Intrastratal karst at the WIPP site, southeastern New Mexico

Carol A. Hill

2006, pp. 233-242. https://doi.org/10.56577/FFC-57.233

in:

Caves and Karst of Southeastern New Mexico, Land, Lewis; Lueth, Virgil W.; Raatz, William; Boston, Penny; Love, David L. [eds.], New Mexico Geological Society 57th Annual Fall Field Conference Guidebook, 344 p. https://doi.org/10.56577/FFC-57

This page is intentionally left blank to maintain order of facing pages.

INTRASTRATAL KARST AT THE WIPP SITE, SOUTHEASTERN NEW MEXICO*

CAROL A. HILL
Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, carolannhill@aol.com

Abstract. — The possibility of intrastratal karst at the WIPP site has been evaluated with respect to karst principles and processes and to dissolution/hydrological studies. While little direct evidence exists for intrastratal karst at the WIPP site, many indirect lines of evidence suggest the possible presence of karst: surface topographic depressions, negative gravity anomalies, lack of surface runoff, collapse breccias, insoluble residue horizons, WIPP-33 sinkholes and caves, anomalous drawdowns, and salinity variations within boreholes. Intrastratal karst, if it exists, would bypass slow matrix flow in the Culebra Dolomite aquifer and be subject to fast flow in cave conduits.

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is a Department of Energy (DOE) facility located in southeastern New Mexico near Carlsbad (Fig. 1), which has been designed for the safe disposal of transuranic nuclear waste. To insure that the WIPP site is safe, two hydrologic criteria need to be met according to DOE guidelines:

(1) It must be shown that water will not invade the Salado Formation where radioactive waste is interned in the WIPP repository.
(2) It must be shown that radioactive waste cannot escape via some aquifer unit should an accidental breach of the repository occur.

The Culebra Dolomite Member of the Rustler Formation is considered to be the principle aquifer overlying the WIPP repository, and one of the primary objectives of past hydrologic studies has been to demonstrate that the Culebra will not discharge water to the surface within the regulatory time frame of 10,000 yrs.

While the Culebra aquifer has been intensely studied over the past 20 years, another possible hydrologic route for radioactive waste transport exists that has been only minimally studied: intrastratal karst. Barrows et al. (1983), and then Barrows (1985) and Barrows and Felt (1985), were the first to put forth what was dubbed "the karst proposition." This proposition was briefly reviewed by Chaturvedi and Channel (1985) and Lambert and Carter (1987), but after these reviews the topic of karst at the WIPP site seems to have been almost entirely dropped – except by Hill (1996), who cited karst as having been underestimated as a potential pathway for groundwater flow at the WIPP site.

This report is based on the paper study of Hill (1999), which was funded by DOE/Sandia Laboratories. The author is neither a proponent nor opponent of WIPP.

REGIONAL DISSOLUTION STUDIES

In order to understand dissolution at the WIPP site, past studies have focused on a number of dissolution features within and around the Delaware basin (Fig. 1): (1) dissolution troughs, (2) breccia pipes, (3) solution and fill, (4) karst domes and mounds, (5) lateral dissolution, (6) vertical dissolution, and (7) surface evaporite karst. These features will only be briefly described here; for a more detailed discussion refer to Hill (1996; 1999) and references therein.

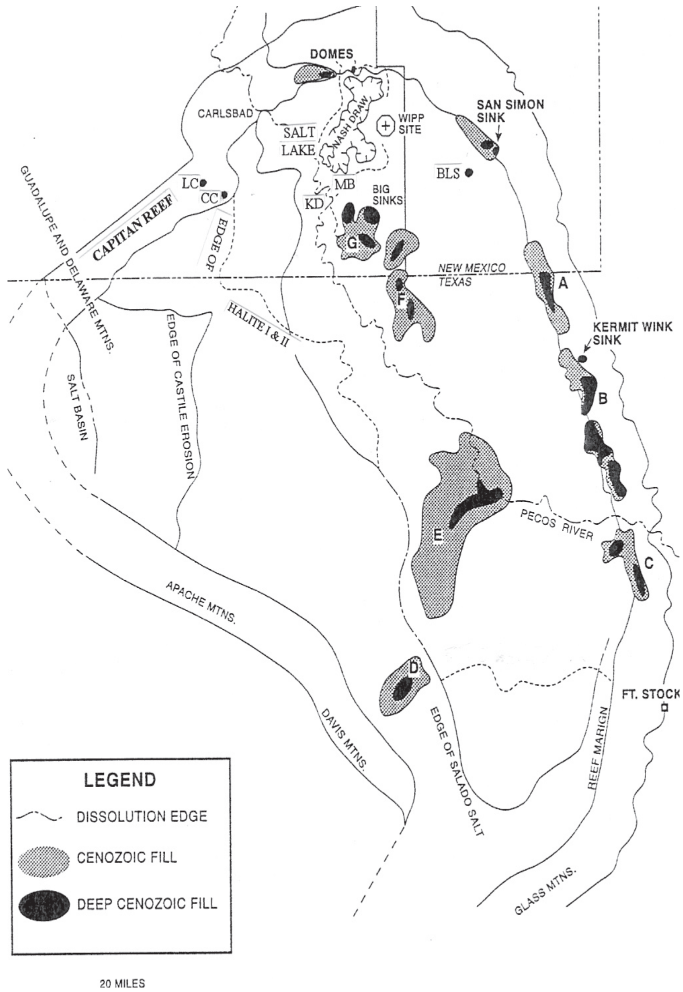

FIGURE 1. Map of the Delaware Basin showing location of the Capitan reef, major dissolution depressions (troughs), and western dissolution edge of evaporites. A, B, C, D, E, F, and G correspond to the dissolution troughs of Maley and Huffington (1953), "DOMES" are Vine's domes/breccia pipes, CC = Carlsbad Cavern, LC = Lechuguilla Cave, BLS = Bell Lake Sink, MB = Malaga Bend of the Pecos River, and KD = karst domes. Laguna Grande de la Sal (Salt Lake), Nash Draw, and the WIPP site are also shown. From base map of Anderson (1981), modified by Hill (1996).

*Originally published in: Oklahoma Geological Survey Circular 109, p. 197-209, 2003. **Reprinted with permission.**

Dissolution troughs

Dissolution troughs are large-scale dissolution features in and around the Delaware basin. First described by Maley and Huffington (1953), these occur both along the eastern edge of the basin above the Capitan reef (A, B, C; Fig. 1) and within the basin proper (D, E, F, G). The largest of these — the Belding-San Simon Trough, San Simon Swale/Sink, and Kermit Wink Sink — are located directly over the inner edge of the Capitan reef, and are related to dissolution caused by undersaturated artesian water leaching salts from overlying evaporite units. Since the WIPP site is not located directly over the Capitan reef, these dissolution troughs have no bearing on its integrity.

Within the basin proper are the Toyah (D), Balmorhea-Loving (E to F), and Big Sinks-Poker Lake (G) troughs. The origin of these features is debatable, but they are most likely related to vertical (upwards) dissolution from sandstone channels in the Bell Canyon Formation (Anderson et al., 1978). No such basinal troughs are known to exist near the WIPP site, and thus these are also of no concern.

Breccia Pipes

Breccia pipes are found in the Delaware basin around its north side, directly over the Capitan reef, and also within the basin proper. Vine (1960) was the first to describe a series of domes on the north side of the basin ("DOMES"; Fig. 1), which are the surface expression of breccia pipes. These formed when artesian water from the Capitan Limestone dissolved salt in the above-lying Salado Formation, creating space (and collapse) by a brine-density flow mechanism (Davies, 1984; Hill, 1996). Vine's domes/breccia pipes are dissolution features related to the Capitan reef and have no bearing on WIPP site integrity.

