

Hydrogeology of the WIPP Site

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Introduction

The northern part of the Delaware Basin is filled with approximately 24,000 ft of Phanerozoic sedimentary rocks (Hills, 1984). At the WIPP site, the upper 4,000 ft of sedimentary rocks contain evaporites (Powers and others, 1978) (Figure 1). The nearest major aquifer is the Capitan reef, which is located about 10 miles from the WIPP site (Figure 2). The water-bearing zones within the rocks which underlie, host, and overlie the WIPP repository have low permeabilities and storativities, are generally confined, and contain waters with high salinities and long residence times. As part of WIPP site characterization activities, each of the major water-bearing zones has been investigated. Several studies continue to supplement data and refine our understanding of the hydrogeologic system. The major formations of interest at the WIPP site are discussed below, in stratigraphically ascending order.

Bell Canyon Formation

The Bell Canyon Formation is the uppermost formation in the Permian-age Delaware Mountain Group (Figure 1). The upper Bell Canyon is subdivided into five informal members: the Hays sandstone, Olds sandstone, Ford shale, Ramsey sandstone, and Lamar limestone (Figure 3). Individual channel sandstone units are separated laterally by stratigraphically equivalent siltstones and shales.

The most significant hydrologic units within the Bell Canyon are the channel sandstones. The channel sandstone units trend roughly

northeast/southwest through the basin (Figure 4). Intergranular porosity ranges from 20 to 28 percent, while hydraulic conductivities range from 3×10^{-2} to 2×10^{-1} ft/day (Berg, 1979). The siltstones and shaley siltstones have porosities ranging from 10 to 20 percent and hydraulic conductivities less than 2×10^{-4} ft/day (Mercer, 1983). Tests conducted during WIPP site characterization activities at boreholes AEC-7, AEC-8, and ERDA-10 showed the hydraulic conductivities of Bell Canyon sandstones, siltstones, and shales to range from 2×10^{-6} to 5×10^{-2} ft/day (Mercer, 1983). Mercer (1983) reports these values to be consistent with the range of permeability values reported for the Bell Canyon by various oil companies.

Within the Bell Canyon, the shallowest significant hydrologic unit is the Ramsey sandstone. At borehole DOE-2, the most permeable portion of the Ramsey appears to be about 28 ft thick (Beauheim, 1986). The Lamar limestone acts as a confining layer. The Ramsey consists of laterally and vertically interlayered sandstones, siltstones, and shales deposited as deep-basin channels and related deposits (Lappin, 1988).

The Hays sandstone is the most permeable and transmissive unit within the Bell Canyon near the WIPP site based on hydrologic testing in two other WIPP wells (Cabin Baby-1 and DOE-2) (Beauheim and others, 1983; Beauheim, 1986). Bell Canyon hydraulic conductivities were reported by Beauheim and others (1983) to range from 1×10^{-6} (Lamar) to 4×10^{-3} (Hays) ft/day at Cabin Baby-1 and by Beauheim (1986) to be 2×10^{-4} (Ramsey) to 6×10^{-3} (Hays) ft/day at DOE-2.

SYSTEM	SERIES	GROUP	FORMATION	MEMBER
RECENT	RECENT		SURFICIAL DEPOSITS	
QUATERNARY	PLEISTOCENE		MESCALERO CALICHE	
			GATUNA	
TRIASSIC		DOCKUM	UNDIVIDED	
PERMIAN	OCHOAN		DEWEY LAKE RED BEDS	
			RUSTLER	Forty-niner
				Magenta Dolomite
				Tamarisk
				Culebra Dolomite
	unnamed			
			SALADO	
			CASTILE	
	GUADALUPIAN	DELAWARE MOUNTAIN	BELL CANYON	
			CHERRY CANYON	
BRUSHY CANYON				

Figure 1. Generalized stratigraphic column of the Delaware Mountain Group and younger sedimentary rocks at and near the WIPP site.

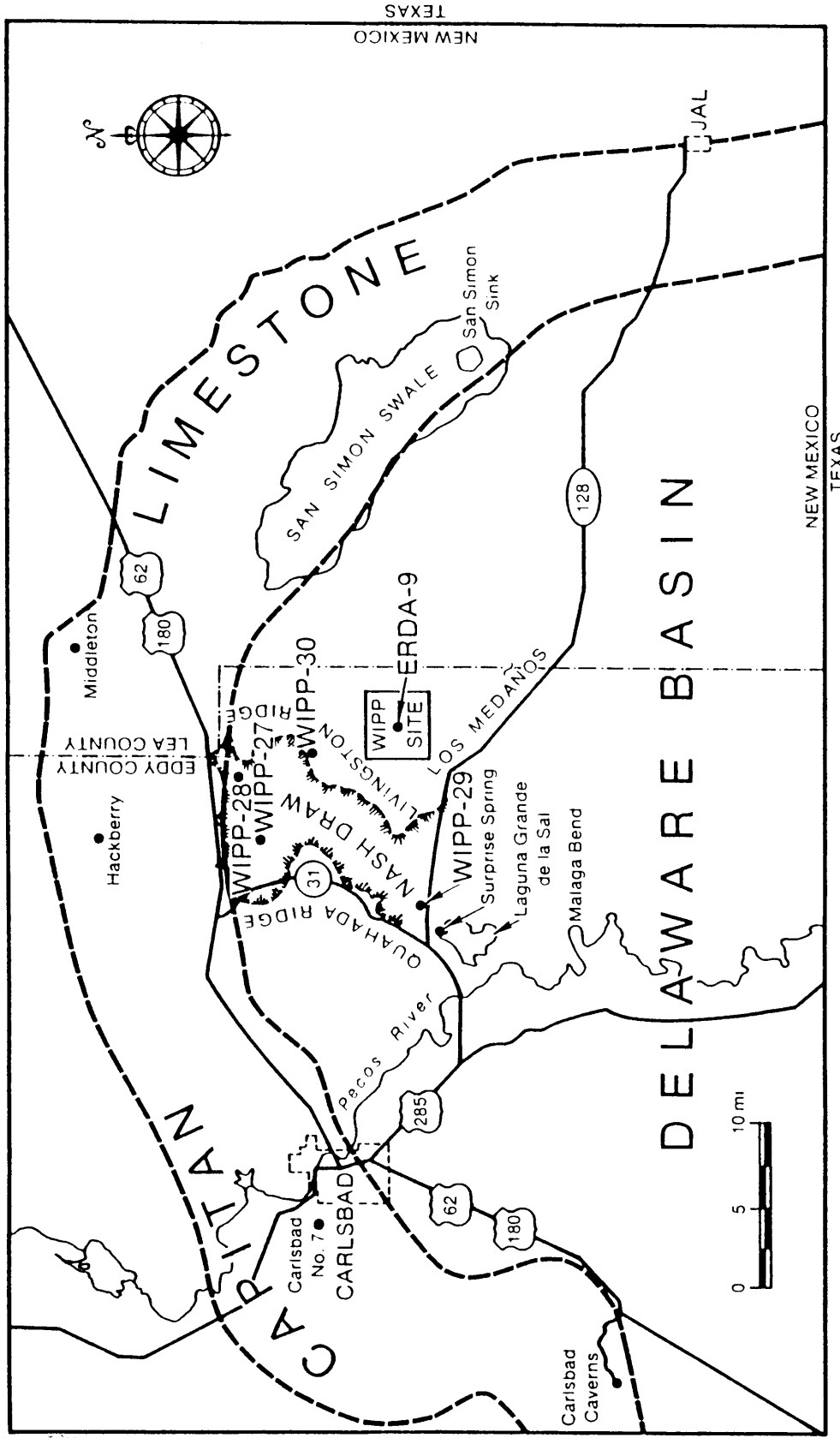


Figure 2. General geological and hydrological setting of the WIPP site relative to the northern Delaware Basin.

SYSTEM	SERIES	FORMATION	MEMBER
PERMIAN	OCHOAN	CASTILE	
	GUADALUPIAN	BELL CANYON	Lamar
			Ramsey
			Ford
			Olds
			Hays
	CHERRY CANYON		

Figure 3. Informal subsurface stratigraphic units of the Bell Canyon Formation, the uppermost formation of the Delaware Mountain Group.

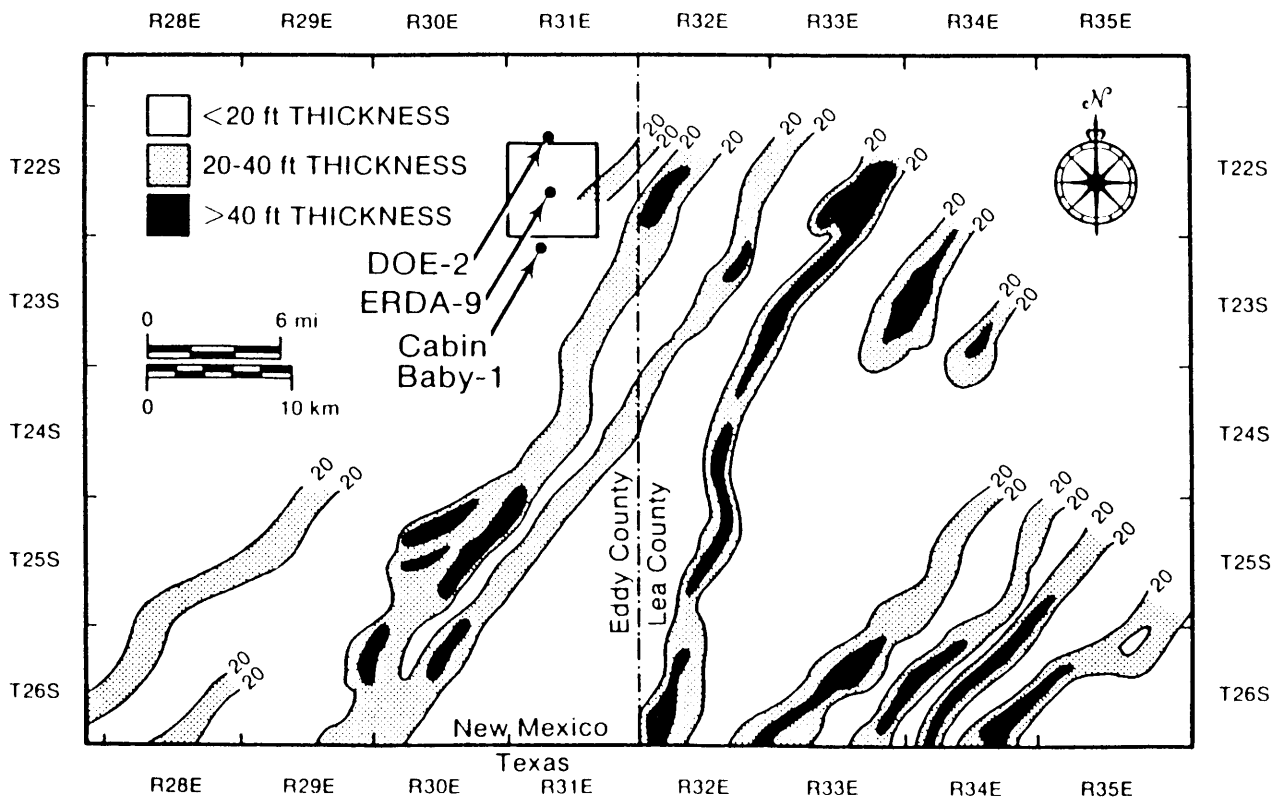


Figure 4. Lateral distribution and thicknesses of channel sands in the informal Ramsey member of the Bell Canyon Formation in the northern Delaware Basin (from Lappin, 1988).

Transmissivity values at Cabin Baby-1 and DOE-2 ranged from 5×10^{-5} to 6×10^{-1} ft²/day (Beauheim and others, 1983; Beauheim, 1986).

