WIPP-12 was deepened during late 1981 to a depth of 1,200 m (3,925 ft) to test for possible brine and gas in the deformed Castile. The probability of encountering brine and gas was considered low because ERDA-6 and other known brine reservoirs in the Castile occurred in areas with greater deformation. During drilling, fractured anhydrite in the upper Castile (lower A3) began to yield pressurized brine and gas. The borehole was deepened to the basal anhydrite (A1) of the Castile. Subsequent reservoir testing (Popielak et al. 1983) was conducted to estimate reservoir properties (see Section 2.2.1.2.2 and Section 6.4.8).

As a consequence of discovering pressurized brine and gas in WIPP-12, the EEG recommended that the design of the facility be changed and that proposed waste disposal areas in the north be moved or reoriented to the south. After additional drilling of DOE-1, the DOE concluded that the design change had advantages, and the disposal facilities were placed south of the site center.

A microgravity survey of the site was designed to delineate further the structure within the disturbed zone, based on the large density differences between halite and anhydrite. The gravity survey was unsuccessful in yielding any improved resolution of the Castile structure.

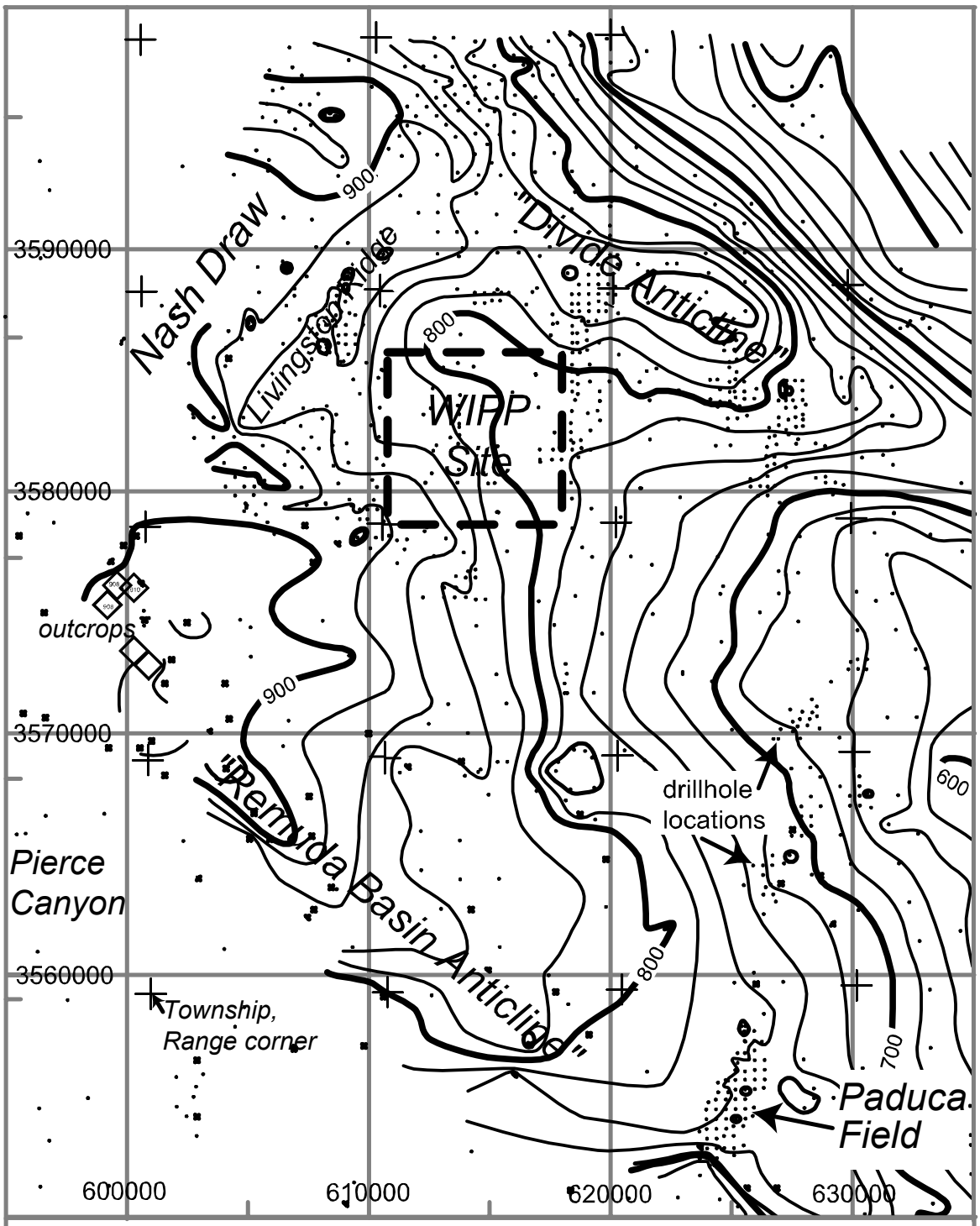
DOE-2 was the last WIPP borehole to examine structure within the Castile. Potash drillhole data suggested a low point in Salado units about 3.3 km (2 mi) north of the site center. It was proposed by Davies (1984, ***p.*** 175) that the Salado low might indicate deeper dissolution of Castile halite, somewhat similar to the dissolution causing breccia pipes (see Section 2.1.6.2 on evaporite dissolution). The borehole demonstrated considerable Castile deformation, but there was no indication that halite had been removed by dissolution (Mercer et al. 1987; Borns 1987).

2.1.6.1.2 Extent of the Disturbed Zone at the Site

Nearby surface drilling, shafts, and underground drilling during early excavations at WIPP showed that the repository horizon varies modestly from the regional structure over the central part of the site; north of the site center, the beds dip gently to the south. Borns ~~in~~ ***(***1987***)*** suggested that the south dip is probably related to the dip on the underlying Castile.

The upper surface of MB 139, under the repository horizon, exhibited local relief in the exploratory salt-handling shaft. Jarolimek et al. (1983, ***pp.*** 4 **-** 6) interpreted the relief as mainly caused by syndepositional growth of gypsum at the water-sediment interface to form mounds and by subsequent partial crushing. Jarolimek et al. ***(1983)*** concluded that the MB relief was not caused by deformation because the base of the MB showed no comparable relief. Based on concerns of the EEG, MB 139 was reevaluated. Borns (1985) found less relief on the upper surface of the MB in the areas they examined; he also concluded that depositional processes were responsible for the relief. In both cases, deformation is not thought to have caused the relief on MB 139.

For the investigation of geologic factors related to hydraulic properties of the Culebra, Powers (2002a; 2002b; 2003a) constructed elevation maps of the top of the Culebra for the region around the WIPP site. A simplified version (Figure 2-28) showing the elevations of the top of the Culebra in meters above mean sea level (m amsl) illustrates that deformation of the Castile propagated upward through the Culebra to the northeast of the WIPP site, forming a northwest-southeast trending anticline informally termed "the Divide anticline." Across the



Explanation

UTM coordinates (m) for Zone 13 (NAD27) are provided for easting and northing.
The contours for the elevation of the top of the Culebra are in meters (m) above mean sea level (amsl) (after Powers et al. 2003). Contour interval is 20 m.

Figure 2-28. Elevations of the Top of the Culebra Dolomite Member

WIPP site, the Culebra is slightly deformed by the deeper deformation, and the "disturbed zone" defined earlier geophysically is slightly evident at this horizon.

2.1.6.1.3 Deformation Mechanisms

In analyzing Castile structure in the northern Delaware Basin, Borns et al. (1983, p. 3) proposed five processes as the principal hypotheses to explain the structure: gravity foundering, dissolution, gravity sliding, gypsum dehydration, and depositional processes. Gravity foundering is the most comprehensive and best-accepted hypothesis of the five. It is based on the fact that anhydrite is much more dense (about 2.9 g/cm^3) than halite (about 2.1 g/cm^3), and anhydrite beds therefore have a potential for sinking into underlying halite. Regardless of which mechanism caused the disturbed zone, the important consideration is the long-term future effects. To evaluate this, Borns et al. ***(1983)*** postulated that both gravity-driven deformation mechanisms could be ongoing. The strain rates from such deformation are such that deformation would progress over the next 250,000 years and that such deformation would not directly jeopardize the disposal system.

2.1.6.1.4 Timing of Deformation of the Disturbed Zone at the Site

Jones (1981a, ***p.*** 18) estimated that deformation of the Castile and overlying rocks took place before the Ogallala Formation was deposited, as he believes the unit is undeformed. Anderson and Powers (1978, ***p.*** 79) inferred that data from ERDA-6 indicate that the Castile was deformed after the basin was tilted. Though these lines of evidence could be consistent with mid-Miocene deformation, there are other interpretations consistent with older deformation ~~(Madsen and Raup 1988)~~. There is no known evidence of surface deformation or other features to indicate recent deformation.

2.1.6.2 Evaporite Dissolution

Because evaporites are much more soluble than most other rocks, project investigators have considered it important to understand the dissolution processes and rates that occur within the site being considered for long-term isolation. These dissolution processes and rates constitute the limiting factor in any evaluation of the site. Over the course of the WIPP project, extensive resources have been committed to identify and study a variety of features in southeastern New Mexico interpreted to have been caused by dissolution. The subsurface distribution of halite for various units has been mapped. Several different kinds of surface features have been attributed to dissolution of salt or karst formation. The processes proposed or identified include point-source (brecciation), deep dissolution, shallow dissolution, and karst. These are each discussed in more detail in ***CCA*** Appendix DEF, Section DEF.3. Screening arguments relative to dissolution are presented in Appendix ***PA, Attachment*** SCR, ***FEPs N17 and N21*** (including dissolution associated with abandoned boreholes in ~~Sections SCR.1.2.1 and SCR.3.3.1~~ ***the discussion for FEP H34***). These arguments are based principally on the observed rates and processes in the region. These are described below.