Breccia pipes identified within the basin proper are of two types: (1) paleokarst breccia pipes in the north-central part of the basin, and (2) breccia pipes near the WIPP site, which may still be actively forming. Paleokarst breccias are a key target of sulfur exploration (Crawford, 1990), and occur primarily along the halite margin of the Castile Formation ("edge of Halite I and II"; Fig. 1). Such paleokarst has not been found near the WIPP site.

Closer to WIPP are breccia pipes that extend to the surface, an example of which is Bell Lake Sink (BLS; Fig.1). Hill (1993) performed sulfur, carbon, oxygen, and strontium isotope analyses on the selenite, celestite, barite, and calcite at Bell Lake Sink, and found that these values supported Anderson's (1980a) model of deep-seated dissolution originating in the Bell Canyon Formation. Bell Lake Sink is located only about 20 km southeast of the WIPP site; however, no structures comparable to it have been found at the WIPP site.

Solution and Fill

The term "solution and fill" was first proposed by Lee (1924) for a process whereby "solution" from surface runoff and groundwater penetrates rocks through joint and fracture systems and "fill" occurs where rock collapses into solution voids. Nash Draw, just west of the WIPP site (Figs. 1, 2), is a karst valley formed by solution and fill. Solution-subsidence troughs are elongated depressions where solution and fill has formed along graben-boundary faults or fracture zones. These troughs are prevalent in the Castile Formation where it is exposed on the Gypsum Plain (Olive, 1957), but they are not known to occur near the WIPP site.

Karst Domes and Mounds

Bachman (1980) introduced the terms "karst mounds" and "karst domes" for positive relief features associated with the dissolution of evaporite rock in the Delaware basin. Karst domes are circular to elongate, roughly symmetrical structures up to 200 m or more in diameter. They may represent the surface expressions of breccia pipes or salt anticlines (Hill, 1996). Karst domes seem to be concentrated in the Malaga Bend area (MB; Fig. 1); none have been identified at or near the WIPP site.

Karst mounds are circular, elongate, to linear residual hills of dissolution breccia usually having a relief of ~3-10 m. These appear to be related to shallow surface karst processes, where the surrounding strata weathers faster than the collapse breccia. Karst mounds do not occur at the WIPP site because evaporite rock there is deeply buried (Fig. 3).

Lateral Dissolution

Lateral (or "stratabound" or "blanket") dissolution is where water works its way down the dip slope of evaporite beds, dissolv-

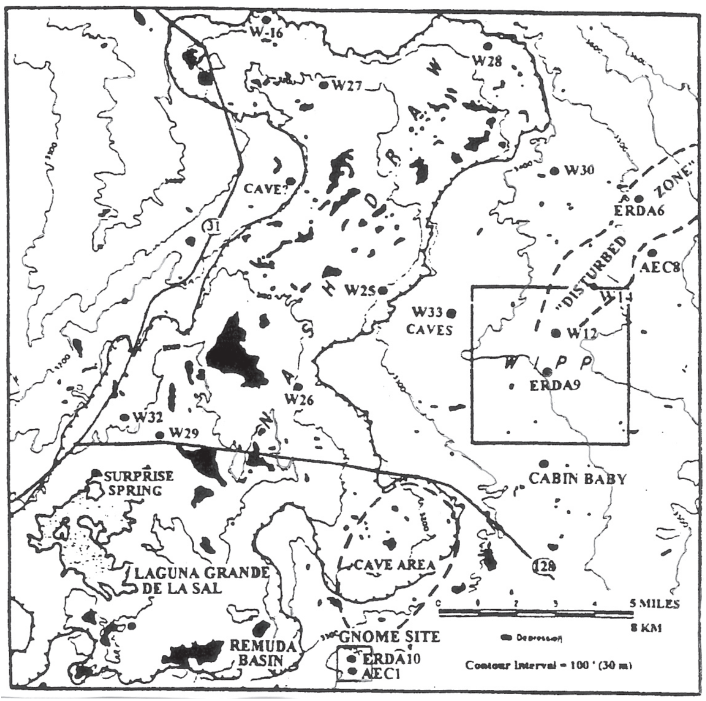

FIGURE 2. The karst valley, Nash Draw, showing location of the WIPP site, Gnome site, and Laguna Grande de la Sal. Also shown are cave areas and the "disturbed zone". Black areas are closed depressions interpreted to be collapse features. Fourth-order Nash Draw should be fed from all sides by first- to third-order karst channels. From Chaturvedi and Channell (1985), modified by Hill (1996)

System	Series	Group	Formation	Member
Recent	Recent		Surficial Deposits	
Quater-nary	Pleisto-cene		Mescalero Caliche	
			Gatuña	
Triassic		Dockum	Undivided	
Permian	Ochoan		Dewey Lake Red Beds	
			Rustler	Forty-niner
				Magenta Dolomite
				Tamarisk
				Culebra Dolomite
				lower
			Salado	
			Castile	
	Guadalupian	Delaware Mountain	Bell Canyon	
			Cherry Canyon	
			Brushy Canyon	

FIGURE 3. Stratigraphic column of rock formations at the WIPP site, including members of the Rustler Formation. Black horizon in the Salado represents the level of the WIPP repository.

ing soluble salt and gypsum along bedding planes. “Blanket dissolution breccias” are typical of bedding-plane horizons that have experienced this type of dissolution. Calculations of Chaturvedi (1993) have estimated that it should take ~225,000 yrs for the dissolution front in the Delaware basin to reach the western edge of the WIPP site. Thus, lateral dissolution – if indeed it has ever occurred at the WIPP site (Holt and Powers, 1988; Powers and Holt, 2000) – does not appear to be a threat within the regulatory time frame of 10,000 years.

Vertical Dissolution/Brine-Density Flow

Vertical dissolution can take place from above (the surface), or from below. Downward dissolution is not a problem at WIPP because it occurs much too slowly. However, the possibility of vertical dissolution from below has been a controversial subject. Anderson and Kirkland (1980) proposed a “brine-density flow” mechanism whereby water under artesian pressure in the Bell Canyon Formation dissolves away salt in the overlying Salado Formation. This may be the mechanism by which the “disturbed zone” formed in the Castile and Salado Formations (Anderson, 1980b; Fig. 2), and by which “brine reservoirs” in the Castile Formation formed within salt anticlinal structures. Brine reservoirs have been encountered in a number of boreholes in the northern, WIPP-part of the basin (e.g., WIPP-12 and ERDA-6; Fig. 2), and these brines have been of special concern because they are under anomalously high pressure (Neill et al., 1983). However, this method of dissolution, while probably occurring in the area of WIPP, is also probably too slow to be of concern.

Surface Evaporite Karst

The Delaware basin contains one of the most prominent gypsum karst areas in North America. Parks Ranch Cave (almost 8 km long) and Chosa Draw Sink are two prime examples of the many shallow surface karst features present in this area. Such sinks and caves are conduits for flash-flood water that moves rapidly underground to the Pecos River, and velocities of 2-5 m/sec have been measured for water discharged through these caves (Sares, 1984). Shallow caves and sinks are also known to exist in Nash Draw just west of the WIPP site, in the area of the Gnome site just south of WIPP, and in Remuda Basin (Fig. 2). Shallow evaporite karst does not occur directly over the WIPP site because evaporite rocks are deeply buried there (Fig. 3).

INTRASTRATAL EVAPORITE KARST

All of the above studies cover dissolution features that occur *around* the WIPP site, but none of these have been shown to directly affect fluid flow *at* the WIPP site. The one dissolution mechanism that has not been well studied – and the one with the highest potential for fluid transport – is intrastratal karst.