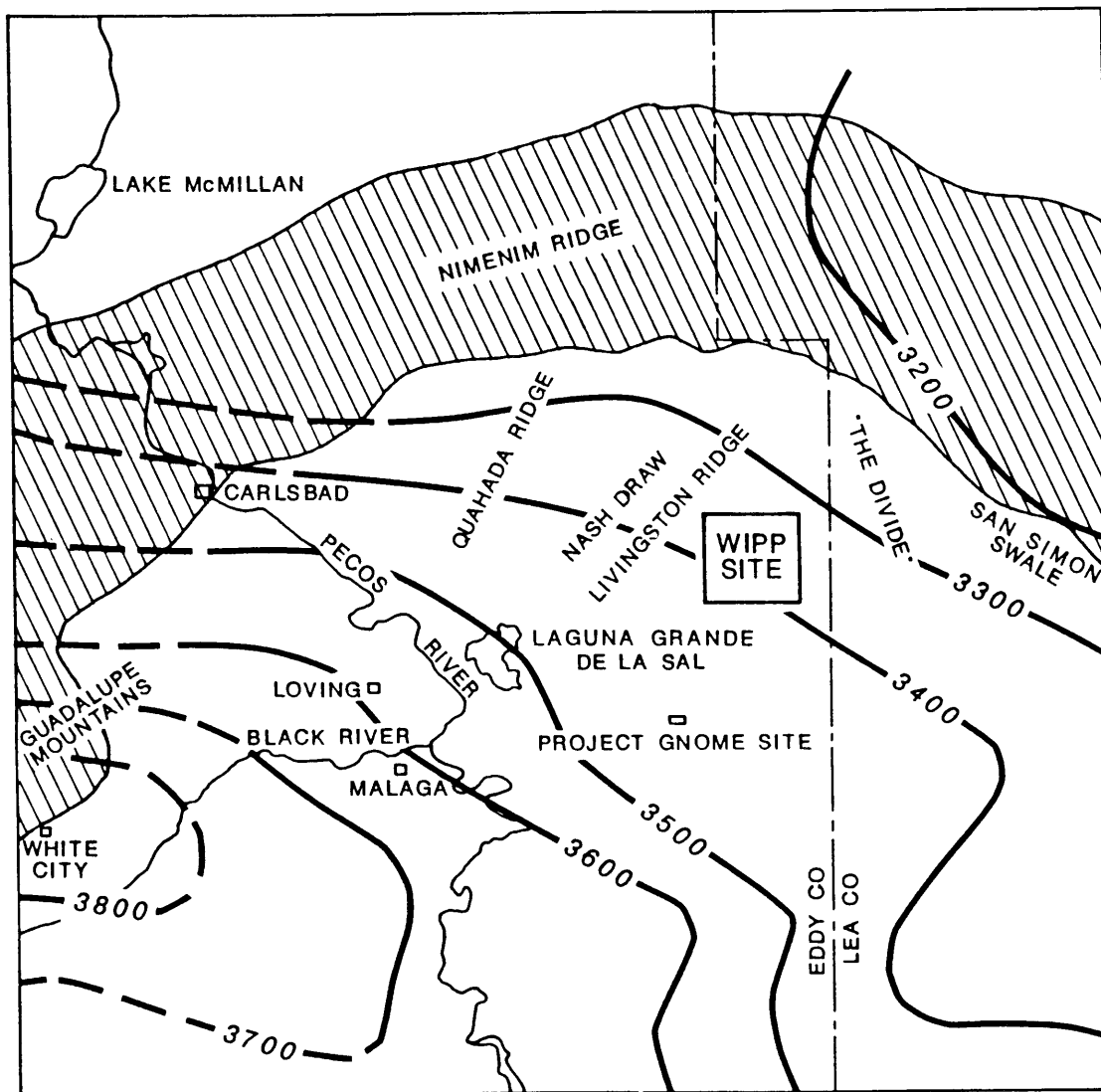
Mercer (1983) revised the equivalent freshwater potentiometric surface map of Hiss (1976) to include data from WIPP boreholes (Figure 5). The potentiometric contours generally follow the regional structural trend. Flow directions are generally northeastward across the WIPP site area (Figure 5). Recharge occurs along the western margin of the Delaware Basin. The salinity of groundwater within the Bell Canyon increases from fresh to very saline (300,000 mg/L TDS) from the recharge area to the structural trough of the basin (Grauten, 1965; McNeal, 1965), indicating abundant rock-water interaction. The Bell Canyon may discharge into the Capitan aquifer along the northeastern rim of the basin, but little is known about Capitan hydraulic heads at those depths.

Castile Formation

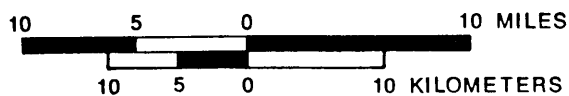
The Castile Formation directly underlies the Salado Formation (Figure 1). It is an aquitard that forms a hydrologic barrier between the Bell Canyon Formation and the Salado Formation.

General Hydrology

Near the WIPP site, the Castile Formation is approximately 1,200 ft (400 m) (Lappin, 1988), and it consists of thick units of laminated anhydrite/carbonate and halite (Figure 6). The Castile has low permeabilities and usually only minute quantities of in situ fluid. Regional hydraulic gradients have never been established within the Castile across the Delaware Basin, although localized zones of brine and gas under high pressure have been encountered by several drillholes intersecting deformed and fractured anhydrite within the Castile. The hydraulic properties of undisturbed Castile anhydrite and halite have not been determined because the transmissivity



Contour Interval is 100 feet.



SCALE

EXPLANATION

 GUADALUPIAN REEF COMPLEX

Figure 5. Contour map of the estimated freshwater head elevation for the hydrologic unit in the upper part of the Bell Canyon Formation (from Mercer, 1983).

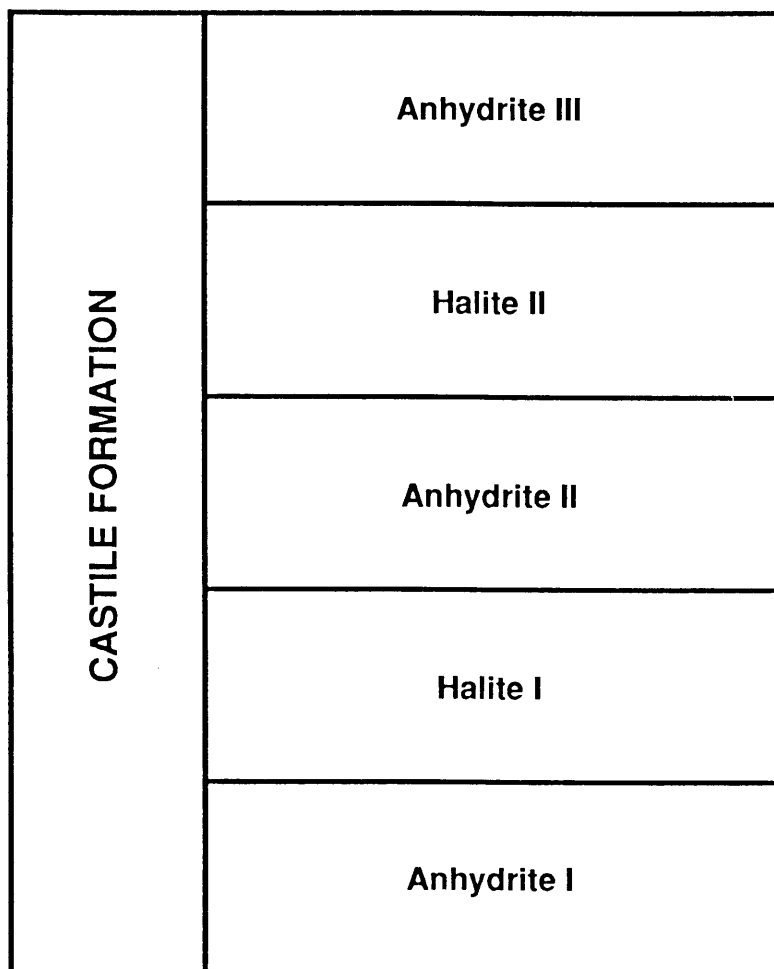


Figure 6. Informal stratigraphic units of the Castile Formation near the WIPP site.

is too low to measure with current test methods. Hydraulic properties of fractured anhydrite brine reservoirs have been estimated during testing of WIPP boreholes ERDA-6 and WIPP-12 (Popielak and others, 1983).

Castile Brine Occurrences

Pressurized brine and gas occur in some Castile anhydrite that is fractured and deformed (Anderson and Powers, 1978). Borns and others (1983) and Borns and Shaffer (1985) examined deformation in the Castile near the WIPP site and in larger areas of the basin. Borns and others (1983) concluded that the Castile structures were due to gravity-driven salt flowage/deformation.

Isolated zones of pressurized brine have been encountered in the Castile at several hydrocarbon exploration holes and two WIPP drillholes, ERDA-6 and WIPP-12 (Figure 7)

(Popielak and others, 1983). The brine is capable of discharging at the surface. Popielak and others (1983) concluded that the brines originated from ancient seawater with no fluid contributions from present meteoric waters, based upon analysis of major and minor element concentrations in the brines. The gas and brine chemistries, and some isotopic compositions, are distinctly different for each reservoir, indicating isolation and a distinct origin for each reservoir. The brines are saturated, or nearly so, with respect to halite. The reservoirs occur in fractured anhydrites deformed by salt anticlines (Figure 8). Most of the brine is believed to be stored in low-permeability microfractures with only about 5 percent of the total brine in large fractures. The volumes of the ERDA-6 and WIPP-12 brine reservoirs are estimated to be 3.5×10^6 and 9.6×10^7 ft³, respectively. Hydraulic heads within the reservoirs are higher than in other regional groundwater

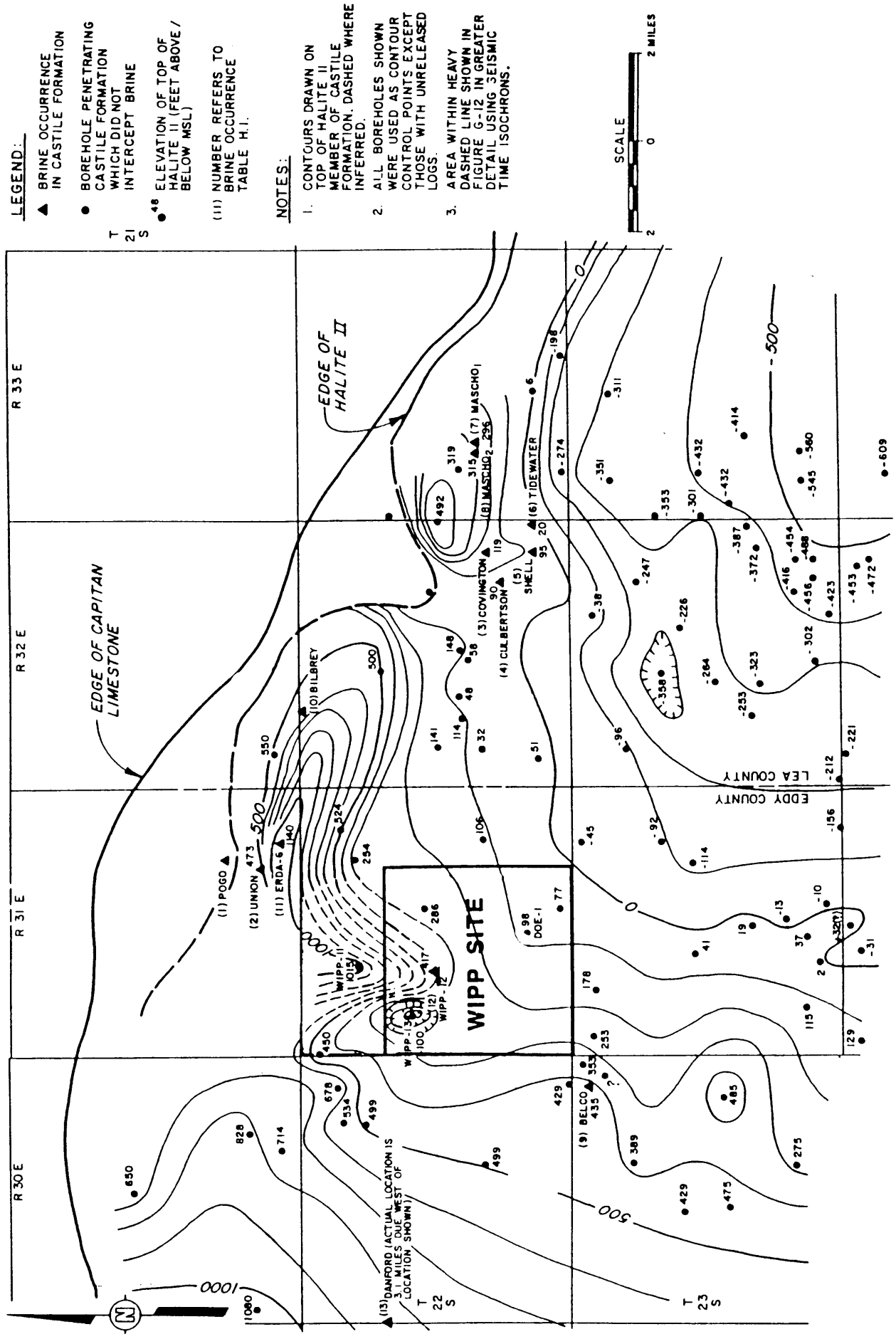


Figure 7. Pressurized brine occurrences in the Castile Formation relative to structure on the top of Halite 2 unit (from Popielak and others, 1983).