2.1.6.2.1 Brief History of Project Studies

Well before the WIPP project, several geologists recognized that dissolution is an important process in southeastern New Mexico***,*** and that it contributed to the subsurface distribution of

halite and to the surficial features. Early studies include those by Lee (1925), Maley and Huffington (1953), and Olive (1957)~~ (in the Bibliography)~~. Robinson and Lang (1938, ***p.*** 100) identified an area under Nash Draw where brine occurred at about the stratigraphic position of the upper Salado-basal Rustler and considered that salt had been dissolved to produce a dissolution residue. Vine (1963, ***p.*** B38 and B40) mapped Nash Draw and surrounding areas. Vine ***(1963)*** reported surficial domal structures, later called breccia pipes and identified as deep-seated dissolution and collapse features.

As the USGS and Oak Ridge National Laboratory (ORNL) began to survey southeastern New Mexico as an area in which to locate a repository site in salt, Brokaw et al. ~~in~~ ***(***1972***)*** prepared a summary of the geology that included solution and subsidence as significant processes in creating the features of southeastern New Mexico. Brokaw et al. ***(***1972***)*** also recognized a solution residue at the top of the salt in the Salado in the Nash Draw area, and the unit commonly became known as the brine aquifer because it yielded brine. Brokaw et al. ***(***1972***)*** also interpreted the east-west decrease in thickness of the Rustler to be a consequence of removal by dissolution of halite and other soluble minerals.

During the early 1970s, the basic ideas about shallow dissolution of salt (generally from higher stratigraphic units and within a few hundred feet of the surface) were set out in a series of reports***,*** ~~by Bachman, Jones, and collaborators,~~ as discussed in the following sections. Piper (1973***;*** 1974) independently evaluated the geological survey data for ORNL. Claiborne and Gera (1974) concluded that salt was being dissolved too slowly from the near-surface units to affect a repository for several million years, at least.

By 1978, shallower drilling around the WIPP site to evaluate potash resources was interpreted by Jones (1978, ***p.*** 9), ~~and he~~ ***who*** felt that the Rustler included "dissolution debris, convergence of beds, and structural evidence for subsidence." Halite in the Rustler has been reevaluated by the DOE, but there are only minor differences in inferred distributions among the various investigators. These investigators do have different explanations about how this distribution occurred (see Section 2.1.3.5 on Rustler stratigraphy): (1) through extensive dissolution of the Rustler's halite after the Rustler was deposited***,*** or (2) through syndepositional dissolution of halite from saline mud flat environments during Rustler deposition.

Anderson (1978) and Anderson et al. (1978) reevaluated halite distribution in deeper units, especially the Castile and Salado formations. ~~He~~ ***They*** identified local anomalies proposed as features developed after deep dissolution of halite by water flowing upward from the underlying Bell Canyon. Anderson ***(1978)*** mapped geophysical log signatures of the Castile and interpreted lateral thinning and change from halite to non-halite lithology as evidence of lateral dissolution of deeper units (part of deep dissolution), and ~~he~~ proposed that deep dissolution might threaten the WIPP site. In response to Anderson's ***(1978)*** developing concepts, ERDA-10 was drilled south of the WIPP area during the latter part of 1977. ERDA-10 intercepted a stratigraphic sequence without evidence of solution residues in the upper Castile.

A set of annular or ring fractures is evident in the surface around San Simon Sink, about 30 km (18 mi) east of the WIPP site. Nicholson and Clebsch (1961, ***p.*** 14) suggested that San Simon Sink developed as a result of deep-seated collapse. WIPP-15 was drilled at about the center of the sink to a depth of 245 m (811 ft) to obtain samples for paleoclimatic data and stratigraphic

data to interpret collapse. Anderson (1978) and Bachman (1980) both interpret San Simon Sink as dissolution and collapse features, and the annular fractures are not considered evidence of tectonic activity.

Following the work by Anderson, Bachman (1980, 1981) mapped surficial features in the Pecos Valley, especially at Nash Draw, and differentiated between those surface features in the basin that were formed by karst and those that were formed by deep collapse features over the Capitan. WIPP-32, WIPP-33, and two boreholes over the Capitan ***R***~~r~~eef were eventually drilled. Their data, which demonstrated the concepts proposed by Bachman ***(1980, 1981)***, are documented in Snyder~~,~~ et al***.*** (1982, ***p.*** 65).

A final program concerning dissolution and karst was initiated following a microgravity survey of a portion of the site during 1980. Based on localized low-gravity anomalies, Barrows et al. ~~in~~ ***(***1983***)*** interpreted several areas within the site as locations of karst. WIPP-14 was drilled during 1981 at a low-gravity anomaly. It revealed normal stratigraphy through the zones proposed to be affected by karst. As a follow-up, ~~in 1985~~ Bachman ***(1985)*** also reexamined surface features around the WIPP and concluded that there was no evidence for active karst within the WIPP site. The nearest karst feature is northwest of the site boundaries at WIPP-33.

2.1.6.2.2 Extent of Dissolution

~~The margins of halite within the anhydrite and claystone members of the Rustler have been mapped by different methods, the findings of which were consolidated by Beauheim (in 1987a, 131—134). There are few differences in interpretation, despite the different methods used (Figure 2-10). Lower members of the Rustler are halitic west of the site, and higher members generally show halite only further east. Snyder interprets these margins as a consequence of post-depositional dissolution of halite. Holt and Powers (Appendix FAC, 6-29) report and interpret sedimentary structures within the Rustler mudstone equivalent to halite beds, indicating that most halite was removed during the depositional process and redeposited in a salt pan in the eastern part of the depositional basin.~~ ***Within the Rustler, dissolution of halite is believed to have occurred only near the depositional margins, as discussed in Section 2.1.3.5. Figure 2-15 shows the only two areas where evidence has been found for halite dissolution from the M3/H3 horizon in the Tamarisk.***

Upper intervals of the Salado thin dramatically west and south of the WIPP site (Figure 2-~~23~~***29***) compared to deeper Salado intervals. There are no cores for further consideration of possible depositional variations. As a consequence, this zone of thinning is interpreted by the DOE as the edge of dissolution of the upper Salado.

2.1.6.2.3 Timing of Dissolution

The dissolution of Ochoan evaporites through the near-surface processes of weathering and groundwater recharge has been studied extensively (Anderson 1981***;*** Lambert 1983a***;*** Lambert 1983b***;*** Bachman 1984***;*** and ~~see also~~ ***CCA*** Appendix FAC). The work of Lambert (1983a) was specifically mandated by the agreement between the DOE and the state of New Mexico to evaluate in detail the conceptual models of evaporite dissolution proposed by Anderson (1981). There was no clear consensus among investigators on the volume of rock salt removed. Hence,

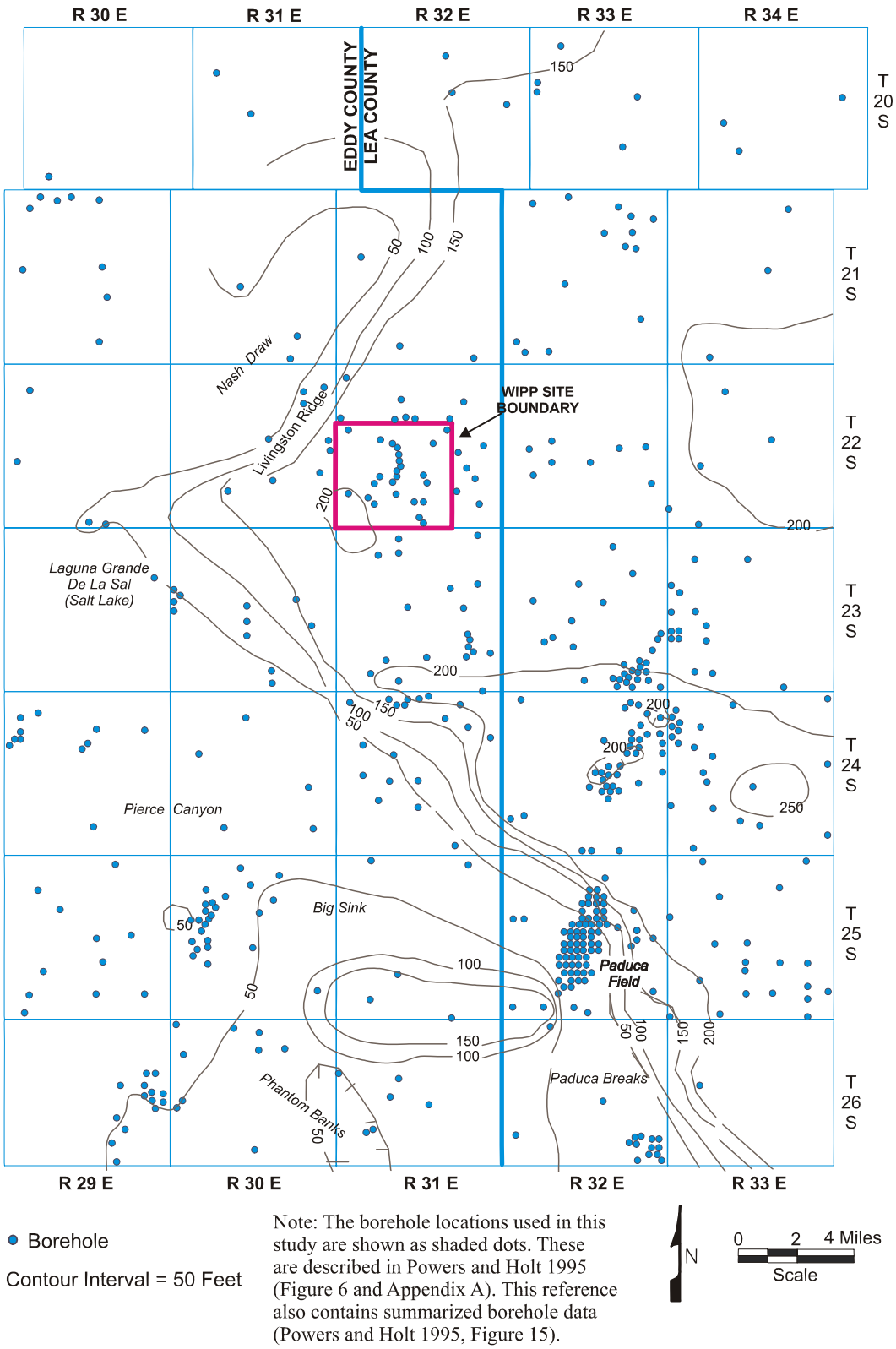


Figure 2-~~23~~29. Isopach from the Base of MB 103 to the Top of the Salado

estimates of the instantaneous rate of dissolution vary significantly. Dissolution may have taken place as early as the Ochoan, during or shortly after deposition. For the Delaware Basin as a whole, Anderson (1981) proposed that up to 40 percent of the rock salt in the Castile and Salado formations was dissolved during the past 600,000 years. Lambert (1983b, ***p.*** 292) suggested that in many places the variations in salt-bed thicknesses inferred from borehole geophysical logs that were the basis for Anderson's ***(1981)*** calculation were depositional in origin, compensated by thickening of adjacent nonhalite beds, and were not associated with the characteristic dissolution residues. Borns and Shaffer (1985, ***p.*** 44 – 45) also suggested in 1985 a depositional origin for many apparent structural features attributed to dissolution.