Intrastratal karst forms where solution processes occur beneath a layer(s) of non-karstic rock. The following characteristics are associated with intrastratal evaporite karst:

(1) It can form within the vadose zone, at or near the water table, or in the phreatic zone, as long as water is “fresh” and circulating.
(2) It is karst that usually does not have surface expression; i.e., it is “covered” karst.
(3) It can form at depth, even where evaporites are buried as much as 1000 m.
(4) It is difficult to detect in the subsurface. It may be accidently penetrated by boreholes or, where exhumed, it may be exposed in the vadose zone and be overprinted by surface (“uncovered”) vadose karst.
(5) It is widespread in evaporite rocks because of their high solubility.

Principles and Processes Applicable to Intrastratal Karst

The following principles and processes of karst may be applicable to the WIPP site.

Horton’s Law of Stream Number

Horton’s law of stream number says that many smaller stream channels (first-order, second-order) feed fewer and fewer larger stream channels (third-order) until a master trunk (fourth-order) is reached. First-order to fourth-order streams and passages exist in caves, just as they do for surface streams, but the testing of Horton's law in caves has been difficult because of the incompleteness of information (some passages are impossible to follow) (Ford and Williams, 1989). Nash Draw is a fourth-order karst valley, and as such, first- to third-order karst tributaries should feed it from all sides – including the eastern WIPP side (Fig. 2).

Vertical Development of Intrastratal Karst

The method of vertical development for intrastratal karst is shown in Fig. 4. At first, water infiltration from the surface is by diffuse reflux, but with preferred flow and dissolution concentrated along fracture zones (A). Dissolution along these fracture zones by "fresh" water creates cavities and thus freer circulation downwards (B). Rock then collapses into the cavities, creating stress in the surrounding rock (C). Stressed rock fractures, and so the area of the fracture zone is enlarged outwards. As the fracture-zone area enlarges, the surface catchment area also enlarges and a sinkhole is formed (D). This enlargement allows for a larger volume of water to pour down the sink in a self-perpetuating cycle.

The result of the above process in evaporite terrain is that, as more surface precipitation is funneled into a stream of "point source recharge," unsaturated water can dissolve its way into lower and lower levels of an evaporite rock sequence. Once water reaches an evaporite horizon (Fig. 5), more material will be dissolved there than in overlying non-evaporite units, thus causing preferential solution and collapse at this horizon. Other consequences of this process are: (1) as more surface-area water gets funneled into sinkholes, less surface-area is available for diffuse reflux and evapotranspiration, and (2) surface runoff becomes predominantly subsurface drainage.

Horizontal Development of Intrastratal Karst

The process by which intrastratal karst develops horizontally in evaporite/dolomite rock (such as occurs at the WIPP site) is shown in Fig. 5. Although a small amount of water may diffuse into the dolomite rock (wiggly arrows; A), most of the water point-sourced down a fracture zone begins to move along the contact of anhydrite/dolomite rock because it is easier and quicker to follow along this bedding plane in soluble evaporite rock than it is to enter the less-soluble dolomite as matrix flow (i.e., the contact acts as a "perched aquifer" for preferred dissolution). "Fresh," unsaturated water entering fractures dissolves the anhydrite at this contact and creates proto-caves (A) and then first-order channels (B). If horizontally moving water meets with a vertical fracture zone in the dolomite, it will transect the dolomite because this vertical fracture zone becomes the easiest route to follow (C). Caves may form either at the top or bottom of contacts, or a newer point source of water, created along the vertical fracture zone, can drill deeper into underlying evaporite rock (D).

Integration of Cave Passages from Input to Output

The development of a cave passage in salt or anhydrite at the contact between evaporite rock and more competent rock follows the principles of conduit propagation, which can apply to either the vadose or phreatic zone (Fig. 6). At first, the mode of flow is laminar within the plane and can be treated as Darcian (A). Distributary patterns of solutional micro-conduits develop that extend preferentially in the direction of the hydraulic gradient (B), their rates of extension being determined by the solvent penetration distance and factors that control it. Courses are random and depend on micro-features of the bedding plane. A high resistance to flow is characteristic of the fracture at this initial stage of development.

As one principle conduit grows ahead of the others (B), it deforms the equipotential field, reducing the gradient at the solution front of its competitors ('subsidiaries'), thus slowing their advance (C). When the principle conduit attains the output boundary (D), the high resistance to flow is destroyed, and a

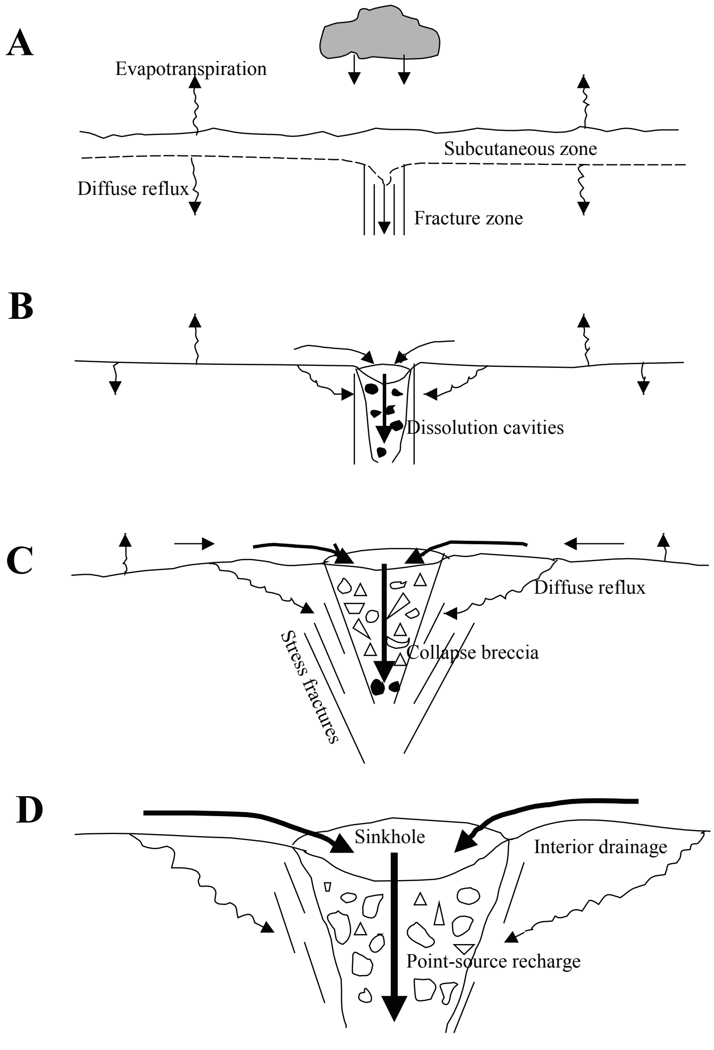

FIGURE 4. Diagrammatic model of the vertical input of water into intrastratal karst. (A) Preferred flow and dissolution along a fracture zone is initiated in the subcutaneous zone. (B) Dissolution creates cavities and freer circulation of water downwards. (C) Rock collapse into cavities, thus enlarging the area of the fracture zone. (D) As the surface catchment area continually enlarges by collapse, even more water pours down the sinkhole. This creates a self-perpetuating cycle by which more and more water is point-sourced underground.

proto-cave now carries flow through the bedding plane fissure from input to output (E). Darcian flow no longer applies once the conduit expands to minimum (5-15 mm) cave (turbulent-flow) dimensions. Once this happens, cave enlargement can be comparatively rapid, especially in evaporite rock as long as "fresh" water is entering the system. Conduits can expand to diameters of

