncomfortable with the term and were using it simply as a shorthand notation, and they specifically state (1980, p. 22) that they applied the term to several units that they did not consider to be residues because the units "have been leached and are residues in other boreholes," although no evidence or references were provided to support the inference of leaching in those holes either.

Nevertheless, Hill (C.A. Hill, unpubl. report for Sandia National Laboratories, 1999, p. 50-52) draws heavily on the Ferrall and Gibbons short-hand interpretation of beds as insoluble residues even though Ferrall and Gibbons were indiscriminate in their application of the term "residue," and their interpretive descriptions are not a valid basis for supporting theories of karst at the WIPP site. Nothing in the Ferrall and Gibbons (1980) report resembles Jones' (1973) description of a residue. 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. Halite should be rare to absent in a true residue since a residue forms by the removal of halite, yet halite cement and even crystalline halite are present in all these siltstone units. Moreover, clay is volumetrically the most common insoluble material incorporated into halite beds, whereas most of the residues so-labeled by Ferrall and Gibbons are composed of silt.

**Timing of Dissolution**

The only potential evidence for definitive solution 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. However, such blocks are also commonly incorporated into evaporite strata by disruption of bedding during the normal course of deposition (e.g., Handford, 1982; Lowenstein, 1988; Powers and Holt, 2000). Gypsum and halite commonly grow displacively in the immediate subsurface in poorly consolidated silts and muds in evaporitic environments, destroying bedding and sedimentary structures. In addition, teepee structures and desiccation cracks can disrupt primary bedding to depths of several meters. When these features are buried and then cored, the strata can look like they were brecciated by post-depositional dissolution. Disrupted bedding is not unique to dissolution, and, without extensive characterization, its mere presence or absence does not provide a solid basis for extensive interpretation.

A residue, if properly interpreted as such, can secondarily be used to decipher the timing of dissolution, i.e., whether it either took place soon after deposition or occurred at depth within the stratigraphic column eons later. Both are valid processes, but the mere interpretation of a rock unit as a residue does not address the timing of dissolution, as often implied by karst proponents. The sedimentary structures reported at WIPP, such as the bedding-plane truncation of bottom-growth evaporite crystals and of up-turned bedding at desiccation cracks (i.e., Powers and Holt, 2000) strongly support an interpretation of syndepositional dissolution. These structures had been noted locally before, but were definitively described only after the new, unparalleled exposures of the Rustler Formation were revealed by excavation of the large-diameter shafts at the WIPP site (Holt and Powers, 1984, 1986, 1990). These authors document definitive, primary sedimentary textures that have usually been obscured or even destroyed by weathering in outcrop, and that are too large to have been recognized in core.

Tim Lowenstein, a widely recognized evaporite sedimentologist who works on both modern and ancient depositional environments and who developed many of the modern sedimentary interpretation techniques, was asked by the State of New Mexico to assess the evidence for post-burial alteration and karsting of the Rustler Formation. Lowenstein (1987) did not reach a definitive conclusion, noting instead that the individual geological features present in the cores are “not unequivocal” (p. 32) in being diagnostic of “late-stage alteration,” and 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 (C.A. Hill, unpubl. report for Sandia National Laboratories, 1999; 2003). However, Lowenstein’s descriptions of truncated halite crystals at syndepositional flooding surfaces (1987, p. 16) support synsedimentary dissolution, and the term “insoluble residue” is notably absent from Lowenstein’s report.

## Stratigraphic Thinning of the Rustler Formation and “Missing” Halite

Hill (C.A. Hill, unpubl. report for Sandia National Laboratories, 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 the area of known dissolution at Nash Draw. Snyder (1985) suggested that more halite, progressively deeper in the Rustler section, has been dissolved westward, and Hill (C.A. Hill, unpubl. report for Sandia National Laboratories, 1999; 2003) used this hypothetical trend to suggest that karst is probable in the Rustler at WIPP. Snyder’s meager and somewhat circular evidence consisted of 1) the fact that the Rustler Formation thins westward, 2) that it contains little halite in the western locations, and 3) the observations that much of the anhydrite has been converted to gypsum in WIPP-25 (located in Nash Draw where dissolution is not questioned).

Although dissolution is an obvious process at Nash Draw, it is not the only process capable of thinning the formation. 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 to local variations in subsidence that accommodated the deposition of thicker or thinner evaporite beds (Fig. 5). 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.