Snyder (1985, ***p.*** 8), as well as earlier workers (for example, Vine 1963***;*** Lambert 1983b***;*** and Bachman 1984), attribute the variations in thickness in the Rustler, which crops out in Nash Draw, to postdepositional evaporite dissolution. Holt and Powers (***CCA*** Appendix FAC, ***p.*** 9-2) have challenged this view and attribute the east-to-west thinning of salt beds in the Rustler to depositional facies variability rather than postdepositional dissolution. Bachman (1974, 1976, ~~and~~ 1980) envisioned several episodes of dissolution since the Triassic, each dominated by greater degrees of evaporite exhumation and a wetter climate, interspersed with episodes of evaporite burial and/or a drier climate. Evidence for dissolution after deposition of the Salado and before deposition of the Rustler along the western part of the Basin was cited by Adams (1944, ***p.*** 1612). Others have argued that the evaporites in the Delaware Basin were above sea level and therefore potentially subject to dissolution, during the Triassic, Jurassic, Tertiary, and Quaternary periods. Because of discontinuous deposition, not all of these times are separable in the geological record of southeastern New Mexico. Bachman (1980) contends that dissolution was episodic during the past 225 million years as a function of regional base level, climate, and overburden.

There have been several attempts to estimate the rates of shallow dissolution in the basin. Bachman ***(1974)*** provided initial estimates of dissolution rates based on a reconstruction of Nash Draw relationships, including the observation that portions of the Gatuña were deposited over areas of active dissolution and subsidence of the underlying evaporites. Though these rates indicate no hazard to the WIPP related to Nash Draw dissolution, Bachman (1980, ***p.*** 85) later reconsidered the Nash Draw relationships and concluded that pre-Cenozoic dissolution had also contributed to salt removal. Thus, the initial estimated rates were too high.

With regard~~s~~ to deep dissolution, Anderson concluded in 1978 that the integrity of the WIPP to isolate radioactive waste would not be jeopardized by dissolution within about ***one*** million years. Anderson and Kirkland (1980, ***pp.*** 66 **-** 69) expanded on the concept of brine density flow proposed by Anderson ~~in~~ ***(***1978***)*** as a means of dissolving evaporites at a point by circulating water from the underlying Bell Canyon. Wood et al. (1982, ***p.*** 100) examined the mechanism and concluded that, while it was physically feasible, it would not be effective enough in removing salt to threaten the ability of the WIPP to isolate transuranic (TRU) waste.

2.1.6.2.4 Features Related to Dissolution

Bachman (1980, ***p.*** 97) separated breccia pipes, formed over the Capitan ***R***~~r~~eef by dissolution and collapse of a cylindrical mass of rock, from evaporite karst features that appear similar to breccia pipes. There are surficial karst features, including sinks and caves, in large areas of the

basin. Nash Draw is the result of combined dissolution and erosion. Within the site boundaries, there are no known surficial features caused by dissolution or karst.

The subsurface structure of the Culebra is shown in Figure 2-~~24~~***28***. South of the WIPP site***, an antiformal structure informally called the "Remuda Basin anticline" has been created by dissolution of salt from the underlying Salado to the southwest of the anticline.*** ~~between Pierce Canyon and Paduca Breaks there is a relationship between this structure and dissolution. Salt has been removed from the underlying Salado to create a general anticline from near Laguna Grande de la Sal to the southeast of the WIPP site.~~ Beds generally dip to the east, and salt removed to the west created the other limb of the structure. Units below the evaporites apparently do not show the same structure.

2.2 Surface Water and Groundwater Hydrology

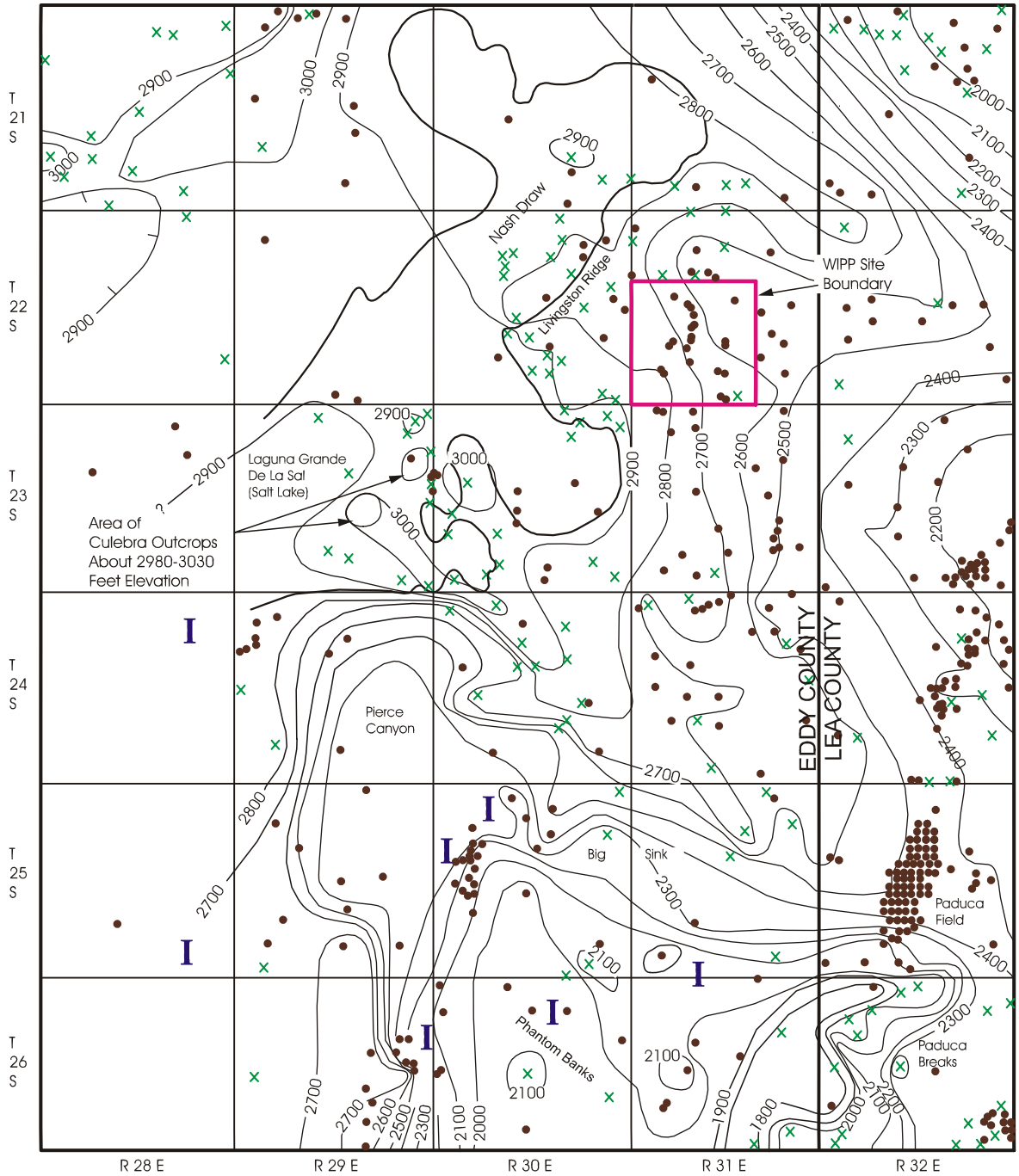
The DOE has determined that the hydrological characteristics of the disposal system are important because contaminant transport via fluid flow has a potential to impact the performance of the disposal system. In addition, the EPA has provided numerous criteria related to groundwater in 40 CFR § 194.14(a). At the WIPP site, one of the DOE's selection criteria was to choose a location that would minimize this impact. This was accomplished when the DOE selected (1) a host formation that contains little groundwater and transmits it poorly, (2) a location where the effects of groundwater flow are minimal and predictable, (3) an area where groundwater use is low, (4) an area where there are no permanent surface waters, (5) an area where future groundwater use is unlikely, and (6) a repository host rock that will not likely be affected by anticipated possible long-term climate changes within 10,000 years.

The following discussion summarizes the characteristics of the groundwater and surface water at and around the WIPP site. This summary is based on data collection programs that were initiated with the WIPP program and that continue to some extent today. The purpose of these programs was to provide information sufficient for the development and use of predictive models of the groundwater movement at the WIPP site.