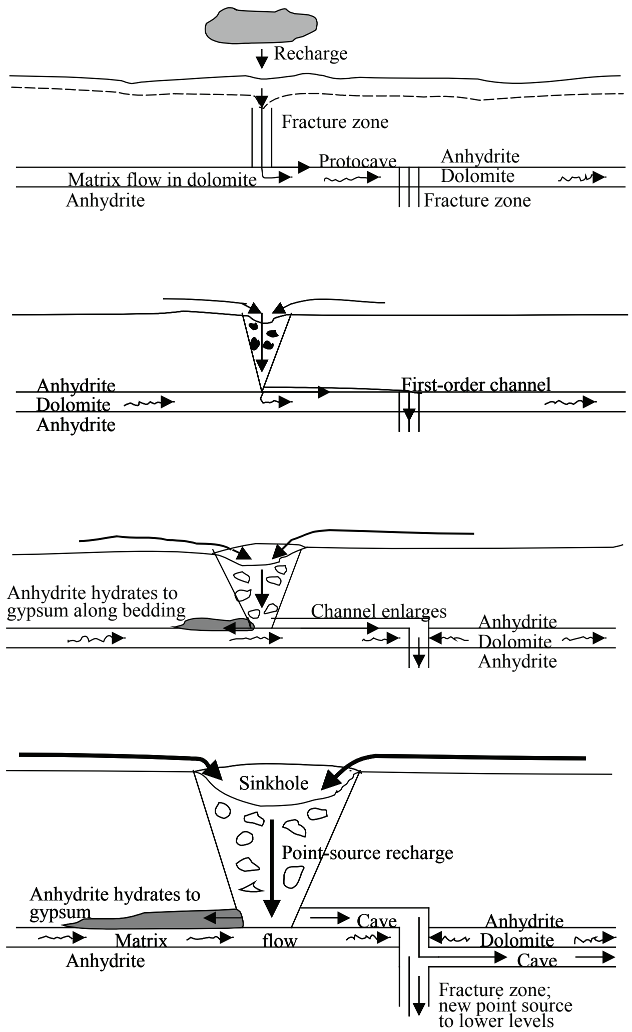

FIGURE 5. Diagrammatic model of the horizontal development of intrastratal karst, corresponding to the vertical development shown in Figure 4. As water progressively gets funneled more rapidly down sinkholes, it must find an equally rapid way of discharge. If this rate exceeds what matrix flow can accomodate, and if the water is unsaturated ("fresh"), then water will begin to form cave conduits in evaporite rock (e.g., anhydrite) at its contact with more competent rock (e.g., dolomite). (A) Water moves primarily along the anhydrite/dolomite contact because this is the easiest route to follow, and secondarily into the dolomite as matrix flow (wiggly arrows). (B) "Fresh" water entering fractures dissolves the anhydrite at this contact, creating proto-caves and then first-order channels. (C) Where water meets with another vertical fracture zone in the dolomite, it transects the dolomite. (D) Caves may form at the top or bottom of contacts, or a newer point source may drill deeper into underlying evaporite rock. As the first-order channels quickly enlarge to second-order and third-order cave conduits, water can move rapidly towards discharge.

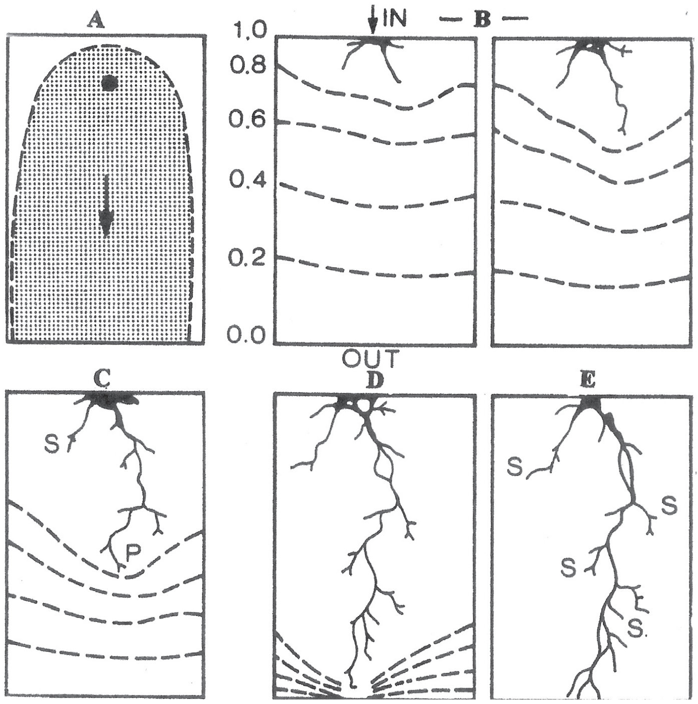

FIGURE 6. The propagation of a proto-cave from a single input to an output boundary in plane A. Shading shows the flow field or envelope at the start of dissolution. Black dot shows point-source vertical input. Dashed lines are equipotentials. P = principal (or victor) tube. S = subsidiary tubes. Scale: 1 m to 10 km. Pressure head: from thickness of a single bed to hundreds of meters. (A) The initial mode of flow is laminar within the plane (planar flow) and can be treated as Darcian. (B) Distributary patterns of solutional micro-conduits develop that extend preferentially in the direction of the hydraulic gradient. Their rates of extension are determined by the solvent penetration distance and factors that control it (e.g., how "fresh" the incoming water is, solubility of the rock, etc.). Courses are random and depend on micro-features of the bedding plane. A high resistance to flow is characteristic of the fracture at this stage. (C)(D) One principle conduit grows ahead of the others. It deforms the equipotential field, reducing the gradient at the solution front of its competitors ('subsidiaries'), thus slowing their advance. (E) When the 'principle' or 'victor' conduit attains the output boundary, the high resistance to flow is destroyed, and a 'proto-cave' (whose diameter is 1 mm or more) now carries flow through the bedding plane fissure. Darcian flow no longer applies once the proto-cave conduit expands to minimum (5-15 mm) cave (turbulent flow) dimensions. After this happens, cave enlargement can be comparatively rapid, especially in evaporite rock as long as "fresh" water is entering the system. As the 'principle' conduits preferentially enlarge over the subsidiary branches, the branches may become disconnected from the flow path or become captured by the principle conduit. These then may be sealed by clay and/or collapse. From Ewers (1982), modified by Ford and Williams (1989).

1-10 m in a few thousand years or less. An example of how fast this process can occur is the case of McMillian dam, which was constructed in 1893 in gypsum/anhydrite rock along the Pecos River, just north of Carlsbad. No caves existed when the dam was built, but after only 12 years the reservoir had drained dry via caves formed in the evaporite rock.

Conduit Flow

As karstification proceeds from a proto-cave system to a cave system with large secondary cavities and channels, there is a further progressive decoupling of flow between that passing relatively rapidly through the cave conduits and that in subsidiary passages and in the surrounding porous and fissured rock matrix. As the principle conduits preferentially enlarge over the subsidiary branches, the branches may become disconnected from the flow path or become captured by the principle conduit. These branches may then be sealed by clay and/or collapse. The effect of this process is to produce only a few active principle underground passages that get progressively larger from input to output. Water movement may be rapid and turbulent in one (the cave passage) while slow and laminar in the other (the rock). In the phreatic zone, where water inputs quickly into a conduit system from the surface during a heavy rain, a recharge wave causes a rise in the water table, and a pressure pulse ("piston flow") is forced through the phreatic conduits. If a cave system is large, the transmissivity of that system is so enormous that it operates only for a few days after a recharge event, and then becomes stagnant until the next major recharge event.