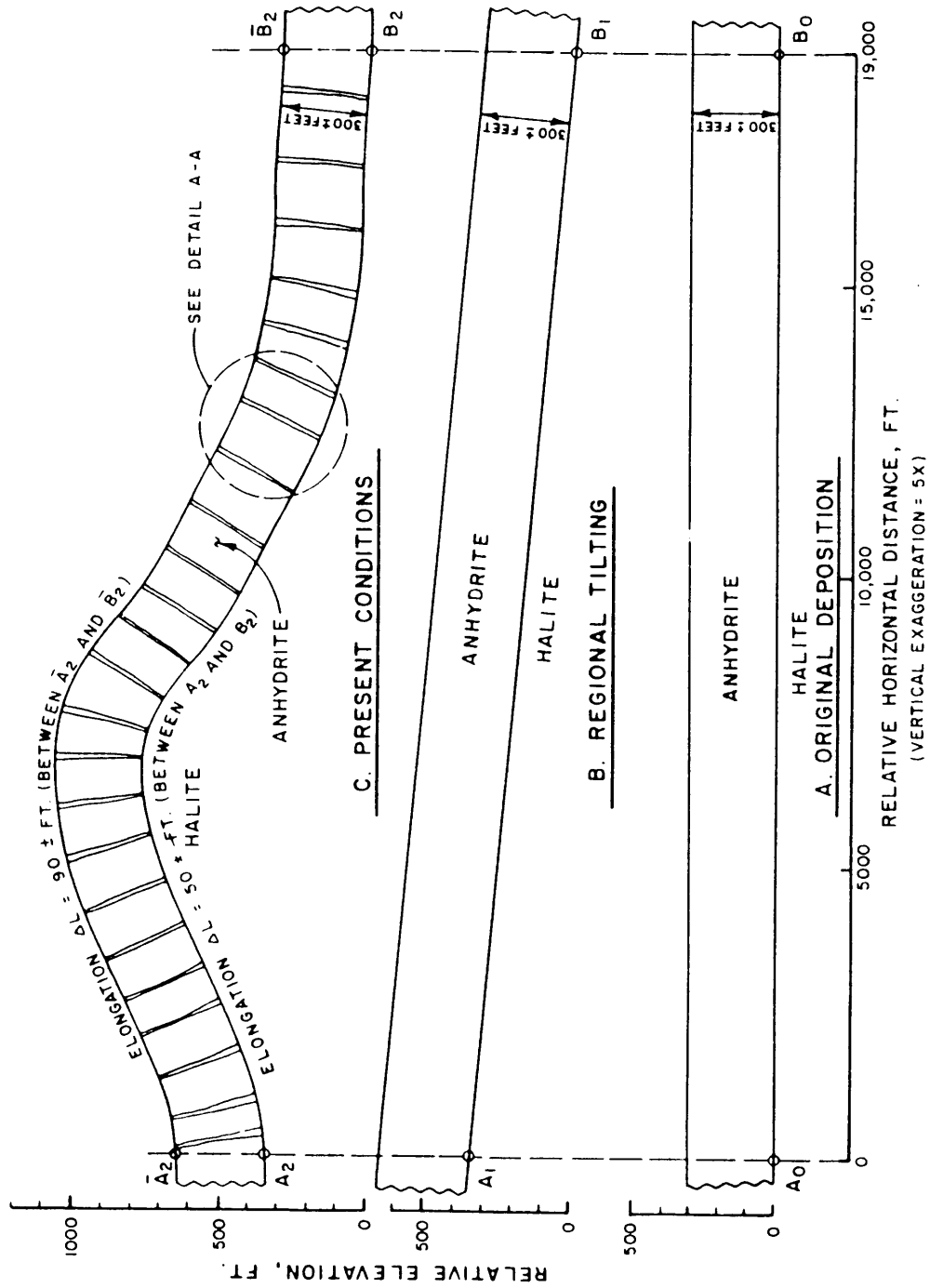
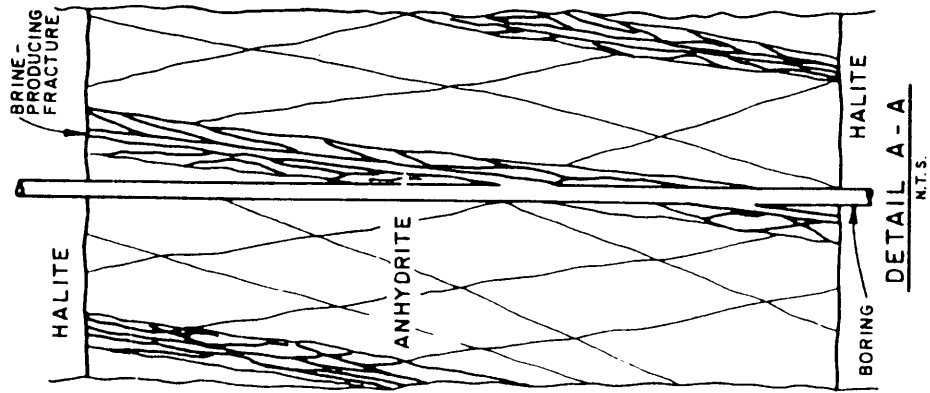


Figure 8. Schematic of brine reservoir formation (from Popielak and others, 1983).

systems, and they have been maintained for at least a million years (Barr and others, 1978).

Time-domain electromagnetic (TDEM) methods suggest that a portion of a brine reservoir underlies the northern and northeastern most waste-emplacment panels (Figure 9; Earth Technology, 1988).

Salado Formation

The Salado Formation is informally divided into three members: unnamed lower and upper members, and a middle member, locally designated the McNutt potash zone (Figure 10). Important sulfate beds are numbered as marker beds. About 85 to 90 percent of the Salado is halite (Jones and others, 1973). Unlike the Castile, the Salado extends well beyond the Capitan reef onto the Northwestern Shelf and the Central Basin Platform. The Salado has been erosionally removed and dissolved by circulating groundwaters along the west and south sides of the Delaware Basin, leaving brecciated insoluble material.

General Hydrology

The Salado is a regional aquiclude; within most of the Delaware Basin, the Salado acts as a regional barrier to fluid flow (Lappin, 1988). Regional hydraulic gradients within Salado halites and interbeds, if present, have never been established. Pressurized brine flows of significant size have never been encountered during the hydrologic testing of the Salado (Lappin, 1988), although a slow build-up of pressure has been observed during the hydrologic testing of some boreholes (Mercer, 1987). Mercer (1987) reports a maximum observed pressure of 472 psi at the WIPP-12 wellhead and suggests that the pressures are supported by a very small volume of brine produced from anhydrite and/or clay interbeds.

Pressurized gas has been encountered within the Salado in surface boreholes, local potash mines, and WIPP excavations (Lappin, 1988). The origin of this gas has not been firmly established. Mercer (1987) reports a large gas flow (predominantly nitrogen) at AEC-8, a surface drillhole, of 2×10^7 ft³ with little

apparent depletion of the gas reservoir. This inflow occurred roughly one year after original drilling. Deal and Case (1987) report that gas exsolves from Salado brines collected in the WIPP underground. The other gas occurrences may be attributable to exsolution of dissolved gases during fluid-pressure relief around boreholes and excavations.

Where halite-unsaturated groundwaters have actively circulated through the Salado, dissolution and collapse have resulted (Holt and others, in prep.). On the basis of geophysical logs, Holt and others (in prep.) evaluated the extent of Salado dissolution in the vicinity of the WIPP site (Figure 11). Although Salado dissolution is currently active in Nash Draw and areas adjacent to the Pecos River, most of the dissolution of Salado materials east of the Pecos River developed during the Cenozoic in response to hydraulic gradients associated with the ancestral Pecos River (Holt and others, in prep.). The Salado was dissolved in response to circulating groundwater related to near-surface groundwater regimes, not by regional confined groundwater systems (Holt and others, in prep.).

Near-Facility Hydrology

The Salado Formation is responding hydrologically to pressure gradients around the WIPP excavations. Brine inflow to drifts and shafts has been well documented (e.g., Deal and Case, 1987; Holt and Powers, 1986, in prep; Nowak and others, 1988). Brine has been observed accumulating in boreholes, as weeps on the surfaces of excavations, and seeping from anhydrite and polyhalite interbeds in the air-intake shaft (Deal and Case, 1987; Holt and Powers, 1990). In most boreholes, fluid-inflow rates vary from a few hundredths to a few tenths of a liter per day (Deal and Case, 1987; Nowak and others, 1988). Brine inflow into boreholes usually is minimal following the initial drilling, increases to a maximum, and then slowly decreases with time (Deal and Case, 1987). Holes drilled downward generally accumulate more brine than holes drilled upward. Brine inflow varies with stratigraphy (Deal and Case, 1987).

Bredehoeft (1988) suggested that the Salado should be considered a saturated medium. Stratigraphic and lateral variability within the

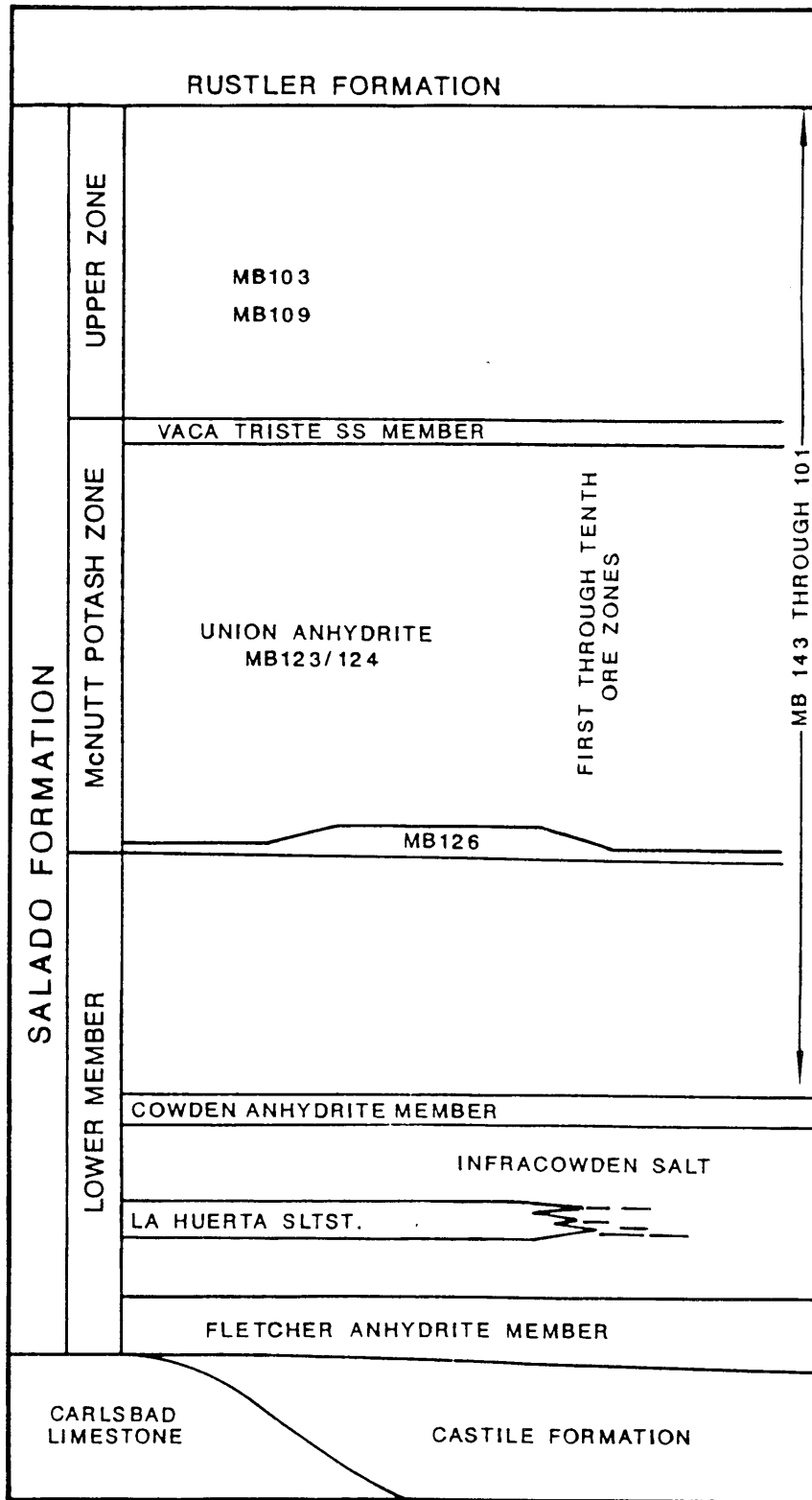


Figure 10. General Salado Formation stratigraphy in the vicinity of the WIPP site (from Holt and others, in prep.).