For a comprehensive understanding of the impact of groundwater and surface water on the disposal system, the following factors have been evaluated:

Groundwater

- Horizontal and vertical flow fluxes and velocities,
- Hydraulic interconnectivity between rock units,
- Hydraulic parameters (porosity, etc.),
- General groundwater use, and
- Chemistry (including, but not limited to, salinity, mineralization, age, Eh, and pH).



Source: Powers and Holt (1995)

~~**Figure 2-24. Structure Contour Map of Culebra Dolomite Base**~~

Surface Water

- Regional precipitation and evapotranspiration rates***,***
- Location and size of surface-water bodies***,***
- Water volume, flow rate, and direction***,***
- Drainage network***,***
- Hydraulic connection with groundwater***,***
- Soil hydraulic properties (infiltration)***,*** and
- General water chemistry and use.

Changes to the hydrological system due to human activity are evaluated in Chapter 6.0.

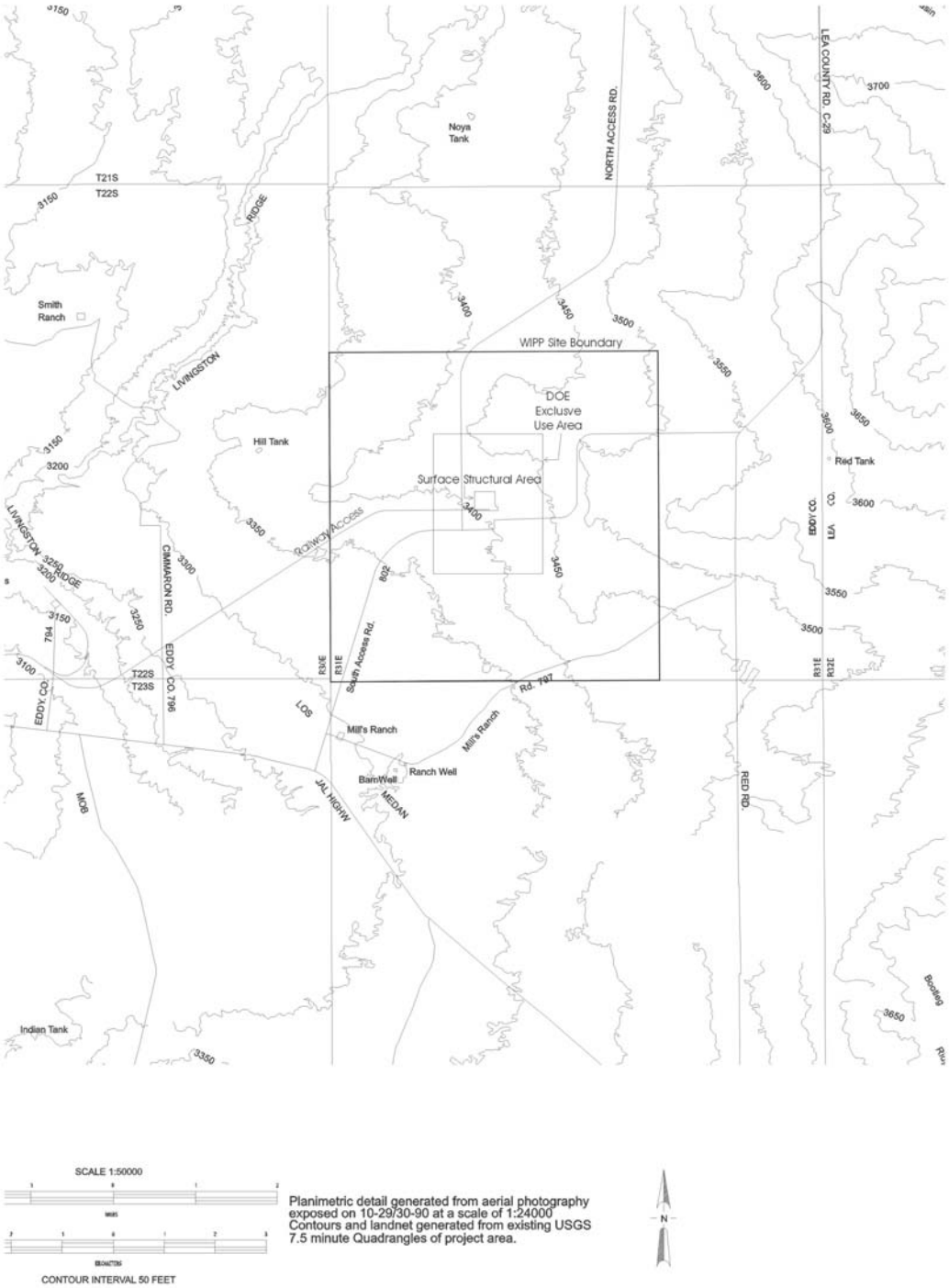
The specifics of groundwater modeling are found in Section 6.4.6, Appendix ***PA, Attachment*** MASS, Section MASS.14.2. The hydrological system is divided into four segments for the discussion in this chapter. These are***:*** (1) the rock units below the Salado, which may impact the disturbed (human intrusion) performance of the disposal system***,*** (2) the Salado, which mostly addresses the undisturbed performance of the disposal system***,*** (3) the rock units above the Salado, which essentially impact only the disturbed (human intrusion) performance of the disposal system***,*** and (4) the surface waters. The groundwater regime is discussed in Section 2.2.1, and the surface-water regime in Section 2.2.2.

The WIPP site lies within the Pecos River drainage area (Figure 2-~~25~~***23,*** see also Section 2.2.2, Figure 2-~~36~~***43***). As discussed in the Final Environmental Impact Statement (FEIS) (DOE 1980, Section 7.1.1), the climate is semiarid, with a mean annual precipitation of about 0.33 m (13 in.), a mean annual runoff of 2.5 to 5 mm (0.1 to 0.2 in.), and a mean annual pan evaporation of more than 2.5 m (100 in.). Runoff is practically nonexistent and the WIPP does not have a well defined drainage pattern. The general movement of runoff can be inferred from the topography in Figure 2-~~25~~***23***. Only one stream flow gaging station has been operated in the vicinity. This is at the location shown as Hill Tank in Figure 2-~~25~~***23***. Observations at Hill Tank are discussed in Section 2.2.2.

Additional information about climatic conditions at the WIPP is given in Section 2.5.2. Brackish water with total dissolved solids (TDS) concentrations of more than 3,000 parts per million is common in the shallow wells near the WIPP site. Surface waters typically have high TDS concentrations, particularly of chloride, sulfate, sodium, magnesium, and calcium. Additional information about water quality is given in Section 2.4.2.

2.2.1 Groundwater Hydrology

At the WIPP site, the DOE ***has obtained*** ~~obtains~~ groundwater hydrologic data from conventional and special-purpose test configurations in multiple surface boreholes. ~~(Figure 2-2 is a map of~~



~~Figure 2-25. Drainage Pattern in the Vicinity of the WIPP Facility~~

~~borehole locations.)~~ Geophysical logging of the boreholes has provided hydrologic information on the rock strata intercepted. Pressure measurements, fluid samples, and ranges of rock permeability have been obtained for selected formations through the use of standard and modified drill-stem tests. Slug injection or withdrawal tests and other flow-rate tests have provided data to aid in the estimation of transmissivity and storage. The hydraulic heads of groundwaters within many water-bearing zones in the region have been mapped from measured depths to water in the boreholes.

Since the CCA was submitted to the EPA in 1996, the DOE has implemented a number of monitoring programs (see Appendix MON-2004), including the Groundwater Monitoring Program, to meet the assurance requirements of 40 CFR § 191.14(b). In addition to the groundwater monitoring program, other hydrologic data gathered since the CCA come from logging of new or replacement wells, piezometers, special-purpose field investigations, and surveys of drilling practices in the Delaware Basin. A data summary of all these activities is provided in Appendix DATA.

Historically, the DOE has obtained hydrological data principally from a conventional well-monitoring network (Figures 2-3 through 2-6 are maps of the well locations) comprising 71 wells located on 45 separate wellpads (DOE 2003). Most of the 71 wells are completed only to a single hydrologic unit; however, six are multiple-completions to allow monitoring of two or more units in the same well. Hydrologic information (such as hydraulic head) is obtained at 80 completion intervals within the 71 wells. The focus of the hydrological monitoring is the Rustler (comprising 72 of the 80 monitored intervals) because this formation contains two of the most transmissive saturated units, the Culebra and Magenta Dolomites, which are important to the modeling of releases during various human intrusion scenarios. Limited hydrological monitoring of the Bell Canyon, Dewey Lake, and Santa Rosa also occurs.

Rock units that are shown in the conceptual models in Section 6.4 to be important to disposal system performance from a hydrological standpoint are the Castile, the Salado, the Rustler, and the Dewey Lake (Figures 2-~~26~~***30*** and 2-~~27~~***31***). However, other units which are discussed due to their significance in screening hydrological processes or because they are less important to the conceptual model include the Bell Canyon, the Capitan, the Rustler-Salado contact zone, and the ***s***upra-Dewey Lake units. These will also be discussed because they are features of the groundwater flow system of the WIPP region.

The Bell Canyon is of interest to the DOE because it is the first regionally continuous water-bearing unit beneath the WIPP ***and is the target stratigraphic horizon for salt-water injection by industry outside of the WIPP site boundary***. The halite and anhydrite layers of the Castile provide a hydrologic barrier between the Salado and the underlying Bell Canyon. The Castile is of interest to ***PA*** because it contains isolated high-permeability zones containing pressurized brine. As discussed in Section 2.1.6.1, several such zones of pressurized brine have been intercepted by boreholes near the WIPP site, and one or more ***of these zones*** may exist at the WIPP site.