The progressive decoupling of subsidiary passages over time results in >95% of the flow being concentrated along only a few principle conduits. Water can recharge rapidly into this conduit system (in a matter of hours to days), while in the surrounding rock matrix recharge may take on the order of thousands to tens of thousands of years. If this rock is drilled – even right next to a principle karst conduit – "fossil" water can be found in the rock matrix (Fig. 7). The integration of cave passages over time into a few principle conduits also has another implication: 1-2% of the total rock volume (the cave passages) may carry >95% of the water through the system from input to output on a very rapid time scale. This water may completely by-pass aquifers having matrix or fracture flow.

Intersection of Karst

Since the majority of flow can become concentrated along a few principle conduits and only about 1-2% of a total rock volume becomes cavernous, this means that the chance for cave intersection by boreholes is slight. For example, at Mammoth Cave, Kentucky (the longest cave in the world; >480 km of passage), only 14 out of 1000 randomly drilled boreholes have intercepted known cave passages (Worthington, 1999) – or a 1.4% chance of intersection. About 60 boreholes (including shafts) have been drilled on the WIPP-site ridge, but only one (WIPP-33) is reported to have actually intersected caves – or a probability of 1.7%, greater than that for Mammoth Cave. If one also considers that the collapsed, displaced (from higher strata) breccias found in boreholes WIPP-13 and H-3 may indicate former cave passages, this would make three possible intersections of karst, or a probability of 5% – or higher than for most known cave regions of the world. Therefore, the fact that the majority of boreholes have not intersected intrastratal karst at the WIPP site is no reason for assuming it is not there.

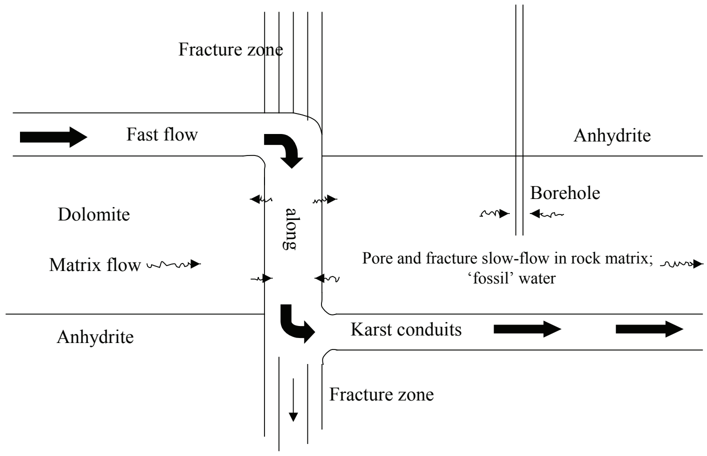

FIGURE 7. Diagram showing how karst conduits can discharge most of the water through a system, while a borehole right next to the cave passage might intersect "fossil" water in the rock matrix. Water may diffuse either into or out of the rock matrix, depending on flow conditions. During low flow, the conduits should receive water from the surrounding matrix, because they are zones of lower head. During high flow the conduits receive water more rapidly than the surrounding matrix, so water is temporarily forced into the surrounding matrix. This two-dimensional diagram shows water in the conduits moving either parallel or perpendicular to matrix flow in the dolomite, but in actuality karst-conduit water can move down gradient in any direction toward a discharge point.

Aggressiveness of Solutions and Annealing of Anhydrite

The capacity of water to dissolve evaporite rock depends on how "fresh" it is. Even brines can be aggressive in most instances because the solubility of gypsum and halite is so great. This is true for both vadose and phreatic water: both have the potential for dissolving intrastratal evaporite karst. Aggressiveness of solutions can explain how deep intrastratal karst in anhydrite can "escape" annealing and clogging with gypsum (Fig. 8). If "fresh" solutions are continually widening cave passages at a rapid rate, there is not enough time for the anhydrite to anneal shut by a gypsum-conversion volume increase. The hydration of anhydrite to gypsum may take place with each input of "fresh" water, but the gypsum will be carried away in solution so that a volume change will not affect closure of the cave passage.

This process was reported by Ferrall and Gibbons (1979) for borehole WIPP-19 in the Forty-Niner Member of the Rustler Formation, where leaching has created voids parallel to bedding as a result of groundwater traveling along bedding laminae. Very little gypsification is found along these leached zones in the Forty-Niner, a situation which Ferrall and Gibbons attributed to water dissolving anhydrite along paleo-waterways and then removing it by groundwater flow before the dissolved calcium sulfate could be re-deposited as gypsum.

Indirect Evidence for Intrastratal Karst

Because of the inherent "covered" nature of intrastratal karst, it can be very difficult to detect. While little direct evidence exists

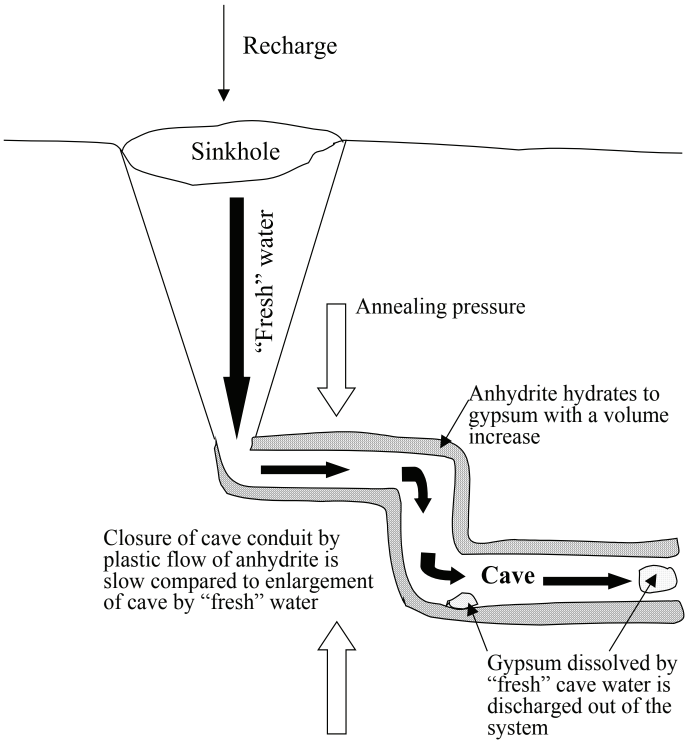

FIGURE 8. Diagram showing how circulating water causes cave passages to "escape" annealing and clogging with gypsum. Intrastratal evaporite karst can form extremely quickly; thus, the passage doesn't have time to anneal shut (opposing block arrows). "Fresh" water input into a phreatic intrastratal karst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

for intrastratal karst at the WIPP site, a number of indirect lines of evidence suggest the possibility of its existence. These indirect lines of evidence are briefly presented with respect to the karst principles and processes discussed above. Again, refer to Hill (1996, 1999) for a more detailed discussion.

Regional Considerations

The Delaware basin is one of the most prominent evaporite karst areas in the world. As previously discussed, it contains a wide variety of dissolution features over its extent (Fig. 1). The WIPP site is located just east of a major karst valley, Nash Draw, and lies adjacent to known cave areas (Fig. 2). Is it reasonable to assume that only the WIPP-site section of the Delaware basin is not influenced by karst processes?

Surface Topographic Depressions

A number of closed topographic depressions occur on the surface of the WIPP site. The largest of these are at WIPP-14 and WIPP-33 (Fig. 2). The WIPP-14 depression is 210 m wide and 3 m deep; it is perfectly round and has interior drainage. The WIPP-33 depression is the largest of a linear chain of four surface depressions that trend eastward, toward the WIPP site. Barrows (1985) interpreted these and other topographic depressions at the WIPP site to be alluvial dolines (sinkholes).