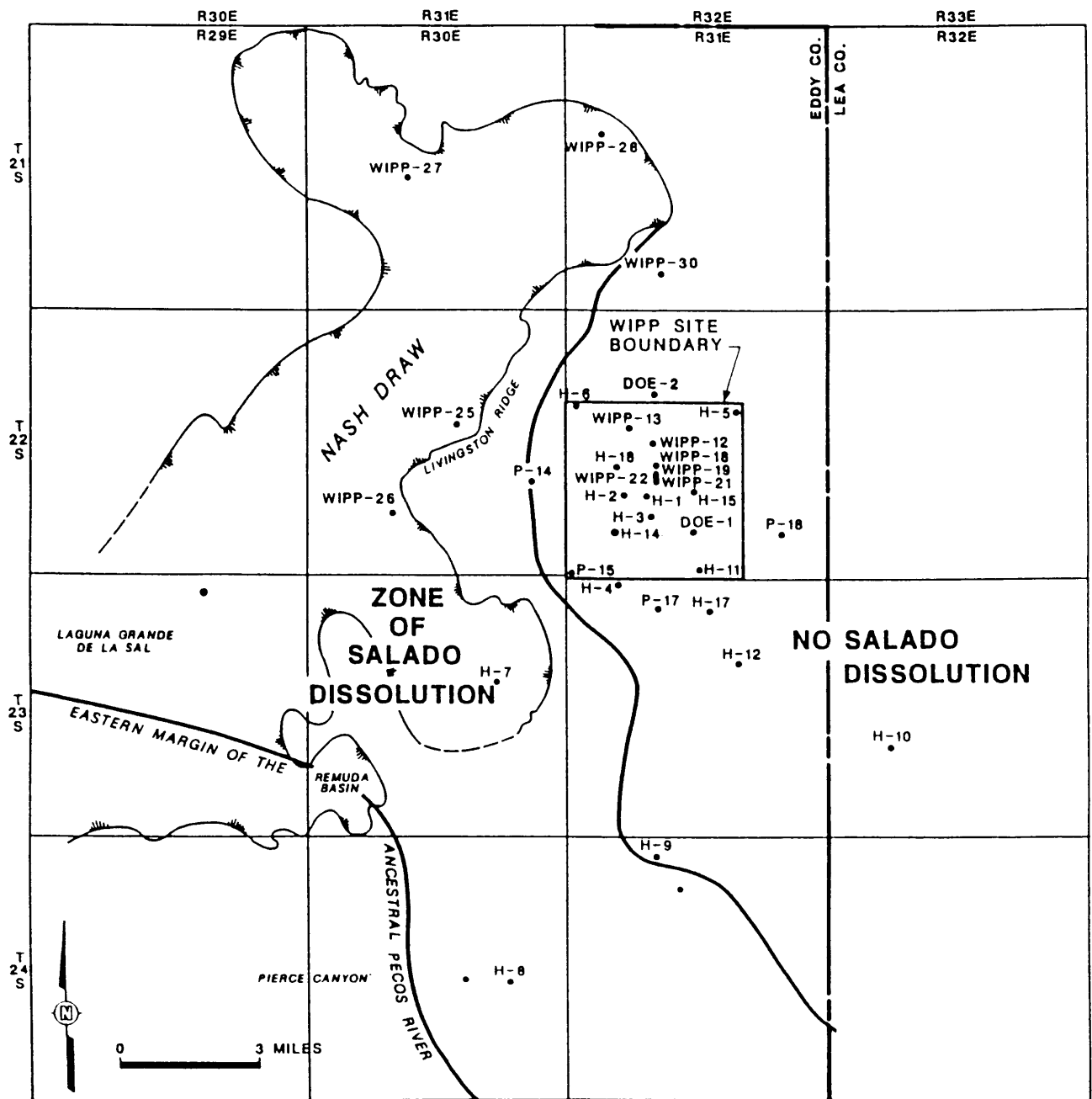


Figure 11. Interpreted extent of Salado dissolution (from Holt and others, in prep.).

salt is high and currently precludes any direct interpretation of the degree of saturation in the Salado.

Continuing hydraulic testing shows that the hydraulic conductivity of argillaceous halite ranges from about 4×10^{-9} to 7×10^{-8} ft/day (Beauheim and others, in prep.). The hydraulic conductivity of relatively pure halite has proven to be immeasurably low ($<10^{-10}$

ft/day), if it exists at all. Marker Bed 139, an anhydrite interbed approximately 3 ft thick, has hydraulic conductivities ranging from 1×10^{-7} to 2×10^{-6} ft/day, apparently depending on the amount of fracturing present. Pore pressures show a distinct gradient towards the underground facility, with pressures as high as 1700 psi being measured at distances of 35 ft and beyond from the excavations.

Generally, permeability increases around the facility within 5-10 ft due to fracturing and possibly matrix dilation (Borns and Stormont, 1988). Fractures develop parallel to the excavation, while low-angle fractures form in the corners of the rooms (Westinghouse, 1988). Some high-angle fractures develop in Marker Bed 139, and pre-existing fractures may open further (Westinghouse, 1988). The fracture development process is time and excavation-geometry dependent (Borns and Stormont, 1988).

The brines which flow into the WIPP facility are not derived from fluid inclusions, but instead are grain-boundary fluids with residence times of at least several million years (Stein and Krumhansl, 1986). Geophysical measurements suggest the far-field brine content of halite to be around two weight percent and a near-field brine content of approximately one weight percent (Pfeifer, 1987; Hudson, 1987).

Rustler Formation

The Rustler Formation is the uppermost of three Ochoan evaporite-bearing formations in the Delaware Basin. The Rustler has been extensively characterized since 1972 as it contains the most transmissive hydrologic units overlying the WIPP facility horizon (as summarized in Powers and others, 1978; Lappin, 1988). The Rustler has a variable lithology consisting of interbedded sulfates, carbonates, clastics, and halite. Within the Rustler, five hydrologic units have been identified: the unnamed lower member/Salado contact area, the Culebra Dolomite Member, the Tamarisk Member claystone (M-3 of Holt and Powers, 1988), the Magenta Dolomite Member, and the Forty-niner Member claystone (M-4 of Holt and Powers, 1988) (Figure 12). The Culebra is the most transmissive and regionally important unit and has been the focus of Rustler hydrologic studies.

The Rustler varies in thickness from tens of feet, where exposed and subjected to solution and erosion, to 560 ft, in the northeastern part of the Delaware Basin (Holt and Powers, 1988; Powers and Holt, this volume). Where the Rustler crops out or is in the shallow

subsurface, it has been extensively altered by near-surface groundwater and karst processes (Holt and others, in prep.). Karst processes do not affect the Rustler across the WIPP site area, although evidence of Rustler karst is abundant in Nash Draw and along its margins (e.g. WIPP-33, about 1 mile east of Livingston Ridge) (Bachman, 1987; Holt and others, in prep.).

Unnamed Lower Member Hydrology

The unnamed lower member of the Rustler consists of interbedded siltstone, sandstone, halite, and anhydrite (Figure 12) (Holt and Powers, 1988). Holt and others (in prep.) recognize two confining beds and two water-producing units within the unnamed lower member.

Holt and others (in prep.) considered the sulfate unit at the base of the Rustler to be the lowermost confining bed within the Rustler, although this hydrologic role is mostly due to low permeability halite in the Salado. Where dissolution has affected the upper Salado, this stratigraphic unit is hydrologically compromised, and the lower confining bed for water-bearing unit 1 is the top of intact Salado halite.

Water-producing unit 1 (WPU-1) of Holt and others (in prep.) consists of the bioturbated clastic interval and the transitional sandstone, and it includes the M-1/H-1 interval when halite is not present. WPU-1 is confined by anhydrite. The bioturbated clastic interval is the principal water-bearing zone within WPU-1. The siltstone and sandstone within this zone are argillaceous and cemented with halite (Holt and Powers, 1988; Holt and others, in prep.). The transitional sandstone is also cemented with halite and locally with sulfate (Holt and Powers, 1988). The M-1/H-1 interval contains bedded and argillaceous halite with some halitic clastic rocks. Halite cements are dissolved in the units to create secondary intergranular porosity and permeability. Dissolution of halite from the upper part of the Salado causes structural collapse of, and upward stoping through, overlying units. Fracture porosity develops around displaced blocks of collapsed material, and the thickness of the water-bearing zone increases to include

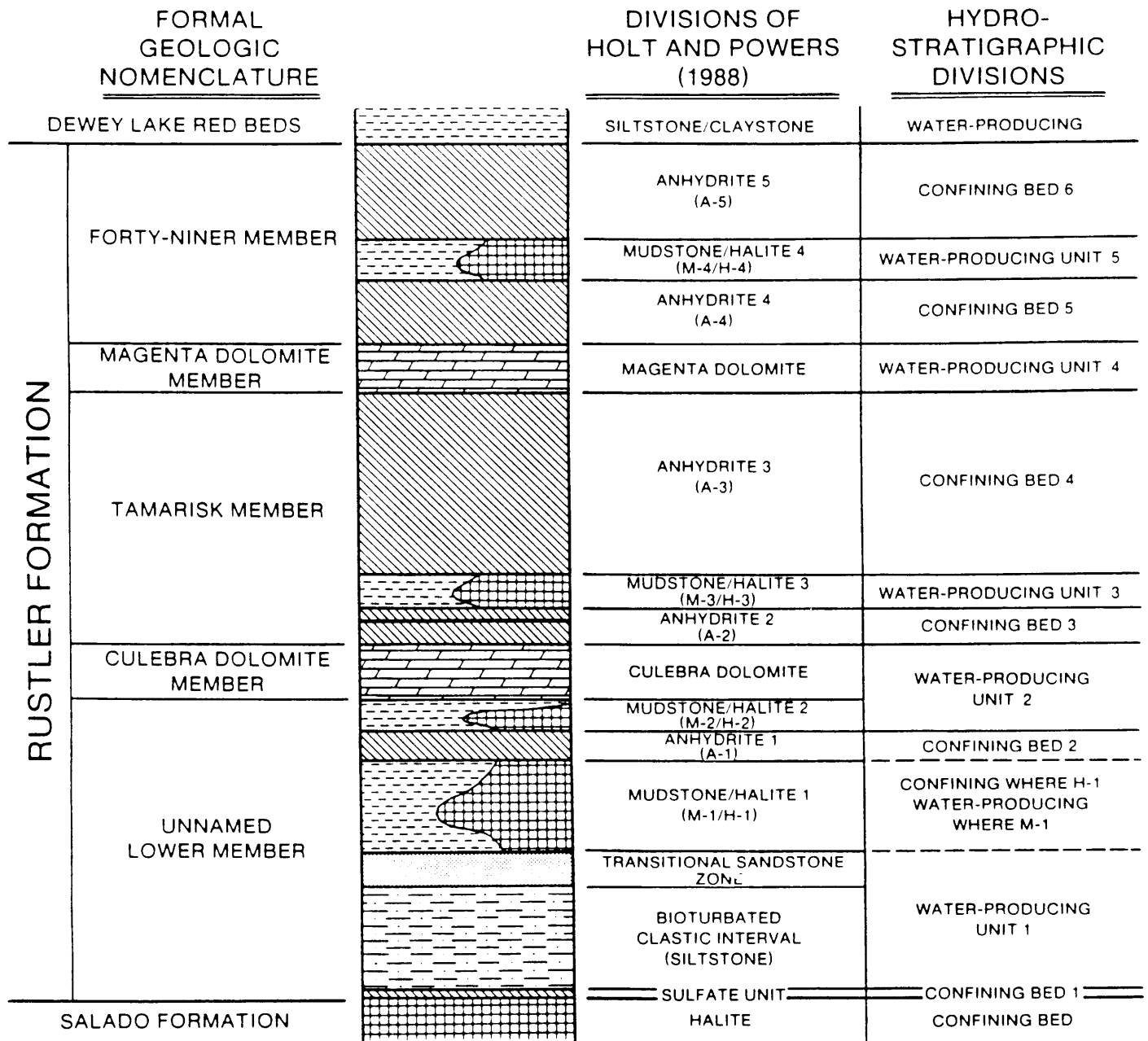


Figure 12. Relationship of lithostratigraphic and hydrostratigraphic units for the Rustler Formation (from Holt and others, in prep.).

the interval hydraulically connected by fractures. After collapse, the evaporite cements within the collapsed blocks are more readily dissolved. Hydrologic testing of WPU-1 is difficult as the borehole may only effectively intersect a few fractures and the permeability between collapse blocks may be limited by clay skins developed on the margins of blocks during the collapse process.

Transmissivity values for WPU-1 (Mercer, 1983; Beauheim, 1987) generally show a transmissivity increase in the direction of Nash Draw (Figure 13). Holt and others (in prep.) suggest that the transmissivity values from areas where Salado dissolution and collapse of overlying strata have occurred may not be representative of the entire WPU-1 interval thickness at the tested locations.