In fact, Snyder and Gard’s hypothesis was definitively tested and disproven when the large-diameter shafts were excavated near the center of the WIPP site. These shafts are located where isopachs of the Rustler Formation show a dramatic thinning, from 485 ft in a well five miles to the east, to 309 ft thick in the shafts. This is a difference of 176 ft, or 36% (see the isopach maps in Holt and Powers, 1988). Moreover, the shafts are located in the zone where Snyder (1985) specifically suggested that halite should have been removed by subsurface dissolution from both the middle (Tamarisk) and upper (Forty-niner) Members of the Rustler Formation. The shafts should have shown good evidence for this dissolution if karst is present, because they were cleaner and more extensive than any previous data from either outcrop or cores, and thus showed important sedimentary details. However, the characteristics of the Rustler Formation in the shafts (Holt and Powers, 1984, 1986, 1990) document a normal, primary depositional sequence. Thus, formation thinning by itself is not good primary evidence for subsurface dissolution and karst as suggested by Snyder and Gard (1982) and as advocated by Hill (C.A. Hill, unpubl. report for Sandia National Laboratories, 1999; 2003).

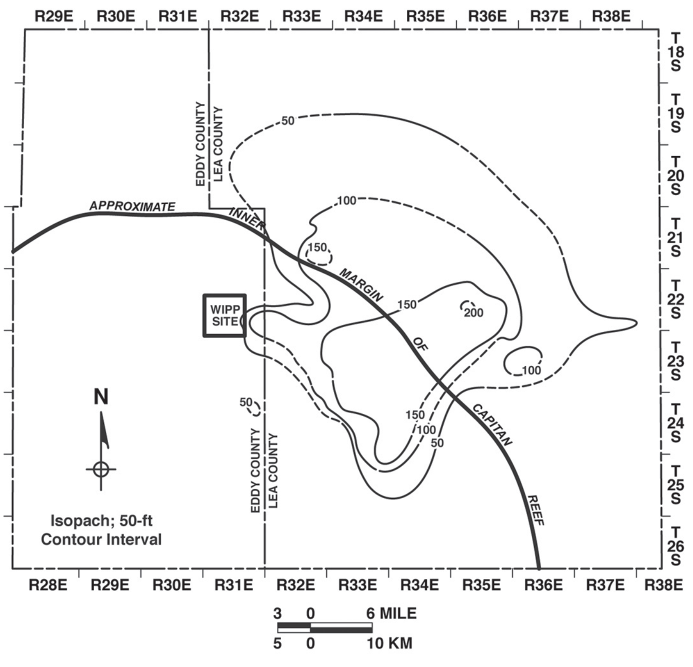


FIGURE 5. Isopach map of the Mudstone/Halite-3 interval of the Tamarisk Member of the Rustler Formation, showing thinning in all directions and indicating that thinning is a function of deposition rather than dissolution (from Powers and Holt (1990), their fig. 26/p. 102). Similar patterns are present in most halite members of the Rustler Formation.

### The Concept of Depositional Facies

Lateral transitions from one lithology to another along a given horizon occur with or without formation thinning in the Rustler Formation. Hill uses such transitions to suggest that "where these residues/breccias exist, corresponding anhydrite rock has been removed" because many of the "residues" occupy approximately the same stratigraphic position (relative to the dolomitic Magenta and Culebra Members) as anhydrite and halite beds in other holes. This ignores the established geological principle of lateral, depositional facies equivalencies, using instead an out-dated and simplistic concept of layer-cake stratigraphy. Most commonly recognized in clastic and carbonate sequences, models of lateral, depositional, facies equivalents are equally valid in evaporites, where halite can be the lateral depositional equivalent to mudstone.

### Volume Constraints

Volumetrically, the total thicknesses of beds labeled as insoluble residues in Rustler cores can not have been reasonably derived from the available volume of halite and its typical percentage of insoluble material (Powers and Holt, 2000). A quick estimation suggests that the cumulative thickness of the massive silty beds labeled as "residues" by Ferrall and Gibbons (1980) in WIPP-19 is over 15 m. 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 15-m residue would require the dissolution of a cumulative thickness of 500 m of halite. This is unreasonable considering that the total thickness of the Rustler Formation, including the non-halite lithologies, is only 100-150 m. The Forty-niner mudstone is about 7-8 m thick at the WIPP shafts. At its thickest, the stratigraphically equivalent halite in drillholes to the east and southeast is about 12-14 m ft thick, and nearly pure. It is unreasonable to infer that a 7-m-thick mudstone was derived from dissolution of 12 m of nearly pure halite.