Surface Runoff

The WIPP site is a gently-sloping, slightly hummocky plain blanketed with partly stabilized windblown sand and sand dunes. It displays almost no surface runoff – a primary characteristic of karst terrains. About 300 mm of precipitation falls annually on the WIPP site, mostly between May and October, with major rainstorms in the monsoon months of July, August, and September. The rain collects in the closed topographic depressions and then sinks into the subsurface.

Campbell et al. (1996) used chloride mass-balance techniques to estimate infiltration and evaporation rates and age of soil water in the sand dunes at the WIPP site. From their data it was concluded that diffuse recharge does not appear to be the major source of water to Rustler aquifers. Rather, the major source "must be water which has been recharged from surface runoff through karst features or other direct conduits that minimize evaporation" (Campbell et al., 1996; p. 164).

Discharge

The discharge (outflow) point for water recharging the WIPP site has never been determined, even after over 20 years of study. Corbet and Knupp (1996), in their computer model of flow within the Culebra, did not specify a discharge point – only that flow is toward the downstream portions of the Pecos River along the southern boundary of their model. However, Snow (2002) reported a karstic discharge into Laguna Pequena after a record rainfall event stimulated spring flow, and showed a person standing knee-deep in water from this discharge (Snow's fig. 7). This water then emptied from Laguna Pequena into Laguna Grande de la Sal (Salt Lake; Figs. 1 and 2) at a measured rate of ~100,000 gallons/minute.

Negative Gravity Anomalies

A gravity survey is a method used for establishing the maximum depth to the top of a causative density structure displaying a minimum amount of missing, or excess, mass. Barrows et al. (1983) performed a gravity survey at the WIPP site, the results of which were found to be consistent with those reported from other gravity surveys in evaporite karstlands, where sharp negative anomalies are attributable to solution caverns in evaporite rock, hydration of anhydrite to gypsum, or low-density fill in local sinkholes. In a detailed traverse across the site, the WIPP gravity survey picked up four main negative anomalies: (1) WIPP-14 (-0.8 mgal), WIPP-13 (-0.15 mgal), H-3 (-0.45 mgal) (all three shown in Fig. 9), and WIPP-33 (-0.8 mgal) (location shown in Fig. 2) . The WIPP-13 and H-3 anomalies correspond to collapse breccias in the subsurface and the WIPP-33 anomaly to surface topographic depressions and subsurface caves. Because of these correlations, Barrows et al. (1983) suggested that the WIPP-14 negative gravity anomaly also represents a karst-related feature caused by solution/removal and a rock-density decrease due to gypsum hydration in the vicinity of karst conduits.

Collapse Breccias and Insoluble Residue

Holt and Powers (1988) and Powers and Holt (2000) described facies variability and post-depositional alteration within the Rustler Formation from observing the rock in two shafts and many cores at or near the WIPP site. These authors interpreted many of the so-called "dissolution residues" of Anderson et al. (1978) to be primary features due to dissolution in the Permian, and considered only breccias to be key indicators of significant post-burial suberosion.

Some collapse breccias and insoluble residues found in stratigraphic horizons at WIPP may be the product of intrastratal karst processes rather than due to either Permian or post-burial erosion. For example, collapse, upward stoping, and mixing of breccia clasts derived from various stratigraphic horizons occur in WIPP-13 and H-3, and both of these boreholes are located within the negative gravity features (sinkholes?) of Barrows et al. (1983; Fig. 9), suggesting that karst processes may be responsible for these breccias. Ferrall and Gibbons (1980) reported 4.5 m of solution residue in the Tamarisk Member immediately overlying the Culebra dolomite of the Rustler Formation. The upper foot of this residue contains breccia clasts, and the lower foot is layered, which caused Ferrall and Gibbons (1980) to speculate that the residue and clasts may have been deposited in the bottom of a solution cavity. At least some solution residues/breccias may be the result of the development of conduit flow, where subsidiary passages become clogged with clay or breccia.

WIPP-33 Sinkholes and Caves

Borehole WIPP-33 (Fig. 2) was drilled in the center of the largest of four topographic depressions (sinkholes) that trend eastward toward the WIPP site. At the base of the Forty-Niner Member of the Rustler Formation (Fig. 3), the drillhole encountered a 2.9 m-high cave, a 1.8 m-high cave, and a 0.6 m-high cave above the Magenta dolomite, all filled with water (i.e., the caves reside within the phreatic zone). These depressions and caves also correspond to the negative gravity anomaly of Barrows et al. (1983). The caves intersected by WIPP-33 raise an important question: Where does the water in these caves come from and go to? Caves cannot be isolated from a recharge/discharge system. Are these third-order channels draining into the fourth-order Nash Draw? Third-order channels, in turn, must be fed by first- and second-order channels (from further east along the sinkhole trend, from beneath the WIPP site?).

Fossil Water Ages

The age of Rustler water was studied by Lambert (1987), who performed radiocarbon measurements on organic matter in this water. Radiocarbon dates for water in the Culebra aquifer were found to vary between 12,000-16,000 YBP, which suggested to Lambert that groundwater in the Rustler is "fossil" water isolated from the atmosphere for at least 12,000 yrs, and that local recharge to the Culebra ceased before the present interglacial

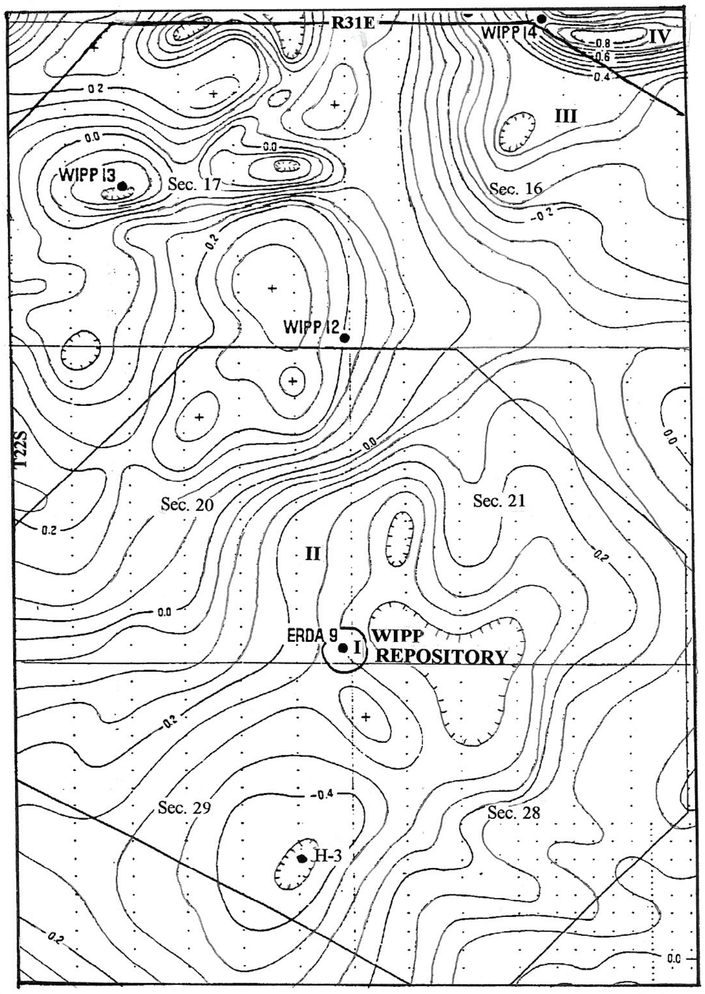

FIGURE 9. Bouguer gravity survey of the WIPP site showing negative gravity anomalies at WIPP-14, WIPP-13, and H-3. (WIPP-33 not shown on this figure). WIPP-14 (and WIPP-33) correspond to topographic depressions. WIPP-13 and H-3 correspond to collapse breccias and mixing of stratigraphic units in the subsurface. Contour interval: 0.05 mgal. Modified from Barrows et al. (1983)

began about 10,000 YBP.