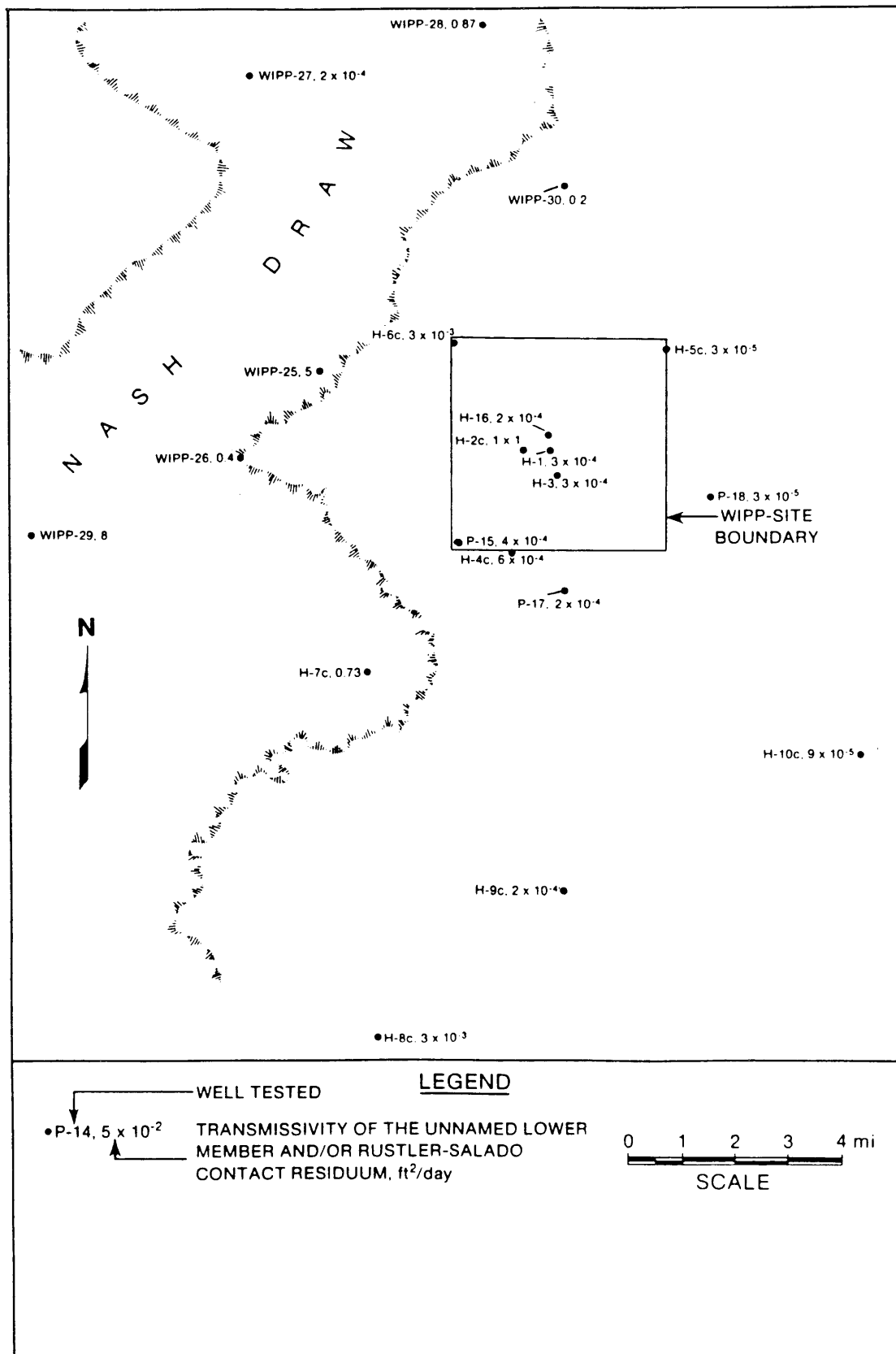


Figure 13. Transmissivity of the unnamed lower member of the Rustler and/or residuum along the Rustler/Salado contact (from Holt and others, in prep.).

Few measurements have been made of the stabilized water level or fluid pressure of WPU-1 (Figure 14). Although freshwater head calculations are somewhat limited due to the quality of specific gravity measurements, estimated freshwater head values are probably accurate to within 10 ft (Holt and others, in prep.). The freshwater heads in those wells completed within the collapse material associated with Salado dissolution do not appear to differ significantly from the hydraulic heads in wells completed in intact Rustler siltstone, indicating good lateral hydraulic connection. The heads are consistent with Mercer's (1983) interpretation that flow through the low transmissivity sections of WPU-1 is generally westerly or southwesterly across the WIPP site towards Nash Draw, while flow within Nash Draw is generally southwesterly towards Malaga Bend on the Pecos River.

Holt and others (in prep.) divided the area of WPU-1 into three distinct hydrogeologic zones (Figure 15). The first zone is characterized by low permeabilities, no Salado dissolution, and intergranular porosity and permeability. Hydraulic properties in zone 1 are related to the dissolution of halite cements, and permeability generally decreases toward the east across the WIPP site area. Within Zone 2, WPU-1 is characterized by permeabilities higher than in Zone 1, Salado dissolution with varying amounts of collapse, and intergranular porosity coupled with fracture porosity proportional to the amount of collapse. Partial confining conditions exist within zone 2, and the zone is not actively tied to the surface groundwater regime, as varying amounts of overburden isolate WPU-1. Zone 3 is actively recharged by the surface groundwater system and is confined to portions of Nash Draw. Overburden is limited, and the zone may be partly confined. Dissolution and collapse are extensive within zone 3, and evaporite cements within collapse blocks are mostly dissolved. It is expected that the hydraulic properties of WPU-1 have great lateral and vertical variability due to the complex nature of collapse and brecciation. Part of zone 2 and all of zone 3 can be considered within Lang's (1938) brine aquifer. Modern flow within zones 1 and 2 is generally west toward Nash Draw, while flow in zone 3 is southwest along the axis of Nash Draw toward Malaga Bend.

Confining bed 2 consists of the transitional sandstone, where evaporite cements are not dissolved; the M-1/H-1 interval, where halite is present as cements and interbeds; and anhydrite 1 (Holt and others, in prep.). This confining unit is most effective across the WIPP site area where no dissolution has affected the Salado (Figure 11; Holt and others, in prep.). Anhydrite 1 is halitic across much of the WIPP area and displays some fractures (Holt and Powers, 1988). Within Nash Draw and other areas of extensive dissolution of Salado evaporites, dissolution of the halite within A-1 and additional fracturing due to collapse may hydraulically breach A-1, allowing vertical leakage between water-producing units 1 and 2.

Mudstone/halite 2 (M-2/H-2) and the Culebra Dolomite Member constitute water-producing unit 2 across the WIPP site area (Holt and others, in prep.). East of the WIPP site, M-2/H-2 contains halite and is considered to be part of confining bed 2. M-2/H-2 consists of interbedded sulfatic mudstone and siltstone across and west of the WIPP area (Holt and Powers, 1988). It is probably in direct hydraulic communication with the Culebra and acts as a source of leakage to the Culebra during hydrologic tests where the hydraulic head of the Culebra is lowered (Holt and others, in prep.). M-2/H-2 is discussed further with Culebra hydrology.

Culebra Dolomite Member

The Culebra is the most transmissive hydrologic unit overlying the WIPP facility horizon. It is considered to be the most important groundwater-transport pathway for radionuclides that may escape from the WIPP repository to the accessible environment. Near the WIPP, the Culebra is finely crystalline, locally argillaceous and arenaceous, vuggy dolomite roughly 25 ft thick (Holt and Powers, 1988). The Culebra has been the subject of extensive hydrologic testing, summarized by Mercer (1983) and Lappin (1988). Culebra groundwater geochemistry has been studied in detail (e.g., Siegel and others, 1990), and the Culebra geology has been extensively characterized (e.g., Holt and Powers, 1988; Holt and others, in prep.).

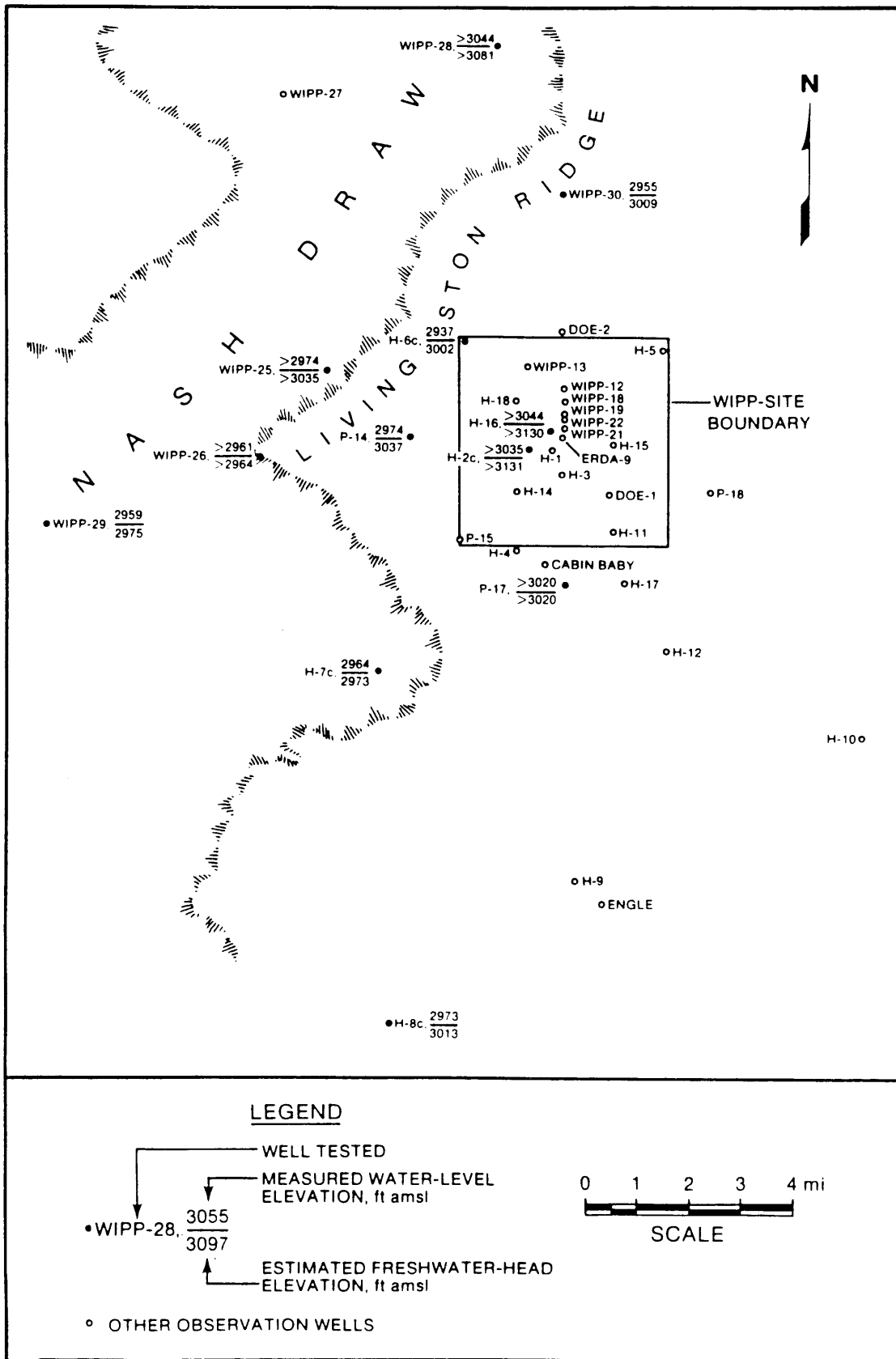


Figure 14. Measured water level and estimated freshwater head elevation of the unnamed lower member of the Rustler and/or residuum along the Rustler/Salado contact (from Holt and others, in prep.).

Culebra Hydrology

The Culebra is the hydraulically most significant portion of WPU-2. M-2/H-2 probably provides some leakage into the Culebra during pumping tests and is therefore considered part of WPU-2. WPU-2 is confined by anhydrites in the unnamed lower member and the Tamarisk Member. Within Nash Draw and adjacent to Nash Draw, collapse following evaporite dissolution may have decreased the effectiveness of the anhydrites as confining beds.

Water levels in 60 wells completed to the Culebra at 41 drilling-pad locations have been measured on a regular basis (Holt and others, in prep.). Culebra water levels at and around the WIPP site have been affected, however, by continuous drainage into one or more WIPP shafts (since late 1981), as well as by numerous pumping tests and water-quality sampling exercises conducted since 1980 (Haug and others, 1987).

Cauffman and others (1990) thoroughly reviewed Culebra water-level data, borehole-fluid density data, and WIPP-related hydraulic stresses, and estimated the undisturbed freshwater heads at 35 wells (Figure 16). Flow is generally to the south (Crawley, 1988; LaVenue and others, 1988) across the WIPP site area (Figure 16). Davies (1989) and Crawley (1988) suggest that flow directions south of the WIPP site may have a larger easterly, down-dip component than is predicted considering only freshwater heads.

The transmissivity of the Culebra across the WIPP region varies by six orders of magnitude (Figure 17) due to varying degrees of fracturing within the Culebra. In the vicinity of the WIPP, the Culebra has been tested in 41 locations, including the combined testing of the WIPP project and Project Gnome (Beauheim, 1988). The highest transmissivity value reported for the Culebra is 1.25×10^3 ft²/day at WIPP-26 within Nash Draw. The lowest value reported is <0.004 ft²/day at P-18. Where Culebra transmissivities are less than 1 ft²/day, the Culebra behaves as a single-porosity medium during pumping and slug tests. Where transmissivities are between 1 and at least 100 ft²/day, the Culebra behaves as a double-

porosity medium, with matrix and fracture porosity sets. Where the Culebra transmissivity exceeds 100 ft²/day, double-porosity behavior is less apparent.

LaVenue and others (1990) calculated Culebra transmissivities across the WIPP site area based upon steady-state calibration against an estimate of the preshaft distribution of freshwater equivalent heads (Figure 17). Aside from the apparent increase of transmissivity toward Nash Draw, several other relationships are important. Transmissivities are relatively high in a wide region south of the WIPP site and west in Nash Draw. A high-transmissivity "finger" penetrates the southern border of the WIPP site. Finally, a zone of higher transmissivity occurs north of, but does not penetrate, the WIPP site area.

Culebra Groundwater Chemistry

Culebra groundwater geochemistry is extremely variable across the WIPP site region. The total dissolved solids (TDS) within the Culebra groundwater increase from less than 5,000 mg/l southwest of the WIPP site to greater than 200,000 mg/l northeast of the WIPP site (Figure 18) (Siegel and others, 1990).