The Salado comprises low-permeability beds of variable composition. The low permeability of the Salado provides a hydrologic barrier in all directions between the repository and the accessible environment or more transmissive beds. ***At the repository horizon, a much higher***

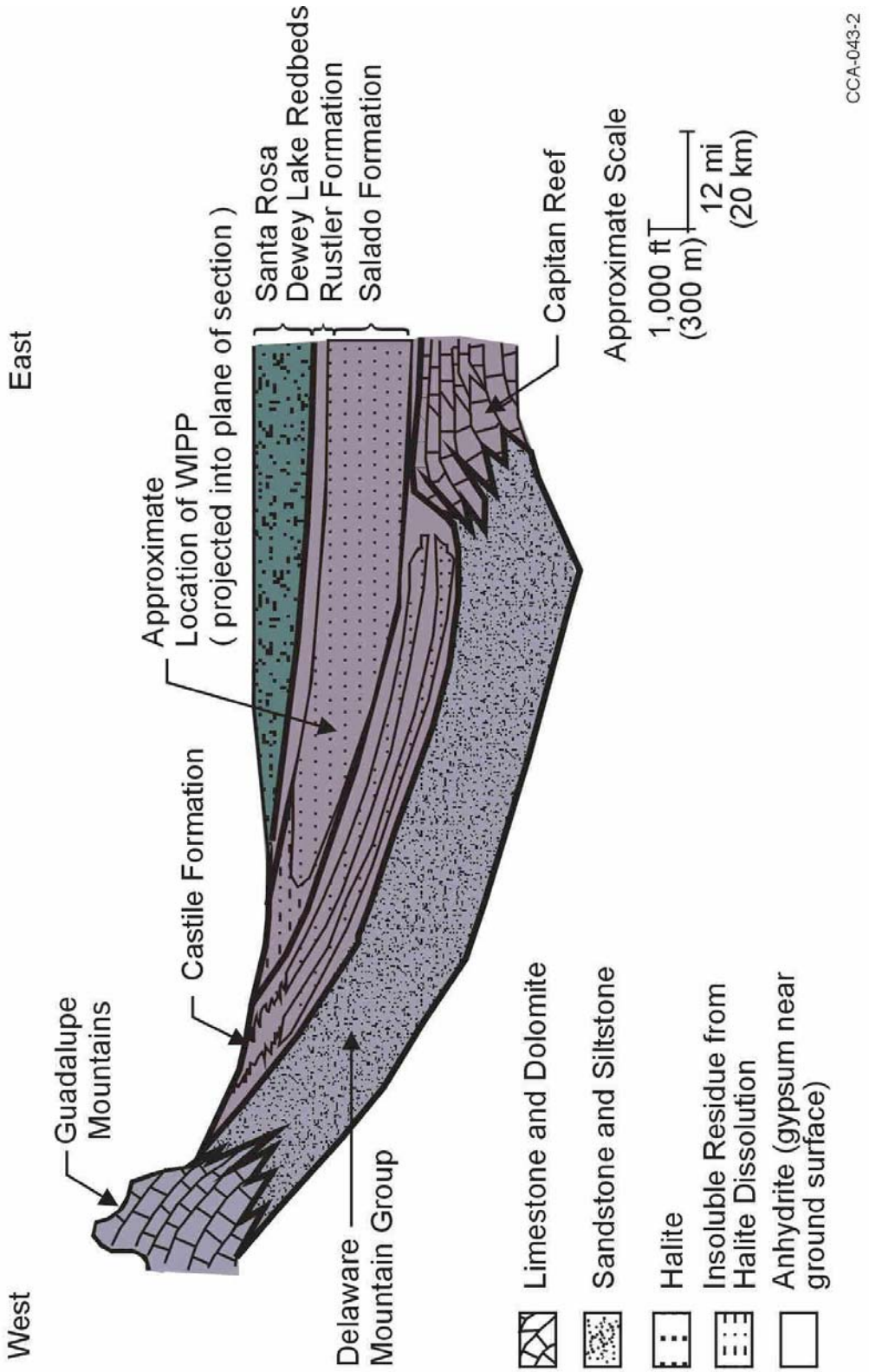


Figure 2-~~26~~30. Schematic West-East Cross Section through the North Delaware Basin

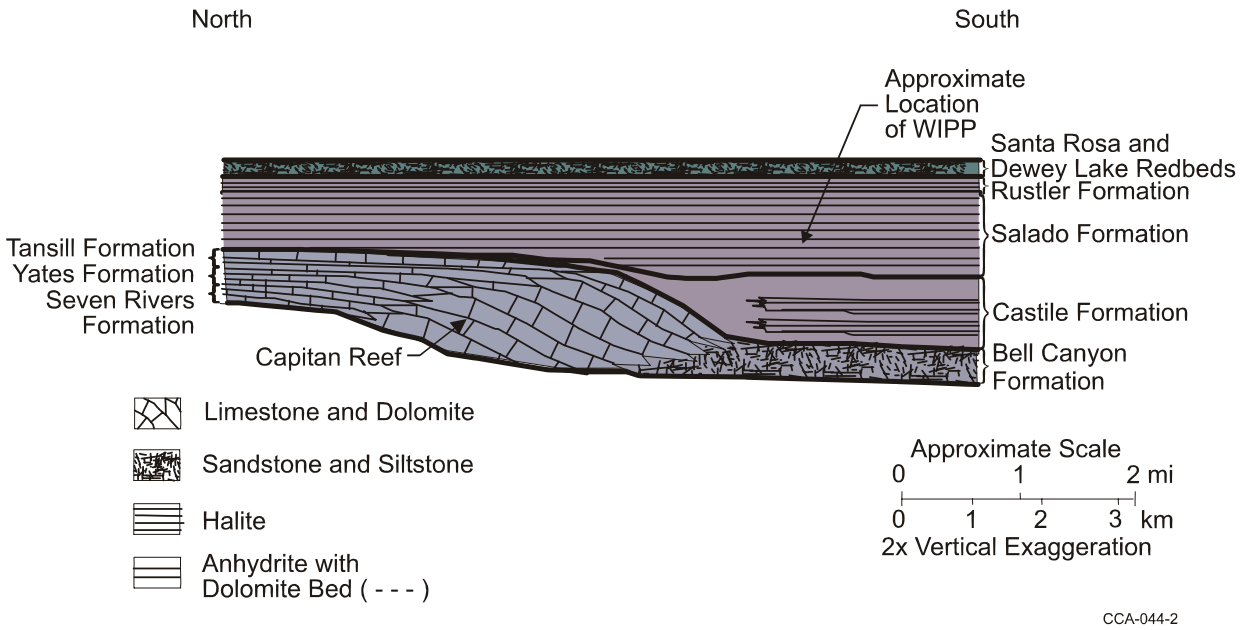


Figure 2-~~27~~*31*. Schematic North-South Cross Section through the North Delaware Basin

permeability DRZ forms locally in the salt around the waste emplacement rooms and operational drifts. As described in Appendix DATA, the DRZ is of limited extent compared to the significant thickness of the Salado low-permeability beds surrounding the repository horizon.

The Rustler contains two laterally transmissive members. The Culebra is the first laterally continuous unit located above the WIPP underground facility to display hydraulic conductivity sufficient to warrant ~~concern about~~ ***investigation for*** lateral contaminant transport. It is also the most transmissive ***continuously saturated*** unit above the ~~Salado~~ ***WIPP repository*** ~~at the WIPP site~~. Therefore, except for a ~~breach~~***release*** directly to the surface, the Culebra provides the most direct pathway between the WIPP underground and the accessible environment. The hydrology and fluid geochemistry of the Culebra are complex and, as a result, have received a great deal of study (see, for example, LaVenue et al. 1988, 1990; Haug et al. 1987; and Siegel et al. 1991~~ in the bibliography~~). The Magenta, although more transmissive than the anhydrite and claystone members of the Rustler, has lower transmissivity than the Culebra, and is unfractured at the WIPP.

There was no inflow of water from the Dewey Lake into the WIPP shafts after they were completed and prior to their lining, indicating unsaturated conditions or low transmissivity. ~~Flow from a fractured zone has been observed at Water Quality Sampling Program (WQSP) 6a. The Santa Rosa is shallow and unsaturated at the site, and the only flow through it is infiltration, which likely occurs at low rates because of the evaporative climate.~~ ***However, since 1995, routine inspections of the WIPP exhaust shaft have revealed water entering the shaft at a depth of approximately 24 m (80 ft) at a location where no water had been observed during construction (the DOE is investigating the source and extent of this water; see Sections***

2.2.1.4.2.1 and Appendix DATA). The quantity and quality of water in the Dewey Lake is also monitored in a deeper fractured zone in the Dewey Lake at well WQSP-6a (WIPP MOC 1995).

The Santa Rosa is shallow and unsaturated at the site ***(with the exception of a perched water table directly below the WIPP surface structures; – see Section 2.2.1.4.2.2 and Appendix DATA), and apparently receives recharge only through infiltration.*** ~~and the only flow through it is infiltration, which likely occurs at low rates because of the evaporative climate.~~

In conclusion, at the WIPP site, the DOE recognizes the Salado as the most significant nontransmissive unit and the Culebra and the Magenta as the most significant transmissive units. Other units are considered to have less important roles. The DOE's sampling and analysis of non-Salado groundwater has focused on the Culebra and Magenta, and their hydrologic background, presented here, is more detailed than for other non-Salado rock units. Table 2-4 provides an overview of the hydrologic characteristics of the Rustler rock units at the WIPP site and the Rustler-Salado contact zone in Nash Draw. In developing this position on modeling the hydrology of the WIPP, the DOE considered several modeling approaches. These are summarized in ***CCA*** Appendix MASS, Section MASS.14.1 ***in*** general and Section MASS.15.1 for the Culebra. The DOE's conceptual models for hydrology are in Sections 6.4.5 and 6.4.6.