However, if intrastratal karst is present at the WIPP site, these ages could be meaningless. As discussed earlier in the karst principles section, if a borehole intersects slow matrix flow in the Culebra, "fossil" water can be obtained even though karst conduits might exist right next to this matrix flow (Fig. 7). Where karst channels provide rapid recharge/discharge through the subsurface, young water in conduits can be surrounded by older water in fractures and pores of the rock matrix (Worthington, 1999). If intrastratal evaporite karst is present at the WIPP site, it could mean that two *separate* flow systems are operating simultaneously:

(1) Slow, lateral, matrix or fracture flow within the Culebra that is responsible for <5% of the total groundwater discharging through the system, and
(2) Fast flow through intrastratal evaporite karst, which transects and bypasses the Culebra and which is responsible for >95% of the total groundwater discharging through the system.

Anomalous Drawdowns

Large-scale pumping tests on the Culebra Dolomite were performed at the WIPP site in early 1987. Among the results of these tests, Beauheim (1987) reported the following anomalous drawdowns:

(1) An "apparent no-flow boundary," probably indicating a decrease in Culebra transmissivity fairly close to WIPP-13 (Beuheim, 1987, p. 39);

(2) Several anomalous responses of ERDA-9 (near the WIPP shaft), including a drawdown that was several hundred hours late, a recovery that when it occurred was sharp, and a drawdown in the middle of the recovery period that appeared to be a response to a separate event;

(3) Exhaust shaft behavior that paralleled ERDA-9, as if a withdrawal of fluid from the Culebra at some location temporarily caused drawdown at the exhaust shaft.

Anomalous pumping drawdowns and spatial or temporal changes in hydraulic heads are characteristic of karst, because karst channels/conduits permit leakage (Ford and Williams, 1989). Leakage may result in variable rates, time lags in recharge transfer, or short-period interruptions or delays in otherwise constant flow (Worthington and Ford, 1995).

Leakage in the WIPP exhaust shaft is known to be already occurring. When this shaft was first built in January, 1984 and was mapped by D. Powers and R. Holt in July 1984-1985, no leakage was observed (D. Powers, personal communication, 1999). Leakage was first detected in 1988 and has increased substantially since that time. The latest videos (1998 and 1999) show far more water leakage than the first video survey in 1995, demonstrating that in less than 15 years a new source of groundwater drainage had become focused in the subsurface by a point-source process (Fig. 6). Essentially, the WIPP exhaust shaft is acting as an "output boundary" for cave dissolution, whereby a high precipitation event could cause rapid enlargement of developing karst channels and water invasion of the WIPP repository via the exhaust shaft.

Salinity Variations

Another characteristic of karst is spatial or temporal changes in water chemistry and salinity. Precipitation that rapidly infiltrates along channel networks commonly has a much lower solute concentration than long residence-time matrix water. Total dissolved solid (TDS) anomalies may be related to karst because karst creates a complex system of fresh water/saline water travel paths.

Chemical/salinity variations are characteristic of water collected in boreholes drilled at the WIPP site. For example, Ramey (1987, p. 11) stated: "Considerable chemical variations exist between the wells H-1, H-2, and H-3, which are closest to the site. Total dissolved solids concentrations range from 9,700 to 62,000 mg/L between these wells, a difference of over 6x, and chloride ranges from 2,800 to 29,600 mg/L, an order of magnitude difference. The reasons for the abrupt chemical changes within the one square mile area surrounding wells H-1, H-2 and H-3 cannot be answered with the limited data currently available...large lateral variations exist between and within testholes (p. 13)." As discussed earlier, borehole H-3 contains what may be karst breccias, and "fresh" water coming into this system through a surface sinkhole (negative gravity anomaly; Fig. 9) could be causing the salinity variations described by Ramey. The values of 9,700 mg/L and 2,800 mg/L are exceptionally "fresh" to have been supplied by diffuse reflux from the surface. Instead, such "fresh" water is more typical of karst where water moves rapidly through the system.

Regions of low salinity are also known to exist hydraulically down-gradient from regions of intermediate salinity at the WIPP site, and a facies change is known to exist from Na-Cl to Ca-SO_4 over this same region (Chapman, 1988). Obviously there must be an imput of relatively "fresh" water to the down-gradient segment to produce this trend. Corbet and Knupp (1996) and Corbet (1998) modelled this "fresh" water into the system as diffuse, vertical reflux; however, relatively more dilute and oxidized water could be obtained by vertical input along karst. Diffuse reflux should produce saturated water with an evaporative signature from the soil-subcutaneous zone, whereas karst water should be relatively "fresh" and have an isotopic signature characteristic of meteoric water, as was demonstrated by Campbell et al. (1996) to be the case at the WIPP site.

SUMMARY

Karst aquifers pose more problems to the hydrologist than any other because their characteristics are poorly defined and water flow within them is of a very particular type. With direct observations limited to caves, boreholes, and recharge and discharge, the rest of the aquifer characteristics must necessarily be deduced from indirect evidence. One cannot treat the system as a "black box" – such treatment can be far removed from physical reality and tell one little about the structure of the aquifer and how it really operates. This is especially true for intrastratal (covered) karst.

In the case of the WIPP site, documenting intrastratal karst by direct evidence is very difficult. The method of recharge is diffuse, so that dye cannot be easily put into the system in order to trace water from input to output. The discharge point is unknown, and possible discharge springs (e.g., Malaga Bend) have not yet been monitored hydrographically to correlate with rainfall on and around the WIPP site. And, without the parameters of recharge and discharge, water balance studies are hypothetical at best. With deep, phreatic, intrastratal karst such as may possibly exist at the WIPP site, caves cannot be explored and geophysical techniques cannot detect caves that deep. Many boreholes have been drilled at the WIPP site, but even their lack of intersection with caves is not a guarantee that instrastratal karst is not present.

It should be kept in mind that while well and drawdown tests have characterized fracture and matrix flow in the Culebra dolomite aquifer, they have not characterized possible channel network flow that may be occurring between wells. To quote Palmer (1995, p. 61): "The laminar flow so commonly detected by well tests is tributary to conduits that convey water and contaminants at high velocities to spring outlets. Unless monitor wells happen to intercept these conduits, contaminants can pass right between them without the slightest chance of detection."

ACKNOWLEDGMENTS

This project was funded by DOE/Sandia Labs under Contract #BF-4551. Derek Ford and Ken Johnson reviewed the manuscript.

REFERENCES CITED

Anderson, R. Y, 1980a, Field trip notes for salt dissolution features in the Delaware Basin; *in* Chaturvedi, L. (ed.), WIPP site and vicinity geological field trip: Environmental Evaluation Group, Albuquerque, NM, EEG-7, p. 112-129.

Anderson, R. Y., 1980b, Summary of session on deep dissolution and breccia pipes, *in* Geotechnical consideration for radiological hazard assessment of WIPP: Environmental Evaluation Group, Albuquerque, NM, EEG-6, p. 13-15.

Anderson, R. Y., 1981, Deep-seated salt dissolution in the Delaware Basin, Texas and New Mexico; *in* Wells, S. G.; and Lambert, W. (eds.), Environmental geology and hydrology in New Mexico: New Mexico Geological Society, Special Publication no. 10, p. 133-145.

Anderson, R. Y.; and Kirkland, D. W., 1980, Dissolution of salt deposits by brine density flow: Geology, v. 8, p. 66-69.