Culebra water has been typed by Siegel and others (1990) and Holt and others (in prep.) on the basis of major element concentrations (Figure 19). Using different sample sets and slightly different criteria, both Siegel and others (1990) and Holt and others (in prep.) report four coinciding "type areas" of Culebra water (Figure 19). The easternmost type area of Siegel and others (1990) and Holt and others (in prep.) (Zone A and Type Area 1, respectively) is characterized by highly saline NaCl brines rich in Mg and Ca. Culebra water from Zone B of Siegel and others (1990) and Type Area 2 of Holt and others (in prep.) is relatively fresh, with calcium and sulfate as the dominant solutes. NaCl-dominated waters of variable compositions occupy Zone C and Type Area 3, with the salinity of this water increasing to the east (Siegel and others, 1990; Holt and others, in prep.). Holt and others (in prep.) suggest that mixing of the highly saline NaCl brines in Type Area 2 with the sulfate-rich water in Type Area 1 may have generated the Type Area 3 water. Located in the western

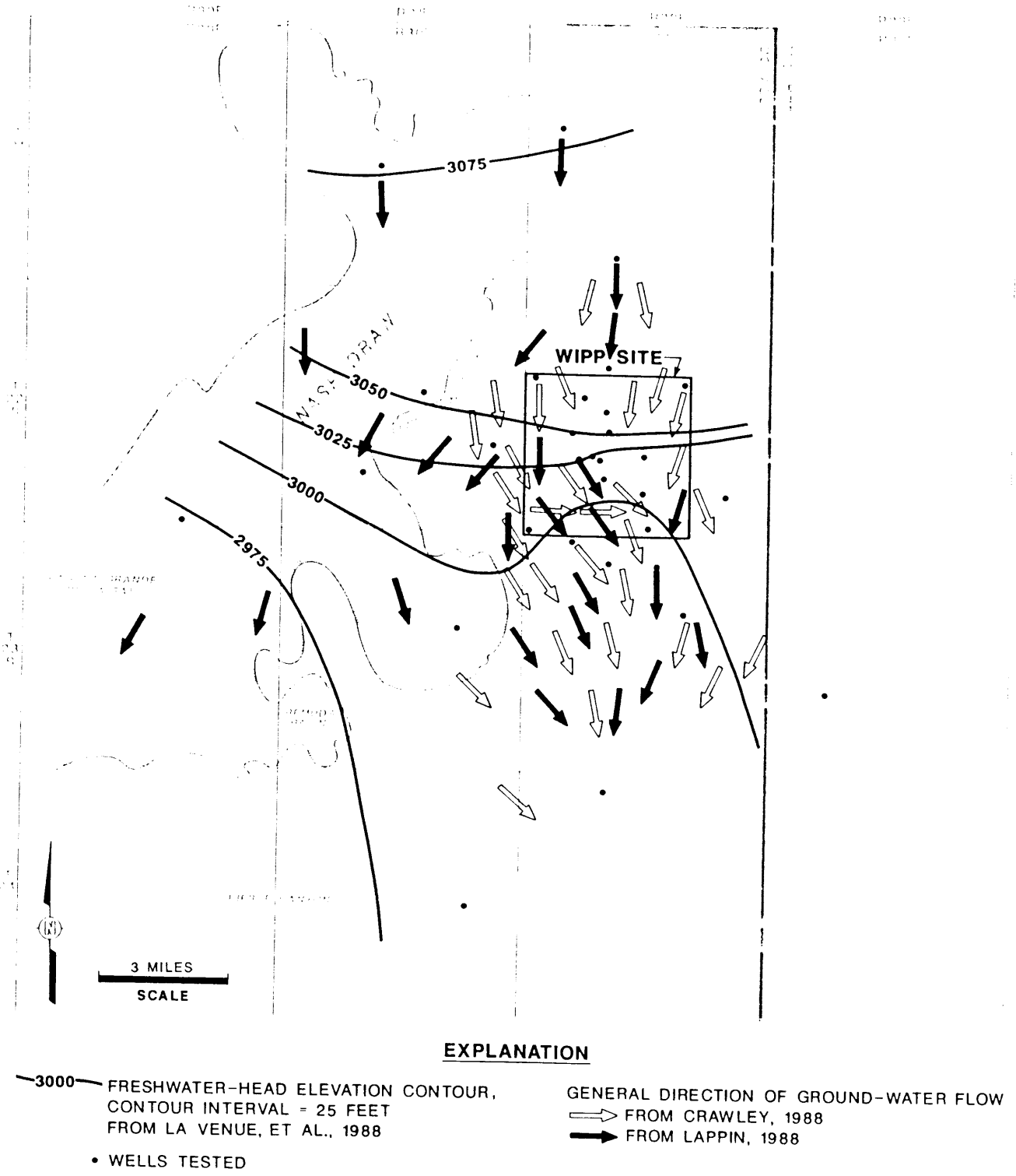


Figure 16. Estimated Culebra Dolomite Member freshwater heads and flow directions (from Holt and others, in prep.).

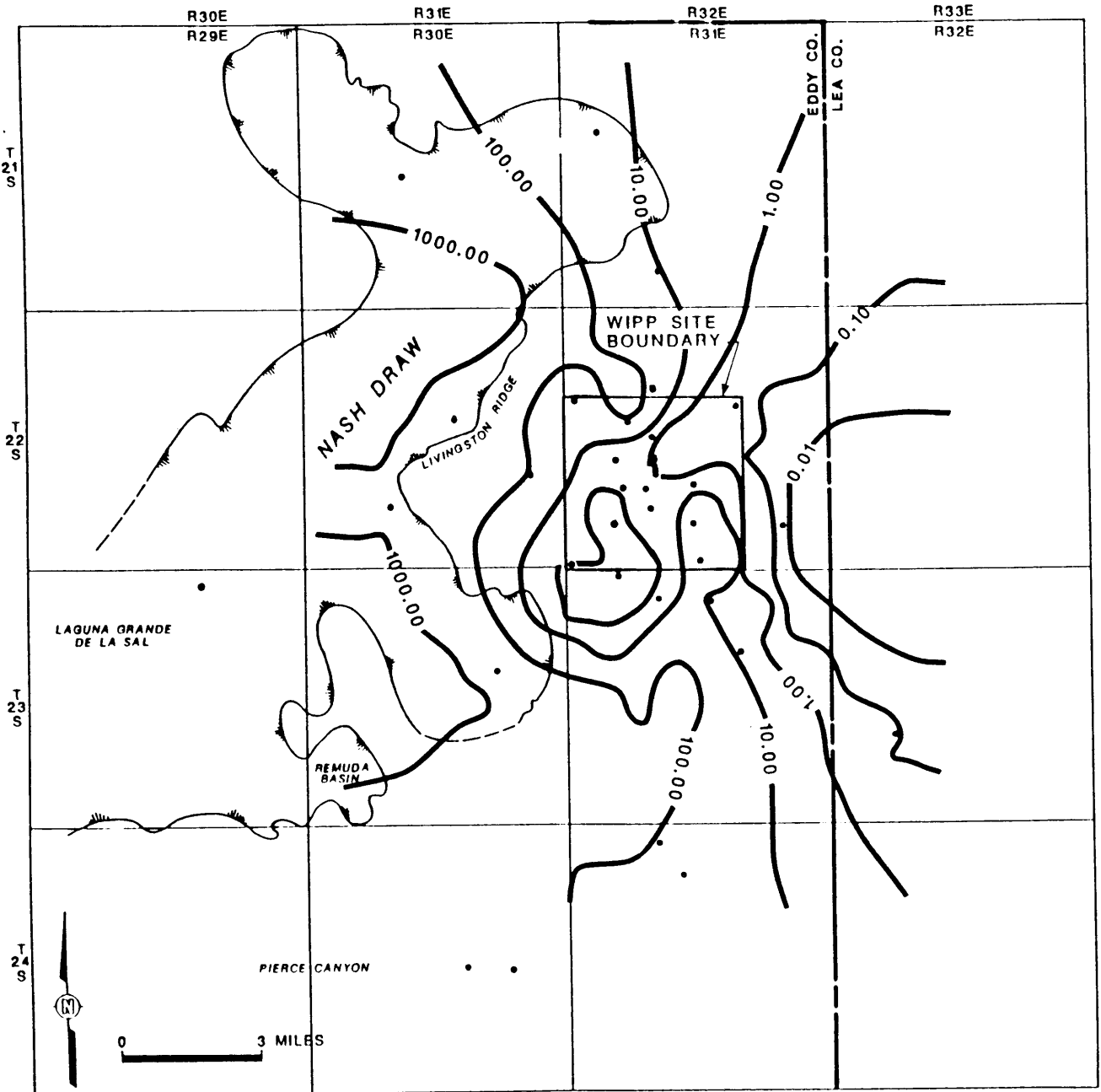


Figure 17. Calculated transmissivities for the Culebra Dolomite Member (ft²/day) (from LaVenue and others, 1988).

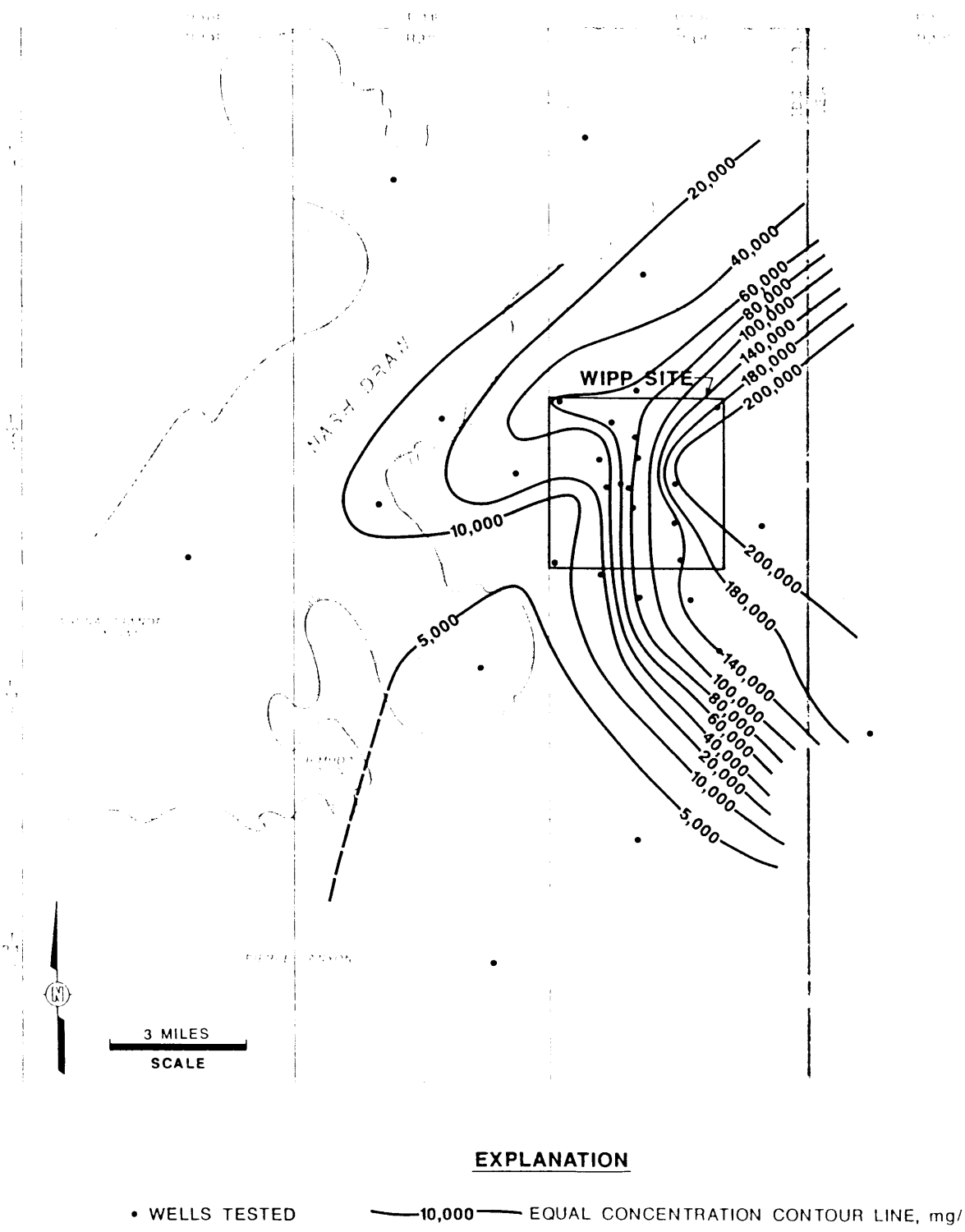
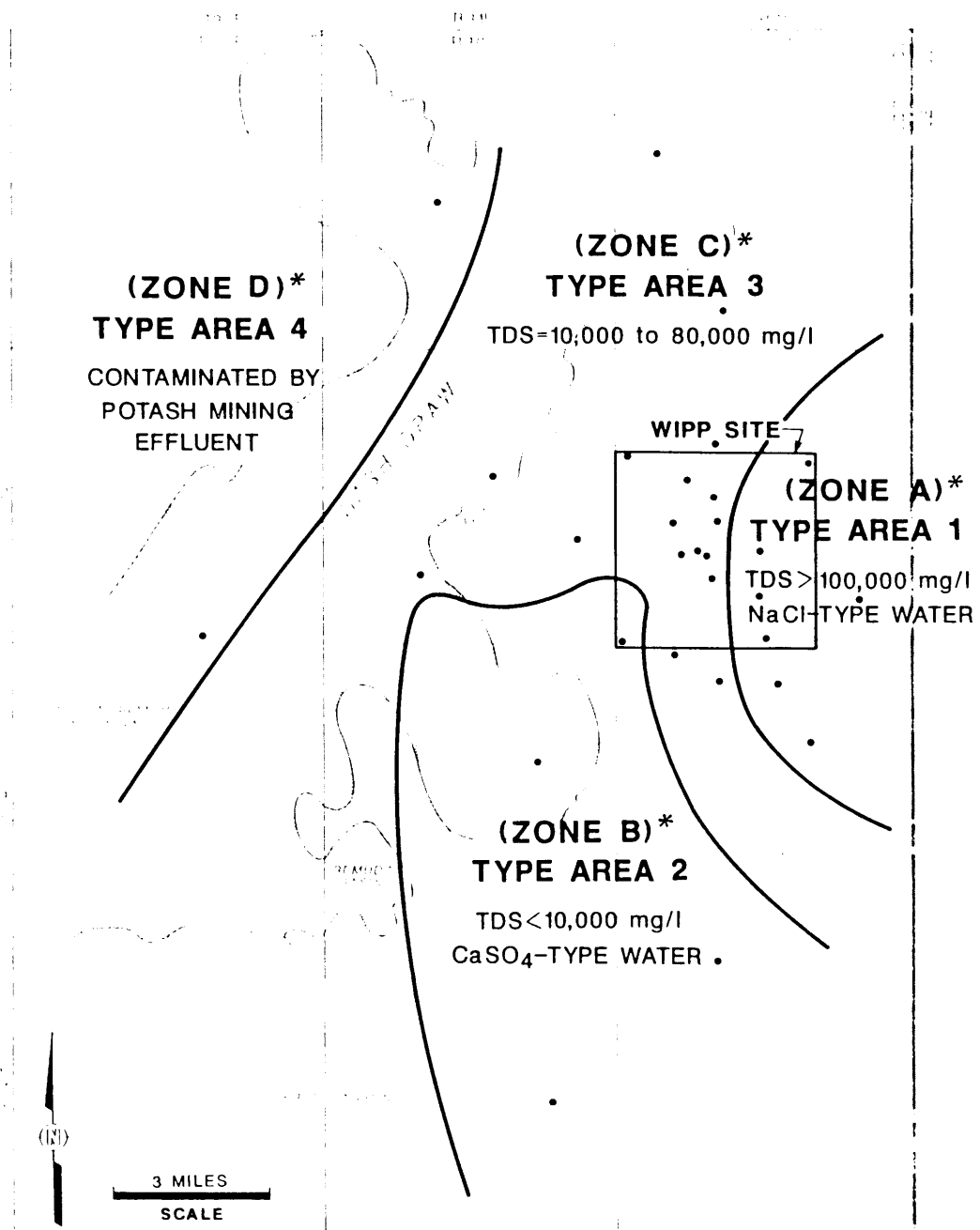