Table 2-4. Hydrologic Characteristics of the Rustler at the WIPP and in Nash Draw

Member	Thickness (meters)		Transmissivity (square meters per second)		Porosity	
	max	min	max	min	max	min
Forty-niner	23	13	8×10^{-8}	3×10^{-9}	—	—
Magenta	8.5	7	4×10^{-4}	1×10^{-9}	0.25	0
Tamarisk	56	26	2.7×10^{-11}	—	—	—
Culebra	11.6	4	1×10^{-3}	1×10^{-9}	0.30	0.03
~~unnamed lower~~ ***Los Medaños***	38	29	2.9×10^{-10}	2.2×10^{-13}	—	—
Rustler-Salado Contact Zone in Nash Draw	18	3	8.6×10^{-6}	3.2×10^{-11}	0.33	0.15

The EPA sought information supporting the conceptualization of the disposal system and the major site-related characteristics included in the PA modeling during the compliance review process for Section 194.14(a)(3). In general, the EPA concluded that the groundwater hydrology information for the various geologic and hydrostratigraphic units at the WIPP site identified the important characteristics of the PA and was therefore technically sufficient. The EPA also noted that the primary hydrogeologic units of concern relative to containment capability of the WIPP are the Castile, Salado, Rustler, and the Dewey Lake.

The EPA noted that the potential for fluid migration through Salado marker beds and the Culebra were acknowledged by DOE and included in the PA calculations. While the Dewey Lake is a potential underground source of drinking water (Section 8.2.2), DOE's modeling

indicated that radionuclides will not reach the Dewey Lake, thus removing the formation as a unit needing consideration as a pathway (Docket A-93-02, Item II-G-26 and Docket A-93-02, Item II-G-28). The EPA concluded that Salado marker beds, and the Culebra were adequately identified and characterized to the level necessary for PA calculations.

2.2.1.1 Conceptual Models of Groundwater Flow

The DOE addresses issues related to groundwater flow and radionuclide transport within the context of a conceptual model of how the natural hydrologic system works on a large scale. The conceptual model of regional flow around the WIPP that is presented here is based on widely accepted concepts of regional groundwater flow in groundwater basins (see, for example, Hubbert 1940~~,~~***;*** Tóth 1963~~,~~***;*** and Freeze and Witherspoon 1967~~ in the bibliography~~).

See ***CCA*** Appendix MASS, Sections MASS.14.1 and MASS.14.2 for a summary of the DOE's activities leading to the acceptance of the groundwater basin model as a reasonable representation of groundwater flow in the region.

An idealized groundwater basin is a three-dimensional closed hydrologic unit bounded on the bottom by an impermeable rock unit (units with much smaller permeability than the units above), on the top by the ground surface, and on the sides by groundwater divides. The water table is the upper boundary of the region of saturated liquid flow. All rocks in the basin are expected to have finite permeability; in other words, hydraulic continuity exists throughout the basin. This means that the potential for liquid flow from any unit to any other units exists, although the existence of any particular flow path is dependent on a number of conditions related to gradients and permeabilities. All recharge to the basin is by infiltration of precipitation to the water table and all discharge from the basin is by flow across the water table to the land surface.

Differences in elevation of the water table across an idealized basin provide the driving force for groundwater flow. The pattern of groundwater flow depends on the lateral extent of the basin, the shape of the water table, and the heterogeneity of the permeability of the rocks in the basin. Water flows along gradients of hydraulic head from regions of high head to regions of low head. The highest and lowest heads in the basin occur at the water table at its highest and lowest points, respectively. Therefore, groundwater flows from the elevated regions of the water table, downward across confining layers (layers with relatively small permeability), then laterally along more conductive layers, and finally upward to exit the basin in regions where the water table (and by association, the land surface) is at low elevations. Recharge is necessary to maintain relief on the water table, without which flow does not occur.

Groundwater divides are boundaries across which it is assumed that no groundwater flow occurs. In general, these are located in areas where groundwater flow is dominantly downward (recharge areas) or where groundwater flow is upward (discharge areas). Topography and surface-water drainage patterns provide clues to the location of groundwater divides. Ridges between creeks and valleys may serve as recharge-type divides, and rivers, lakes, or topographic depressions may serve as discharge-type divides.

In the groundwater basin model, rocks can be classified into hydrostratigraphic units. A hydrostratigraphic unit is a continuous region of rock across which hydraulic properties are

similar or vary within described or stated limits. The definition of hydrostratigraphic units is a practical exercise to separate rock regions with similar hydrologic characteristics from rock regions with dissimilar hydrologic characteristics. Although hydrostratigraphic units often are defined to be similar to stratigraphic units, this need not be the case. Hydrostratigraphic unit boundaries can reflect changes in hydraulic properties related to differences in composition, fracturing, dissolution, or a variety of other factors that may not be reflected in the definition of stratigraphic formations.

Confining layers in a groundwater basin model can be characterized as allowing vertical flow only. The amount of vertical flow occurring in a confining layer generally decreases in relation to the depth of the layer. Flow in conductive units is more complicated. In general, flow will be lateral through conductive units. The magnitude (in other words, volume flux) of lateral flow is related to the thickness, conductivity, and gradient present in the unit. Gradients generally decrease in deeper units. The direction of flow is generally related to the distance the unit is from the land surface. Near the land surface, flow directions are influenced primarily by the local slope of the land surface. In deeper conductive units, flow directions are generally oriented parallel to the direction between the highest and lowest points in a groundwater basin. Thus, flow rates, volumes, and directions in conductive units in a groundwater basin are generally not expected to be the same.

In the WIPP region, the Salado provides an extremely low-permeability layer that forms the base for a regional groundwater-flow basin in the overlying rocks of the Rustler, Dewey Lake, and Santa Rosa. The Castile and Salado together form their own groundwater system, and they separate flow in units above them from that in units below. Because of the plastic nature of halite and the resulting low permeability, fluid pressures in the evaporites are more related to lithostatic stress than to the shape of the water table in the overlying units, and regionally neither vertical nor horizontal flow will occur as a result of natural pressure gradients in time scales relevant to the disposal system. (On a repository scale, however, the excavations themselves create pressure gradients that may induce flow near the excavated region.) Consistent with the recognition of the Salado as the base of the groundwater basin of primary interest, the following discussion is divided into three sections: hydrology of units below the Salado, hydrology of the Salado, and hydrology of the units above the Salado. The DOE has implemented the groundwater basin model in the conceptual model for groundwater flow within the rocks above the Salado. The details of the model are discussed in Section 6.4.6. Key modeling assumptions associated with the implementation are provided in Appendix ***PA, Attachment*** MASS, Section MASS.14.2.

Technical issues related to the Castile brine, Salado marker bed permeability, and Culebra hydraulic properties (e.g., transmissivity variation) were raised by the EPA in a letter dated December 19, 1996 (Docket A-93-02, Item II-I-01). The DOE provided additional information regarding these issues in letters dated January 24, 1997; February 7, 1997; April 15, 1997; June 13, 1997; June 27, 1997; and July 3, 1997 (Docket A-93-02, Items II-I-03, II-I-07, II-I-24, II-H-44, II-H-45, and II-H-46, respectively).

A request was made in the December 19, 1996 EPA letter (Docket A-93-02, Item II-I-01) that DOE provide general hydraulic characteristic information for all geologic units within the disposal system by revising a partially complete table included in the letter. The DOE letter,

dated February 14, 1997 (Docket A-93-02, Item II-I-08), transmitted the summary table providing the EPA with additional groundwater hydrology information related to hydraulic conductivity, storage coefficients, transmissivity, permeability, thickness, matrix and fracture characteristics, and hydraulic gradients for each of the geologic units in the WIPP disposal system. This information was reproduced as Figure IV-10 in EPA Technical Support Document for Section 194.14: Content of Compliance Certification Application (Docket A-93-02, Item V-B-3).

In addition, the EPA in the December 19, 1996 EPA letter (Docket A-93-02, Item II-I-01) required the DOE to include the following in the discussion of conceptual models for groundwater flow: (1) the estimated infiltration at the surface and to the Dewey Lake, and (2) the estimated vertical flow of groundwater into other transmissive units within the area surrounding the WIPP. The DOE provided the estimates in a letter dated February 26, 1997 (Docket A-93-02, Item II-I-10) to EPA.

2.2.1.2 Units Below the Salado

Units of interest to the WIPP project below the Salado are the Bell Canyon and the Castile. These units have quite different hydrologic characteristics. Because of its potential to contain brine reservoirs below the repository, the hydrology of the Castile is regarded as having the most potential of all units below the Salado to impact the performance of the disposal system.

2.2.1.2.1 Hydrology of the Bell Canyon Formation

The Bell Canyon is considered for the purposes of regional groundwater flow to form a single hydrostratigraphic unit about 300 m (1,000 ft) thick. Tests at five boreholes (Atomic Energy Commission [AEC]-7, AEC-8, ERDA-10, DOE-2, and Cabin Baby ***[CB]-1***) (***CCA*** Appendix HYDRO, ***pp.*** 29-31; Beauheim et al. 1983, ***pp.*** 4-9 to 4-12; Beauheim 1986, ***p.*** 61-1]) indicate a range of hydraulic conductivities for the Bell Canyon from 1.7×10^{-7} to 3.5×10^{-12} m/s~~ec~~ (5×10^{-2} ft/day to 1×10^{-6} ft/day). The pressure measured in the Bell Canyon at the DOE-2 and ***CB-1*** ~~Cabin Baby~~ boreholes ***at the time of the CCA ranged*** ~~ranges~~ from 12.6 to 13.3 megapascals. ***Under the current groundwater-monitoring program, Bell Canyon water levels are measured in only two wells: CB-1 and AEC-8 (see locations in Figure 2-6).***

After recovery from well work in 1999, the Bell Canyon water levels at CB-1 have remained steady for more that three years at 919 m (3,015 ft) above mean sea level (SNL 2003a). In contrast, since the beginning of 1994, the Bell Canyon water levels at AEC-8 have steadily risen by more than 32 m (106 ft) at a rate of approximately 0.5 m/month (1.6 ft/month) and stood at over 933.4 m (3,062 ft) above mean sea level (SNL 2003a) at the end of 2002. This water-level rise is hypothesized to be the result of deterioration of the well and not a response to actual Bell Canyon hydrologic conditions at this location. The well will be inspected and repaired or plugged and abandoned, as necessary, according to the requirements of DOE's groundwater monitoring program (see Appendix MON-2004).