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

Perhaps the least ambiguous evidence for some degree of subsurface dissolution 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 subsurface conduits related to karst in the Rustler Formation at this site (e.g., C.A. Hill, unpubl. report for Sandia National Laboratories, 1999; Phillips, 1987; L.J. Barrows, unpubl. memo to W. D. Weart, 1982). The drilling records for this hole (Sandia National Laboratories and the U.S. Geological Survey, 1981), show that the bit drops occurred only while coring the basal Forty-niner and the top of the underlying Magenta Member. The four 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, three-meter "cavity" near the bottom of the Dewey Lake section alluded to by Philips (1987, p. 16, 50) consists only of notations of "lost circulation" and rapid drilling rates on the imprecise Geolograph from the drill rig floor, and is not supported by any record of an actual bit drop.

Fourteen cores were cut in the Forty-niner/Magenta and Culebra intervals, with poor 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 intervals of drilling ahead without cuttings or mud returns to the surface. The record briefly mentions but does not describe or explain "lost dolomite" in the Magenta interval, and anhydrite that has been hydrated to gypsum.

However, 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. The caliper log that was run in the hole after drilling showed that the hole diameter exceeded 15 inches in only two of the bit-drop zones, encompassing less than 9 ft of the hole.

*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 lateral extent of the voids is debatable. However, void space and poor recovery of core are not unique to karst intervals; they are also common where the cored material is broken by fractures or faults. Drilling operations through evaporites can even create their own local solution cavities if the mud is not properly maintained at full saturation while drilling. More telling, perhaps, is that the porosity encountered in the WIPP-33 hole, while allowing drilling fluids to seep out and making drilling difficult, was not so large or so well developed that it allowed drilling fluid to completely drain away, which would have made drilling with fluids impossible. This lost circulation was in fact controlled by the use of standard oil-field lost-circulation material (the "LCM" noted in the drilling reports). Typical LCM consists of relatively small bits of things like cottonball hulls and/or walnut shells that can be pumped down a hole. Material of this size would not be capable of preventing lost circulation where the voids are extensive or much more than centimeters to a few tens of centimeters in scale.

The data from WIPP-33 provide direct evidence for subsurface void space, but they are not quantitative. WIPP-33 is an isolated data point and the bit-drop evidence comes only from a limited stratigraphic level. There are no data for similar voids in the nearby holes, and there is no evidence for an interconnected subsurface karst network.

It is unclear whether Hill suggests that surface depressions such as that at WIPP-33 are caused by collapse into karst voids in the underlying Rustler strata or whether she infers that the depressions result from large-scale dissolution of the sandstone layers nearer to the surface. Regardless, neither theory is supported by the data. The latter case is improbable since the Triassic and Permian siliceous sandstones, siltstones, and claystones that underlie the thin recent deposits are largely insoluble. 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 recognized in the holes drilled to test these structures, and the holes have encountered neither.

**Potential for Karst at WIPP-14**

The WIPP-14 drillhole was purposefully sited to investigate whether or not a circular surface topographic depression, about 200 m in diameter, 3 m 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. The controversy that exists over the nature of the rocks interrogated by this drillhole typifies the poorly constrained discussion over data from this and other drillholes.

Hill (C.A. Hill, unpubl. report for Sandia National Laboratories, 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. Phillips (1987, p. 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 trends of vegetation, no watercourses, were apparent during a low-level aerial reconnaissance over this area in March 2005.

Maps of this area presented by Phillips in support of a correlation between the gravity anomaly and the irregular patterns of both “calcareous dissolution residues” and “structural depressions in the [Mescalero] caliche” surface are self-fulfilling. Phillips’ maps (his fig. 69 and 70, p. 207) show only the patterns of the depressions that are within and near the general outline of the gravity contours. Demonstration of an absence of these 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.

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, p. 1; Sandia National Laboratories and D’Appolonia Consulting Engineers, 1982). The lithology penetrated by the rest of the hole was reconstructed from cuttings and the geophysical logs. The core and logs from the WIPP-14 drillhole document a normal stratigraphic section at this location, i.e., the stratigraphic tops have not been displaced relative to their expected depths projected from nearby control points, and bedding is in a normal, flat-lying attitude (Sandia National Laboratories and D’Appolonia Consulting Engineers, 1982; Bachman, 1985). The daily drilling reports and the geologist’s lithologic log record no unusual lost-circulation or fluid-entry zones, and core-recovery percentages were consistently high. The geophysical logs run in the hole also indicate normal lithologies, normal depths, and no anomalous hole diameters.