Figure 18. Distribution of total dissolved solids (TDS) in groundwater of the Culebra Dolomite Member (from Holt and others, in prep.).



EXPLANATION

- WELLS TESTED

Figure 19. Hydrochemical type areas for the Culebra Dolomite Members (from Siegel and others, 1990, and Holt and others, in prep.).

half of Nash Draw, anomalously high salinities and potassium contents characterize Zone D and Type Area 4 groundwater (Siegel and others, 1990; Holt and others, in prep.). The water quality in Zone D and Type Area 4 is dominated by effluent from potash refining operations (Siegel and others, 1990; Holt and others, in prep.).

Ramey (1985) and Siegel and others (1990) noted that modern flow directions within the Culebra do not appear consistent with the modern salinity distribution. The TDS within the Culebra generally decreases in the direction of flow, which is not a typical steady state TDS/groundwater-flow relationship. Isotopic evidence (Lambert and Harvey, 1987; Siegel and others, 1990), as well as modern Rustler transmissivities and head distributions, preclude using modern vertical recharge to the Culebra (Lappin, 1988), to account for the modern flow/salinity relationship. One possible mechanism involves fluid flow to the northeast during past recharge followed by modern system draining and discharge to the south (Lambert and Harvey, 1987; Holt and others, in prep.). Lambert and Harvey (1987) interpret the hydrologic setting for the WIPP area as transient, with no active recharge to the Culebra, rather than as steady state.

Saturation indices for several evaporite minerals in Culebra groundwater were calculated by Holt and others (in prep.) and by Siegel and others (1990). The saturation index of a particular mineral equals zero at saturation, while positive or negative values indicate that the groundwater is above saturation or below saturation, respectively. Holt and others (in prep.) found Culebra groundwater to be undersaturated with respect to gypsum, although the degree of undersaturation varies (Figure 20). Values between +0.1 and -0.1 can be considered saturated. The Culebra waters are progressively more undersaturated with respect to gypsum from east to west, and a zone of less saturated waters penetrates the WIPP area from the south. The overall trend is similar to the transmissivity distribution in the Culebra, with the degree of undersaturation increasing with transmissivity. However, Siegel and others (1990), using a different geochemical model, found no undersaturation of Culebra waters with respect to gypsum.

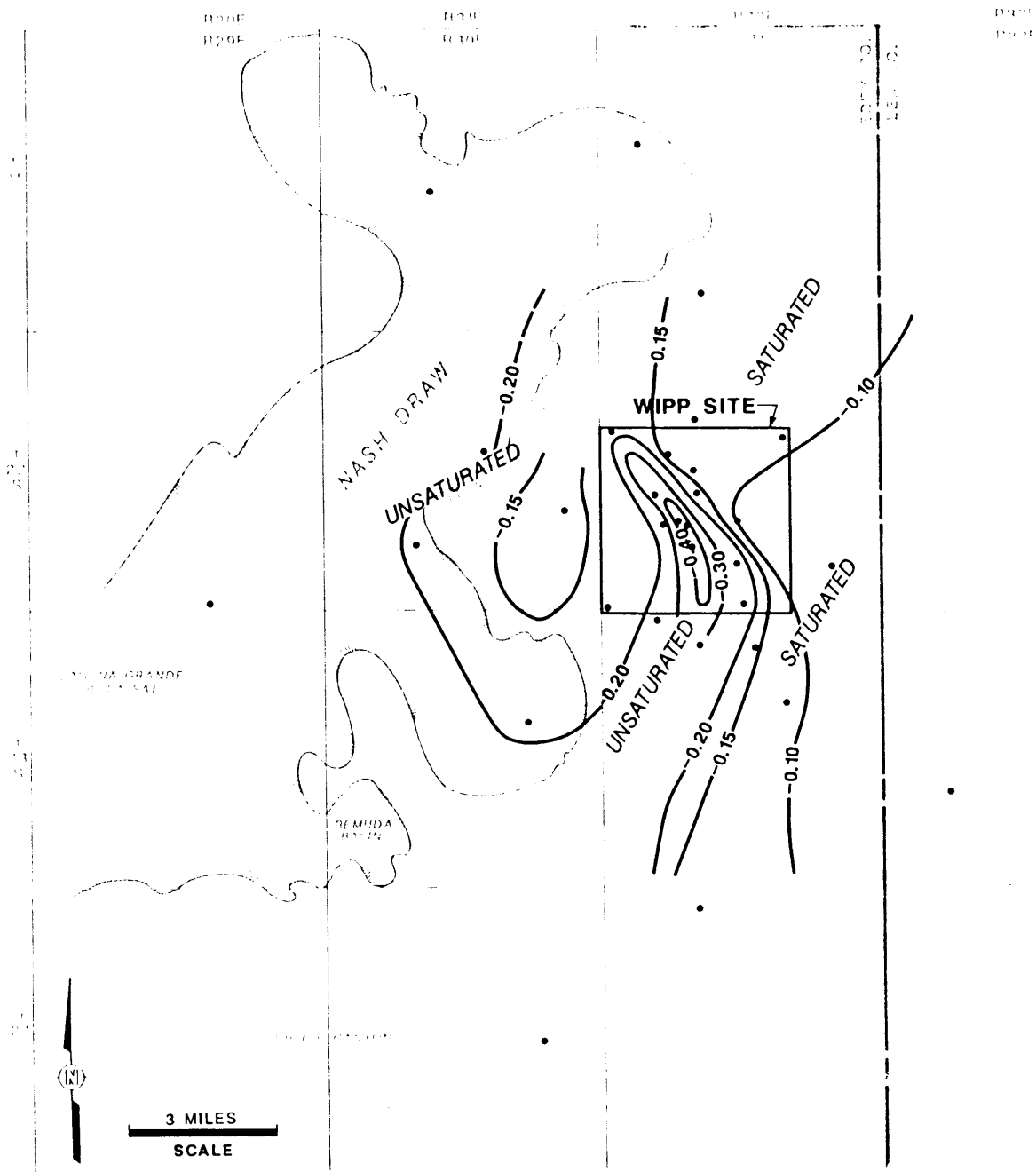
The discrepancy between the two models remains to be resolved.

Culebra Hydrogeology

Open and sulfate-filled vugs and fractures are locally abundant in the Culebra (Holt and Powers, 1988). The large vugs are principally concentrated in the lower portion of the Culebra (Holt and Powers, 1990). Most of the permeability is along fractures, and transmissivity appears to be related to degree of fracturing. Holt and others (in prep.) evaluated the hydrogeology of the Culebra and examined the Culebra for depositional and post-depositional controls on its hydrologic character. The following is a summary of their efforts.

The Culebra was deposited in an areally extensive carbonate-rich lagoonal environment following a rapid marine transgression over a salt pan/saline mudflat environment (Holt and Powers, 1988). As the water-depth was stable over most of the WIPP area, the Culebra was uniformly deposited with slight increases in thickness in those areas where dissolution of the underlying saltpan/saline mudflat evaporites had occurred (Holt and Powers, 1988). The lagoonal environment was persistent for all of Culebra deposition with only episodic shoaling contributing minor amounts of lateral and vertical variability, so facies changes do not affect the hydrologic properties of the Culebra. Slumping of Culebra sediments occurred in response to compaction of algal laminae, dewatering, and dissolution within and compaction of the underlying sediments. This deformation provided a vertical to subvertical fabric for later fracture reactivation.

Much of the Culebra sediment was uniformly fine-grained carbonate mud, lithified to produce finely crystalline dolomite of low permeability. Poorly sorted, commonly very fine-grained, dolomitic and possibly organic-rich interbedded sediment was locally interspersed by bioturbation and sediment slumping throughout the fine-grained carbonate mud. This material provided a pathway of higher permeability for circulating waters containing solutes for syndepositional displacive growth of anhydrite and gypsum within the soft Culebra sediment. Sulfate nodules and crystals grew more often within



EXPLANATION

- WELLS TESTED

Figure 20 Contour map of gypsum saturation indices of Culebra waters (from Holt and others, in prep.).

this poorly sorted material than within the uniformly sized carbonate mud. Most of the interparticle porosity within this poorly sorted material was filled with sulfate cement. During early diagenesis, much, if not all, of the gypsum in the Culebra was replaced by anhydrite. During late-stage diagenesis, the hydraulic properties of the Culebra were enhanced when diagenetic pore-filling materials dissolved, opening additional porosity.

Gypsum and anhydrite commonly fill pores within the Culebra near the WIPP site. Sulfate (usually gypsum) occurs as cements, passive void-fillings, nodules, and incremental fracture-fillings. A clear pattern of alteration occurs within the Culebra from east to west. Anhydrite vugs and crystals are replaced by gypsum, and gypsum occurs as incremental fracture fillings within the Culebra dolomite. Further west, all sulfate consists of gypsum, and gypsum fracture-fillings, cements, and vug-fillings are partly to completely dissolved. Continuing west, gypsum is almost totally removed, and many of the vugs and vug complexes are collapsed, thereby increasing local fracture porosity. In the westernmost part of the region, no gypsum occurs. The areal distribution of this relationship is best shown by the percentage of natural fractures filled with gypsum (Figure 21). This map shows a general inverse relationship between the presence of gypsum pore-fillings and transmissivity (Figure 17). Presence or absence of gypsum pore-fillings may, therefore, be one of the factors controlling the distribution of transmissivity within the Culebra.