Anderson, R. Y.; Kietzke, K. K.; and Rhodes, D. J., 1978, Development of dissolution breccias, northern Delaware Basin, New Mexico and Texas; *in* Austin, G. S. (complier), Geology and mineral deposits of Ochoan rocks in Delaware Basin and adjacent areas: New Mexico Bureau of Mines and Mineral Resources Circular 159, p. 47-52.

Bachman, G. O., 1980, Regional geology and Cenozoic history of Pecos Region, southeastern New Mexico: U.S. Geological Survey Open-file Report 80-1099, 116 p.

Barrows, L. J., 1985, WIPP geohydrology — the implication of karst; *in* Chaturvedi, L.; and Channel, J. K. (eds)., 1985, The Rustler Formation as a transport medium for contaminated groundwater: Environmental Evaluation Group, Albuquerque, NM, EEG-32, 21 p.

Barrows, L. J.; and Felt, J. D., 1985, A high-precision gravity survey in the Delaware Basin of southeastern New Mexico: Geophysics, v. 50, no. 5, p. 825-833.

Barrows, L. J.; Shaffer, S. E.; Miller, W. B.; and Felt, J. D., 1983, Waste Isolation Pilot Plant (WIPP) site gravity survey and interpretation: Sandia National Labs, Albuquerque, NM, SAND82-2922, 113 p.

Beauheim, R. L., 1987, Interpretation of the WIPP-13 multipad pumping test of the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) site: Sandia National Labs, Albuquerque, NM, SAND87-2456, 171 p.

Campbell, A. R.; Phillips, F. M.; and Van Landingham, J., 1996, Stable isotope study of soil water, WIPP site, New Mexico: estimation of recharge to Rustler aquifers. Radioactive Waste Management and Environmental Restoration, v. 20, p. 153-165.

Chapman, J. B., 1988, Chemical and radiochemical characteristics of groundwater in the Culebra Dolomite, southeastern New Mexico: Environmental Evaluation Group, Albuquerque, NM, EEG-39, 63 p.

Chaturvedi, L., 1993, WIPP-related geological issues; *in* Love, D. W., et al. (eds.), Carlsbad region, New Mexico and West Texas: New Mexico Geological Society Guidebook, 44th Annual Field Conference, p. 331-338.

Chaturvedi, L.; and Channell, J. K., 1985, The Rustler Formation as a transport medium for contaminated groundwater: Environmental Evaluation Group, Albuquerque, NM, EEG-32, 84 p.

Corbet, T. F., 1998, Integration of hydrogeology and geochemistry of the Culebra Member of the Rustler Formaton in the vicinity of the Waste Isolation Pilot Plant (USA); *in* Use of hydrogeohemical information in testing groundwater flow models: NEA, Organization for economic cooperation and development, Workshop Proceedings, Börgholm, Sweden, Sept. 1-3, 1997, p. 135-149.

Corbet, T. F.; and Knupp, P. M., 1996, The role of regional groundwater flow in the hydrogeology of the Culebra Member of the Rustler Formation at the Waste Isolation Pilot Plant (WIPP), southeastern New Mexico: Sandia National Labs, Albuquerque, NM, SAND96-2133, 148 p.

Crawford, J. E., 1990, Geology and Frasch-mining operations of the Culberson sulfur mine, Culberson County, West Texas; *in* Kyle, J. R., (ed.), Industrial mineral resources of the Delaware Basin, Texas and New Mexico: Society of Economic Geologists Guidebook, v. 8, p. 141-162.

Davies, P. B., 1984, Deep-seated dissolution and subsidence in bedded salt deposits: Stanford University, Unpublished PhD dissertation, 379 p.

Ewers, R. O., 1982, Cavern development in the dimensions of length and breadth: McMaster University, Hamilton, Ontario, Unpublished PhD dissertation.

Ferrall, C. C.; and Gibbons, J. F., 1980, Core study of Rustler Formation over the WIPP site: Sandia National Labs, Albuquerque, NM, SAND79-7110, 80 p.

Ford, D. C.; and Williams, P. W., 1989, Karst geomorphology and hydrology: Unwin Hyman, London, 601 p.

Hill, C. A., 1993, Barite/celestite/selenite/calcite mineralization at Bell Lake Sink, Lea County, New Mexico; *in* Love, D. W. et al. (eds.), Carlsbad region, New Mexico and West Texas: New Mexico Geological Society Guidebook, 44th Annual Field Conference, p. 117-128.

Hill, C. A., 1996, Geology of the Delaware Basin — Guadalupe Mountains, Apache Mountains, Glass Mountains, New Mexico and West Texas: Society of Economic Paleontologists and Mineralogists, Permian Basin Section, Publication no. 96-39, 480 p.

Hill, C. A., 1999, Intrastratal karst at the WIPP site: Report to DOE/Sandia National Laboratories, Contract #BF-4451, September, 1999, 83 p.

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

Lambert, S. J., 1987, Feasibility study: applicability of geochronologic methods involving radiocarbon and other nuclides to the groundwater hydrology of the Rustler Formation: Sandia National Labs, Albuquerque, NM, SAND86-1054, 108 p.

Lambert, S. J.; and Carter, J. A., 1987, Uranium-isotope systematics in groundwaters of the Rustler Formaton, northern Delaware Basin, southeastern new Mexico — principles and preliminary results: Sandia National Labs, Albuquerque, NM, SAND87-0388, 62 p.

Lee, W. T., 1924, Erosion by solution and fill: U.S. Geological Survey Bulletin 760-D, p. 107-121.

Maley, V. C.; and Huffington, R. M., 1953, Cenozoic fill and evaporite solution in the Delaware Basin, Texas and New Mexico: Geological Society of America Bulletin, v. 64, p. 539-546.

Neill, R. H.; Channell, J. K.; Chaturvedi, L.; Little, M. S.; Rehfeldt, K.; and Spiegler, P., 1983, Evaluation of the suitability of the WIPP site: Environmental Evaluation Group, Albuquerque, NM, EEG-23, 157 p.

Olive, W. W., 1957, Solution-subsidence troughs, Castile Formation of the Gypsum Plain, Texas and New Mexico: Geological Society of America Bulletin, v. 68, p. 351-358.

Palmer, A. N., 1995, Presentation of the Kirk Bryan award to Arthur H. Palmer — a response: GSA Today, March, p. 61.

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

Ramey, D. S., 1987, Chemistry of the Rustler fluids; *in* Chaturvedi, L. (ed.), The Rustler Formation at the WIPP site: Environmental Evaluation Group, Albuquerque, NM, EEG-34, p. 8-13.

Sares, S.W., 1984, Hydrologic and geomorphic development of a low-relief evaporite karst drainage basin, southeastern New Mexico: University of New Mexico,Unpublished M.S. thesis,, 123 p.

Snow, D. T., 2002, Unsafe radwaste disposal at WIPP: Proceedings of Solution Mining Research Institute, April 28-May 1, 2002, Banff, Alberta, Canada, 22 p.

Vine, J. D., 1960, Recent domal structures in southeastern New Mexico: American Association of Petroleum Geologists Bulletin, v. 14, no. 6, p. 765-788.

Worthington, S. R., 1999, A comprehensive strategy for understanding flow in carbonate aquifers; *in* Palmer, A. N.; Palmer, M. V.; and Sasowsky, I. D. (eds.), Karst modeling, Proceedings of the Karst Water Institute, Special Publication no. 5, p. 30-37.

Worthington, S. R.; and Ford, D. C., 1995, Borehole tests for megascale channeling in carbonate aquifers: Proceedings of the 26th Congress of International Association of Hydrogeologists, Edmonton, Alberta, June 5-9.