Hill (C.A. Hill, unpubl. report for Sandia National Laboratories, 1999, p. 38) suggests that the WIPP-14 borehole “did not intersect karst, but it did intersect 9.5 ft of gypsum and 10 ft of gypsiferous anhydrite in the Forty-niner Member directly overlying the Magenta dolomite”, and that this is the same interval of the bit drops encountered when drilling WIPP-33, “where one should expect to find karst.” The lithologic log for this hole (Sandia National Laboratories and D’Appolonia Consulting Engineers, 1982, Table 3) shows that gypsum and gypsiferous anhydrite were indeed encountered above both the Magenta and Culebra units, but this would not be unexpected since the Magenta and Culebra are water-bearing, and hydrated anhydrite in these positions is not unusual. The presence of gypsum is not a strong argument for karsted Rustler in this drillhole.

Hill (C.A. Hill, unpub. report for Sandia National Laboratories, 1999, p. 38) also 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.” However, without concurrent removal of some of the strata, for which there is no evidence, hydration should add mass to the system, resulting in a gravity high as well as increased bed thicknesses.

Barrows et al. (1983) dismissed lateral facies changes as the possible cause for thickening and thinning of the evaporite facies of the Rustler Formation at WIPP-14 because the related and less soluble Magenta and Culebra units are uniformly thick and laterally persistent across the area. This is a specious geological argument: the dolomite layers were deposited in marine environments that are not as sensitive to the subtle topography of a depositional surface as are evaporites in shallow salt pans, thus using the Culebra and Magenta Members of the Rustler Formation as standards for the original lateral continuity of other facies is an apples-to-oranges comparison.

Five cuttings samples in the WIPP-14 drillhole, in an interval 81.4 ft thick at the top of the Los Medaños Member, were recorded in the well records as consisting of “mud, dark-reddish-brown (10R ¾)” (Sandia National Laboratories and D’Appolonia Consulting Engineers, 1982, Table 3, p. 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 and a complete stratigraphic sequence that is the same as that found in nearby drillholes.

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 and it is easily distinguished from grayish-brown drilling mud. Why the mudlogger omitted the “-stone” ending of “mudstone” in describing what were, after all, cuttings samples, is unknown. No lost returns were noted during drilling, and the recorded 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 this interval. There is no support for the alleged presence of a large cave in the subsurface at WIPP-14.

Finally, the lithologic log for the WIPP-14 drillhole (Sandia National Laboratories and D’Appolonia Consulting Engineers, 1982, their fig. 5) labels an uncored 240-ft interval with the term “No Core.” This notation was suggested to be evidence of cavernous zones by Snow (D.T. Snow, unpubl. report for NAS Committee on WIPP, 1998), presumably because he interpreted that "No Core" meant that no core was recovered. The interval should have been 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 to be zones of lost core are 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) confirm the logistical rather than geological nature of this section.

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 is found in positions that are consistent with expected hydration adjacent to the Culebra and Magenta water-bearing units. The ambiguous data that have been suggested as evidence of karst do not all come from the same intervals and thus do not support a cross-referenced, integrated concept of karst development in this drillhole.

## SUMMARY

Analysis of primary data suggests that the overwhelming majority of data support an interpretation of unkarsted strata in the Rustler Formation at and near the WIPP site. There is some evidence for local dissolution at the top of the Magenta horizon in the WIPP-33 drillhole, but extrapolation of the known karst features in Nash Draw eastward to the WIPP site is unwarranted. The arguments offered for karst in the Rustler Formation at the WIPP site are speculative, and what evidence exists for karst is inconsistent and contradictory, and subject to other, more plausible interpretations.

Interpretations of "insoluble residues" in the cores were based on undeveloped theory, faulty analogy, and severely limited exposures. These early interpretations have been erroneously cited as evidence for karst in the Rustler Formation. More recently, better exposures of these strata, and their interpretation by analogy to modern depositional environments, have documented the presence of primary sedimentary structures including the disruption of bedding related to syndepositional desiccation and cracking, proving that they are primary deposits that have not been subjected to post-burial dissolution.

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 depressions are not similar to the characteristics of the 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. Rustler halites were deposited in shallow depressions 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 laterally extensive and uniform dolomite layers are not evidence for the original extents of the halite layers. Finally, it would be impossible to obtain the observed thicknesses of the muddy and silty deposits that have been called "residues" by dissolving the limited available volumes of muddy and silty halite.

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