Fluid flow in the Bell Canyon is markedly influenced by the presence of the extremely low-permeability Castile and Salado above it, which effectively isolate ~~it~~ ***the Bell Canyon*** from interaction with overlying units except where the Castile is absent because of erosion or

nondeposition, such as in the Guadalupe Mountains, or where the Capitan ***R***~~r~~eef is the overlying unit (Figures 2-~~26~~***30*** and 2-~~27~~***31***). Because of the isolating nature of the Castile and Salado, fluid flow directions in the Bell Canyon are sensitive only to gradients established over very long distances. At the WIPP, the brines in the Bell Canyon flow northeasterly under an estimated hydraulic gradient of 4.7 to 7.6 m/km (25 to 40 ft/mi) and discharge into the Capitan aquifer. Velocities are on the order of tenths of feet per year, and groundwater yields from wells in the Bell Canyon are 2.3 to 5.8 liters (0.6 to 1.5 gallons) per minute. The fact that flow directions in the Bell Canyon under the WIPP are inferred to be almost opposite to the flow directions in units above the Salado (see Section 2.2.1.4) is not of concern because, as discussed above, the presence of the Castile and Salado makes the flow in the Bell Canyon sensitive to gradients established over long distances, whereas flow in the units above the Salado is sensitive to gradients established by more local variations in water table elevation.

As discussed in Appendix DATA, oil companies are currently involved in deep-well injection at several locations outside of the WIPP site boundary. Specifically, salt water (brine) produced during oil-field exploitation is injected into the Bell Canyon and Brushy Canyon Formations. For nearly four years, the DOE has monitored injection rates and pressures for a cluster of six of these salt water injection wells located approximately 1.6 to 2.4 km (1 to 1.5 mi) northeast of well H-9. Table 2-5 summarizes the depth intervals of the injection zones for each well. The cluster of six wells is currently injecting approximately 800 to 950 m^3 per day (5,000 to 6,000 barrels per day) of salt water; however, in previous years, injection has ranged from approximately 480 to 1270 m^3 per day (3,000 to 8,000 barrels per day) (SNL 2003a). Wellhead injection pressures typically range between 5.5 to 6.9 MPa (800 to 1,000 psi). Because only two Bell Canyon wells are currently being monitored, the effect of salt-water injection on Bell Canyon water levels is speculative, but water levels in the Bell Canyon monitoring well nearest the cluster (i.e., CB-1, Figure 2-6) indicate no response to the injection. Additional discussion on potential effects of salt-water injection on the WIPP hydrologic setting is provided below in Section 2.2.1.4.

2.2.1.2.2 Castile Hydrology

As described in Section 2.1.3, the Castile is dominated by low-permeability anhydrite and halite zones. However, fracturing in the upper anhydrite has generated isolated regions with much greater permeability than the surrounding intact anhydrite. These regions are located in the area of structural deformation, as discussed in Section 2.1.6.1.1. The higher-permeability regions of the Castile contain brine at pressures greater than hydrostatic and have been referred to as brine reservoirs (see Figure 2-~~28~~***32***). **T**he fluid pressure measured by Popielak et al. ~~in~~ ***(***1983***)*** in the WIPP-12 borehole (12.7 megapascals) is greater than the nominal hydrostatic pressure for a column of equivalent brine at that depth (11.1 megapascals).

Therefore, under open-hole conditions, brine could flow upward to the surface through a borehole.

Results of hydraulic tests performed in the ERDA-6 and WIPP-12 boreholes suggest that the extent of the highly permeable portions of the Castile is limited. As discussed in Section 2.1.3.3 and modeled in Section 6.4.8, the vast majority of brine is thought to be stored in low-permeability microfractures; about ~~5~~ ***five*** percent of the overall brine volume is stored in large

Table 2-5. Depth Intervals of the Injection Zones of Six Salt-Water Injection Wells Located Near Well H-9 (after SNL 2003a)

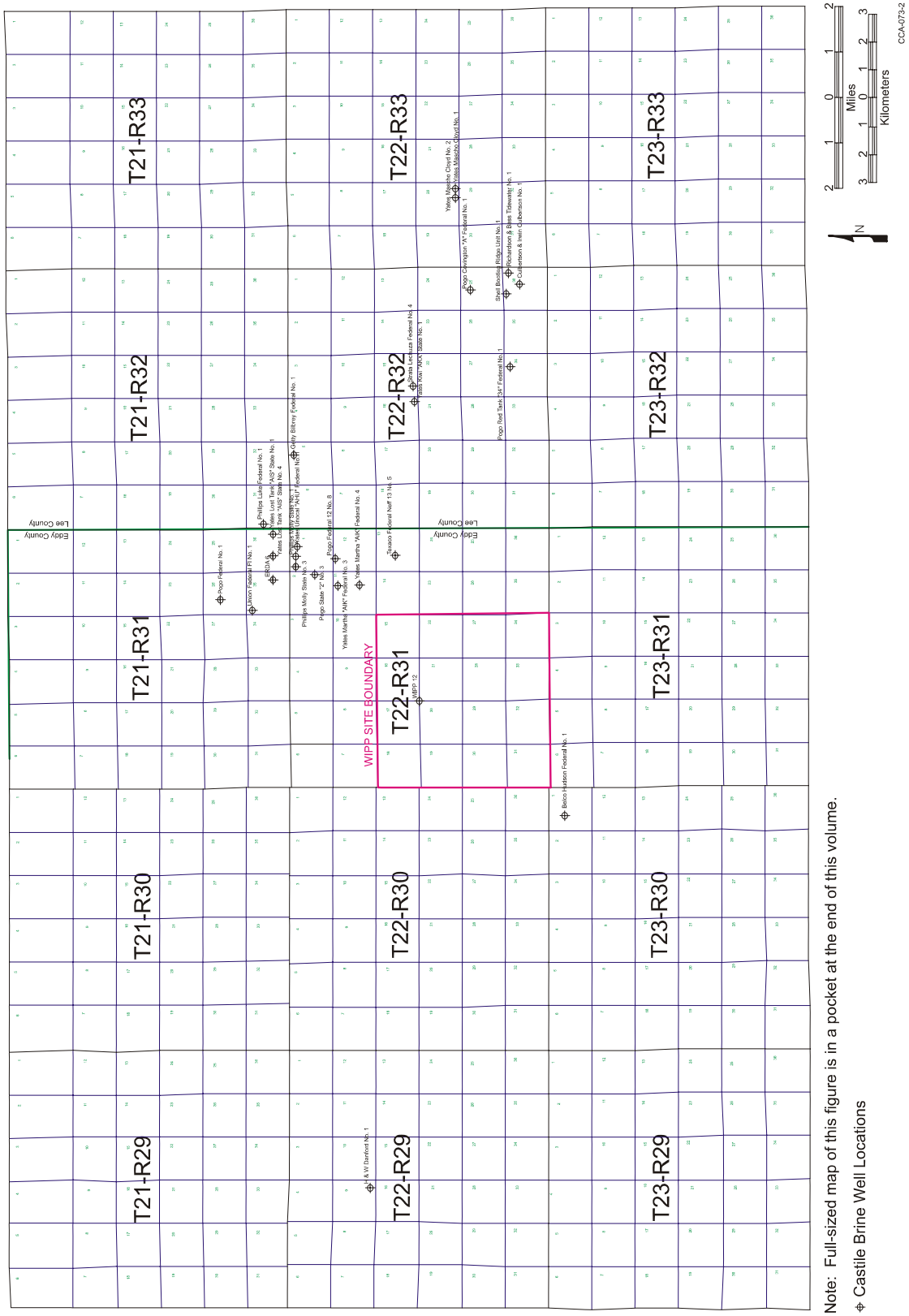
Injection Well	*Depth Interval of Injection Zone, feet*[1]
Cal Mon #5	*4,484 – 5,780*[2]
Sand Dunes 28F#1[3]	*4,295 – 5,570*[2]
Pure Gold B F#20[3]	*7,740 – 7,774*[4]
Todd 26F#2	*4,460 – 5,134*[2]
Todd 26F#3	*4,390 – 6,048*[2]
Todd 27F#16	*4,694 – 5,284*[2]

[1] *Below ground surface, bgs*
[2] *Bell Canyon Formation*
[3] *Wells hydraulically connected to same manifold*
[4] *Brushy Canyon Formation*

open fractures. The volumes of the ERDA-6 and WIPP-12 brine reservoirs were estimated by Popielak et al. ~~in~~ *(*1983*)* to be 100,000 m^3 (3.5×10^6 ft^3) and 2,700,000 m^3 (9.5×10^7 ft^3), respectively. The conceptual model of the Castile brine region is discussed in Section 6.4.8. The model uses parameter values derived from the ERDA-6 and WIPP-12 tests for quantifying some reservoir characteristics. The derivation of some model parameters in Appendix ***PA, Attachment*** PAR***, Table PAR-44***~~(Tables PAR-49 and PAR-50)~~ from the data discussed here is ***also*** given in ***CCA*** Appendix MASS, Section MASS.18.

A geophysical survey using time-domain electromagnetic (TDEM) methods was completed over the WIPP-12 brine reservoir and the waste disposal panels (The Earth Technology Corporation 1988). The TDEM measurements detected a conductor interpreted to be the WIPP-12 brine reservoir and also indicated that similar brine occurrences may be present within the Castile under a portion of the waste disposal panels. ~~In a recent geostatistical analysis,~~ Powers et al. (1996) used 354 drill holes and 27 Castile brine occurrences to establish that there is an ~~8~~ ***eight*** percent probability of a hole drilled into the waste panel region encountering brine in the Castile. This analysis ~~is~~ ***was*** included ~~in the application~~ as ~~Attachment 18-6 in~~ ***CCA*** Appendix MASS, ***Attachment 18-6***.

Initially, the EPA found that DOE's discussion of the size, orientation, and repressurization potential of the Castile brine reservoirs was not well supported (Docket A-93-02, Item II-I-27). The EPA required the probability of encountering a brine reservoir to be sampled between a range of 1 and 60 percent in the PAVT (Docket A-93-02, Item II-G-26 and Docket A-93-02, Item II-G-28). In addition, the EPA modified the values for parameters such as bulk compressibility of Castile rock so that the brine reservoir sampling used in the PA would better represent the larger, higher-end possible brine volumes. Further information on the EPA review of these parameters may be found in CARD 23—Models and Computer Codes (EPA 1998f), EPA Technical Support Document for Section 23: Models and Computer Codes (Docket A-93-02, Item V-B-6), and EPA Technical Support Document for Section 23: Ground



Note: Full-sized map of this figure is in a pocket at the end of this volume.

⌖ Castile Brine Well Locations

Figure 2-~~28~~32. Recent Occurrences of Pressurized Brine in the Castile

Water Flow and Contaminant Transport Modeling at WIPP (Docket A-93-02, Item V-B-7). The PAVT used modified Castile brine reservoir characteristics and showed that the WIPP still meets the containment requirements (Docket A-93-02, Item II-G-26, Figure 7-2).

Based on these analyses, there was no significant impact on releases over the range of probabilities sampled. However, the DOE identified this parameter as a compliance monitoring parameter (see Appendix DATA) and conducts annual surveys as part of the Delaware Basin Monitoring Program (see Appendix MON-2004) to identify Castile brine encounters by drillers in the basin. Since the CCA, these surveys have identified five additional brine encounters. Appendix DATA provides extensive information pertinent to the brine reservoirs. The Delaware Basin Monitoring Annual Report (DOE 2002a), for example, documents three of the five Castile brine encounters. Two were located near well ERDA-6 northeast of the WIPP site and one was located to the southwest of the site. In the two encounters northeast of the site, reports indicated several hundred barrels of brine per hour were produced, but all brine was contained within the pits; thus, it was not necessary to file a report with the New Mexico Oil Conservation Division. In the other encounter, initial flows of from 64 to 79 m^3 (400 to 500 barrels) per hour were observed, but flow dissipated within hours of the encounter. Because of the relatively large number of boreholes (345 wells in the nine-township area drilled between 1996 and 2002), the five brine encounters that occurred do not substantially change the probability defined by Powers et al. (1996) and are unlikely to have any significant impact on PA given the large range of probabilities sampled in the PAVT analyses.

The origin of brine in the Castile has been investigated geochemically. Popielak et al. (1983, ***p.*** 2) concluded that the ratios of major and minor element concentrations in the brines indicate that these fluids originated from ancient seawater and that no evidence exist***s*** for fluid contribution from present meteoric waters. The Castile brine chemistries from the ERDA-6 and WIPP-12 reservoirs are distinctly different from each other and from local groundwaters. These geochemical data indicate that brine in reservoirs has not mixed to any significant extent with other waters and has not circulated. The brines are saturated, or nearly so, with respect to halite and, consequently, have little potential to dissolve halite. The chemical composition of Castile brine is given in Table 2-~~5~~***6***. ***It's the*** use ***of the chemical composition of Castile brine*** as a parameter ~~model~~ in the conceptual model of repository performance is discussed in ~~the~~ ***Appendix PA.*** ~~SOTERM (Section SOTERM.2.2.1).~~

2.2.1.3 Hydrology of the Salado

As described in Section 2.1.3, the Salado consists mainly of halite and anhydrite. A considerable amount of information about the hydraulic properties of these rocks has been collected through field and laboratory experiments. ~~Appendices HYDRO (41-42) and~~ ***Appendix PA*** ~~PAR~~ summarize***s*** this information.

Hydraulic testing in the Salado in boreholes in the WIPP underground ***repository*** provided quantitative estimates of the hydraulic properties controlling brine flow through the Salado (Beauheim et al. 1991***a***; Beauheim et al. 1993; Domski et al. 1996***; Roberts et al. 1999***). ***This work was summarized by Beauheim and Roberts (2002).*** The stratigraphic intervals tested

Table 2-~~5~~6. WIPP Salado and Castile Brine Compositions

	Salado Brine Average (n between 82 and 96)		Castile ERDA-6	Castile WIPP-12
Specific Gravity	1.22	± 0.01	1.216	1.215
pH	6.1		6.17	7.06
Sodium	79100	± 2,100	112000	138000
Potassium	15900	± 800	3800	2900
Calcium	282	± 38	490	350
Magnesium	22700	± 1,400	450	1600
Boron	1450	± 120	680	990
Lithium	nd		240	280
Silicon	1.6	± 0.7	21	27
Strontium	1.6	± 0.6	18	19
Ammonium	148	± 16	1119	476
Nitrate	0.8	(median)	2746	2436
Chloride	193000	± 4,000	170000	178000
Sulfate	17000	± 900	16000	18000
Bromide	1500	± 60	880	510
Iodide	14.8	± 3.1	28	24
Alkalinity (as HCO_3^- equivalent)[1]	883	± 123	2600	2700
Total Organic Carbon	54	± 50	nd	nd
Total Dissolved Solids	374000	± 13,000	330000	328000

[1] Alkalinity measured to an endpoint pH of 2.5 and expressed as equivalent bicarbonate.

Legend:

nd not determined

Note: All determinands reported in units of milligrams per liter ***(mg/L)***, except for pH and Specific Gravity. Only determinands with a concentration in excess of 10 ***mg/L*** in at least one of the brines are shown. Data taken from DOE (1994, Table 3-3) and Popeliak et al. (1983, Table C.2).

include both pure and impure halite***, as well as anhydrite***. Tests influence rock as far as 10 m (33 ft) distant from the test zone and therefore provide results ***representative of rock beyond the zone of mechanical disturbance associated with drilling of the test boreholes*** ~~that are not significantly influenced by disturbances associated with the tests themselves~~. Because tests close to the repository are within the DRZ that surrounds the excavated regions (see Section 3.2), results of the tests farthest from the repository are most representative of undisturbed conditions.

Fifty-nine intervals were isolated and monitored and/or tested in 27 boreholes. Thirty-five of the intervals isolated halite beds, and 24 isolated anhydrite beds. Permeability estimates were

obtained from 14 of the halite intervals and 16 of the anhydrite intervals. ~~Twenty-two hydraulic tests have been performed in impure halite, and two in pure halite.~~ Interpreted permeabilities using a Darcy-flow model vary from ***2***~~1~~ $\times 10^{-23}$ to ***3***4 $\times 10^{-1}$***6***~~8~~ m^2 for impure halite intervals***, with the lower values representing halite with few impurities and the higher values representing intervals within the DRZ of the excavations***. Interpreted formation pore pressures vary from ***atmospheric***~~0.3~~ to 9.***8***~~7~~ ***MPa*** for impure halite, with the lower pressures ~~believed to~~ show***ing the*** effects of the DRZ. Tests in pure halite show no observable response, indicating either extremely low permeability ($<10^{-23}$ m^2), or no flow whatsoever, even though appreciable pressures are applied to the test interval***s***.

~~Fourteen hydraulic tests have been performed in anhydrite.~~ Interpreted permeabilities using a Darcy-flow model vary from 2 $\times 10^{-20}$ to ***9*** ~~7~~ $\times 10^{-18}$ m^2 for anhydrite intervals. Interpreted formation pore pressures vary from atmospheric to 1***4***~~2~~.***8***~~5~~ ~~megapascals~~ ***MPa*** for anhydrite intervals (Beauheim ***and Roberts 2002 p. 82*** ~~et al. 1993, 139~~). Lower values are caused by depressurization near the excavation.

As discussed in Beauheim and Roberts (2002), permeabilities of some tested intervals have been found to be dependent on the pressures at which the tests were conducted, which is interpreted as the result of fracture apertures changing in response to changes in effective stress. Flow dimensions inferred from most test responses are subradial, meaning that flow to/from the test boreholes is not radially symmetric but is derived from a subset of the rock volume. The subradial flow dimensions are believed to reflect channeling of flow through fracture networks, or portions of fractures, that occupy a diminishing proportion of the radially available space, or through percolation networks that are not "saturated" (that is, fully interconnected). This is probably related to the directional nature of the permeability created or enhanced by excavation effects. Other test responses indicate flow dimensions between radial and spherical, which may reflect propagation of pressure transients above or below the plane of the test interval or into regions of increased permeability (e.g., closer to an excavation). The variable stress and pore-pressure fields around the WIPP excavations probably contribute to the observed non-radial flow dimensions.

The properties of anhydrite interbeds have also been investigated in the laboratory. Tests were performed on three groups of core samples from MB 139 as part of the Salado Two-Phase Flow Laboratory Program. The laboratory experiments provided porosity, intrinsic permeability, and capillary pressure data. Analysis of capillary pressure test results indicate***s*** a threshold pressure of less than 1 ***MPa***. Both laboratory and field data were used to establish hydraulic parameters for the Salado for ***PA*** as summarized in ***CCA*** Appendix PAR (Tables PAR-6 and PAR-7).

The EPA believed the DOE's initial information on anhydrite characteristics and response to high pressure was unclear. In response, the DOE provided the EPA with data on modeling implementation and anhydrite characterization clarifying DOE's approach to anhydrite fracture properties under pressurized conditions. The EPA concluded that while fracture distribution and subsequent fluid flow in the Salado marker beds cannot be detailed, the general application of fracturing and subsequent fluid flow appears to be an adequate representation of overall site conditions. The EPA also concluded that DOE's modeling of fractures within Salado anhydrite marker beds is acceptable. For further discussion on this topic, see CARD 23—Models and Computer Codes, Section 1.3.2.