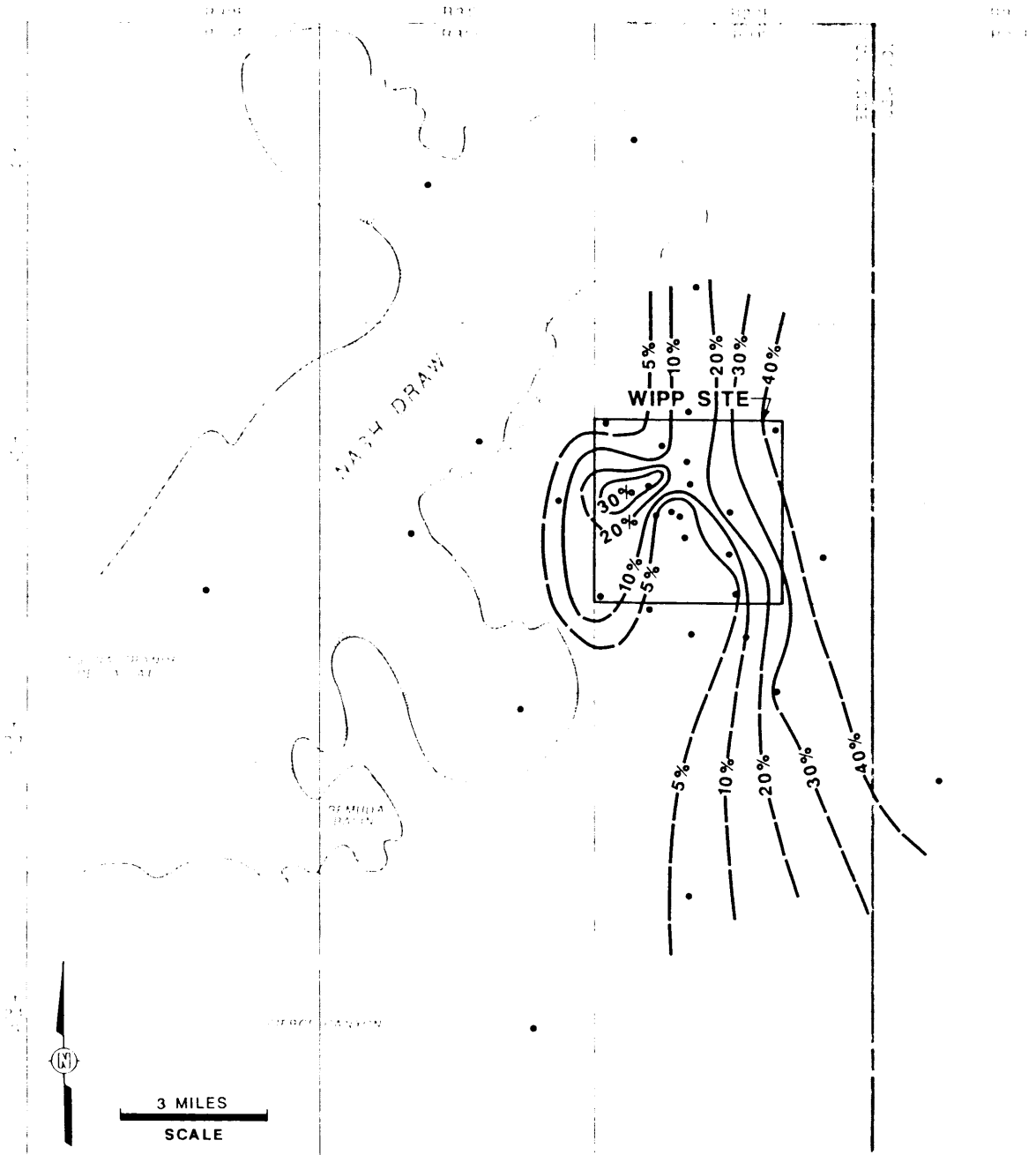
The effective porosity within the Culebra is related to fractures, and the transmissivity values at various locations indicate degree of fracturing. This allows the degree of fracturing to be compared with other geologic information on a regional scale. The Culebra fractured significantly in response to differential unloading, dissolution of evaporites from above or below the Culebra, and dissolution of large vug-fillings or fillings within zones of vugs in the Culebra. Regional or local tectonic activity has not caused significant fracturing within the Culebra.

Culebra cores yield little information concerning the degree of fracturing due to

variable core recovery and zones of poor recovery. Culebra descriptions from three shafts at the WIPP show that the majority of the fractures at the WIPP site are subvertical and occur within a very vuggy zone near the base of the Culebra (Holt and Powers, 1984, 1986, 1990). These fractures usually extend from vug to vug (Holt and Powers, 1990). This zone can be recognized within Culebra cores as a zone of poor or no recovery. Horizontal fractures, parallel to bedding planes, occur throughout the Culebra in core and the WIPP shafts (Holt and Powers, 1984, 1986, 1990). High-angle subvertical fractures are commonly intersected in core near the upper part of the Culebra and may be vertically persistent for several feet. As these nearly vertical fractures are common, the density of these fractures must be relatively high, at least locally.

Externally driven changes in the stress field within and around the Culebra are amplified by the different mechanical responses of underlying claystone to these changes. The claystone below the Culebra is pliable, cohesive, and moist. Abundant arcuate and variably oriented slickensided surfaces and deformed strata within the claystone attest to a complex history of deformation. The claystone accommodates changes in stress relatively rapidly by deforming ductilely and shearing along some surfaces. This rapid response to changes in stress locally increases the strain and deviatoric stress within the overlying Culebra dolomite, resulting in brittle deformation of the Culebra.

The Culebra dolomite is much more likely to fracture in response to changes in stress than are the overlying anhydrites, due to inhomogeneities with the Culebra. Horizontal and subhorizontal bedding planes and near-vertical syndepositional shear planes are bounded by clay-sized material within the Culebra. Fracture response to stress regime variability will initiate along these pre-existing planes of weakness rather than in the more homogeneous dolomite. In addition, abundant large sulfate-filled and open vugs in the lower portion of the Culebra behave differently from the dolomite when the Culebra is strained. Fractures propagate from vug to vug, often along syndepositional shear planes, as the strength of the Culebra is exceeded. The anhydrites contain fewer inhomogeneities, and



EXPLANATION

• WELLS EXAMINED

CONTOUR INTERVAL 10%

5% LINE SHOWN FOR CLARITY

Figure 21. Percentage of natural fractures in the Culebra Dolomite Member filled with gypsum (from Holt and others, in prep.).

the strength across bedding planes within the anhydrites is greater than within the dolomite, because clay is absent along the anhydrite bedding plane surfaces and microscopic anhydrite crystals interlock across these surfaces.

As tectonism is not a feasible external mechanism for generating major changes in the stresses acting on the Culebra at the WIPP site, other external mechanism must control external stress changes. Within the regional context, only differential unloading and dissolution of evaporites from within and below the Rustler are capable of effecting external stress-field changes. Internal stress-field changes can be generated from within the Culebra by dissolution of pore-filling materials.

Much of the fracturing within the Culebra in the vicinity of the WIPP site can be attributed to unloading (Holt and others, 1988). An isopach map of the Culebra overburden shows a general decrease of overburden from east to west, with the overburden north and south of the WIPP site slightly less than that across the WIPP site (Figure 22). Culebra transmissivity (Figure 17) is generally higher where there is less overburden. As the transmissivity contours do not correlate precisely with the amount of overburden present, other mechanisms must contribute to the variations of transmissivity and the degree of fracturing in the Culebra across the WIPP area.

Aside from unloading, the most significant control on fracturing within the Culebra is the dissolution of evaporites from strata above and below the Culebra. The overlying strata collapse, and stress in the underlying strata is relieved. Both collapse and stress relief can cause or enhance the fracturing within a brittle unit such as the Culebra. Holt and others (in prep.) evaluate the extent of dissolution from the Salado and Rustler on the basis of core, shaft, and geophysical log data (Figure 23). Salado dissolution affects the area south and west of the WIPP site, while Rustler dissolution is concentrated along the depositional margins of halite within the Rustler.

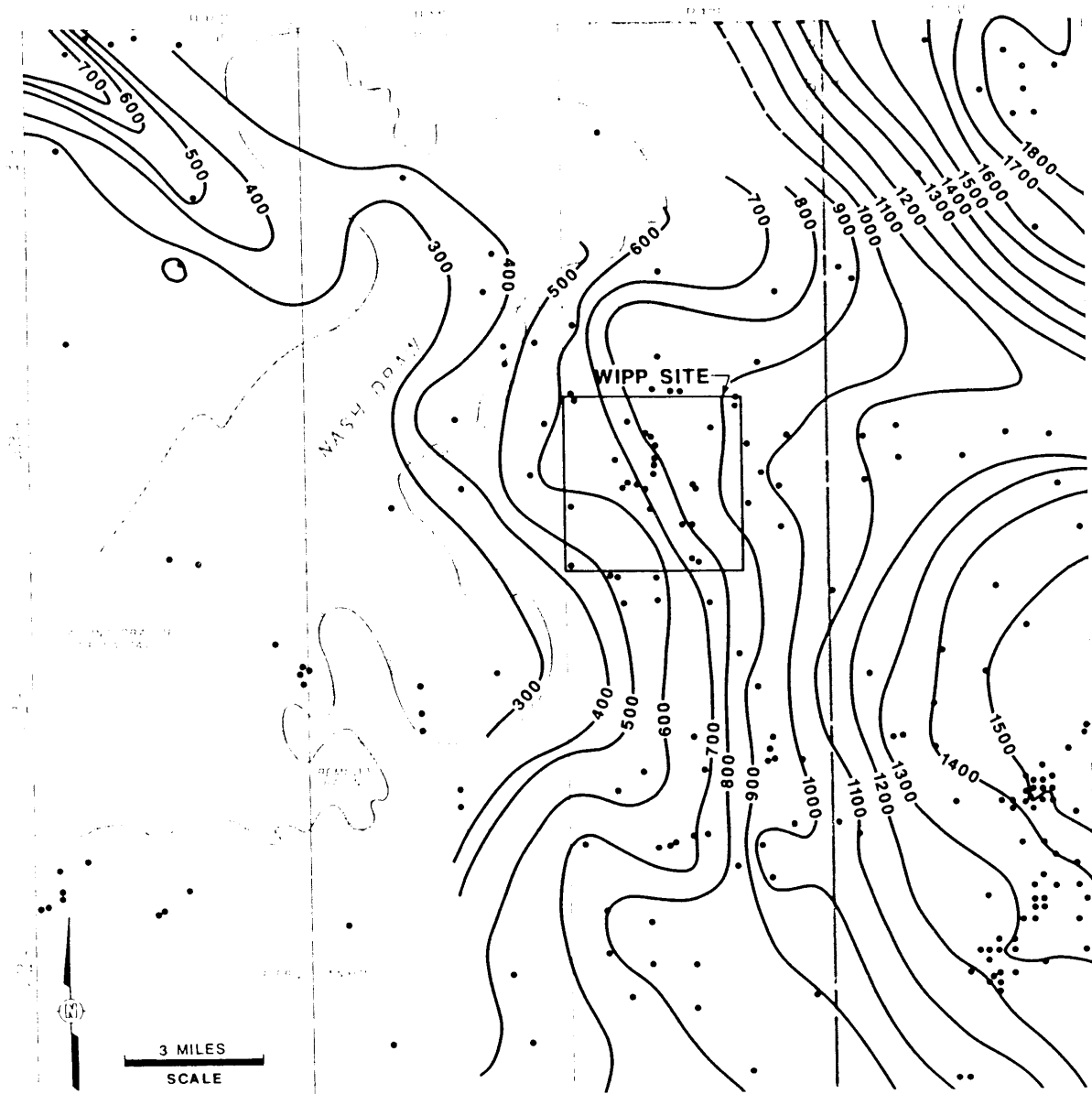
The uppermost halite within the Salado is dissolved in the area in and around Nash Draw and in a region south of the WIPP site.

Salado dissolution parallels the course of the ancestral Pecos River and its major tributaries, such as Nash Draw. Salado dissolution was hydrologically driven by the groundwater system associated with the ancestral Pecos River and its major tributaries. This system was most active during the Cenozoic, although dissolution of Salado halite continues to occur within Nash Draw. Culebra core from areas of Salado dissolution shows evidence of fracturing and high transmissivity values due to collapse.

Salado dissolution close to a halite depositional margin within the Rustler increases the potential for dissolution of halite within the Rustler. Collapse associated with Salado dissolution tends to increase the vertical hydraulic connection between Rustler water-bearing zones and Rustler intervals containing halite. One such zone penetrates the southern part of the WIPP site. Features attributable to dissolution of halite and attendant collapse are found within the interval M-3/H-3 (Holt and Powers, 1988). This zone, although not well defined, corresponds with the highly transmissive zone within the Culebra in the southern part of the WIPP site. As dissolution has not occurred below the Culebra at this location, fracturing responded to stress-relief following dissolution.

Holt and Powers (1988) observed collapse features within the M-3/H-3 interval at WIPP-13 at the northwest corner of the WIPP site. The collapse features at WIPP-13 may be due to late-stage dissolution of a thin outlying M-3/H-3 halite pan with little or no direct connection to the main M-3/H-3 halite pan (east of the WIPP site). This zone corresponds with high Culebra transmissivity values.

The easternmost zone of potential dissolution within the upper Rustler lies along the limits of H-3 and H-4, representing the depositional margins of halite in the M-3/H-3 and M-4/H-4 intervals. East of the zone, halite is present, while west of the zone, halite does not occur. In the vicinity of the WIPP site, halite was removed from the M-3/H-3 and M-4/H-4 intervals syndepositionally and therefore could not have been dissolved after the deposition of the overlying anhydrites (Holt and Powers, 1988). The depositional margin of halite represents the location where dissolution would be found if it were present. Although

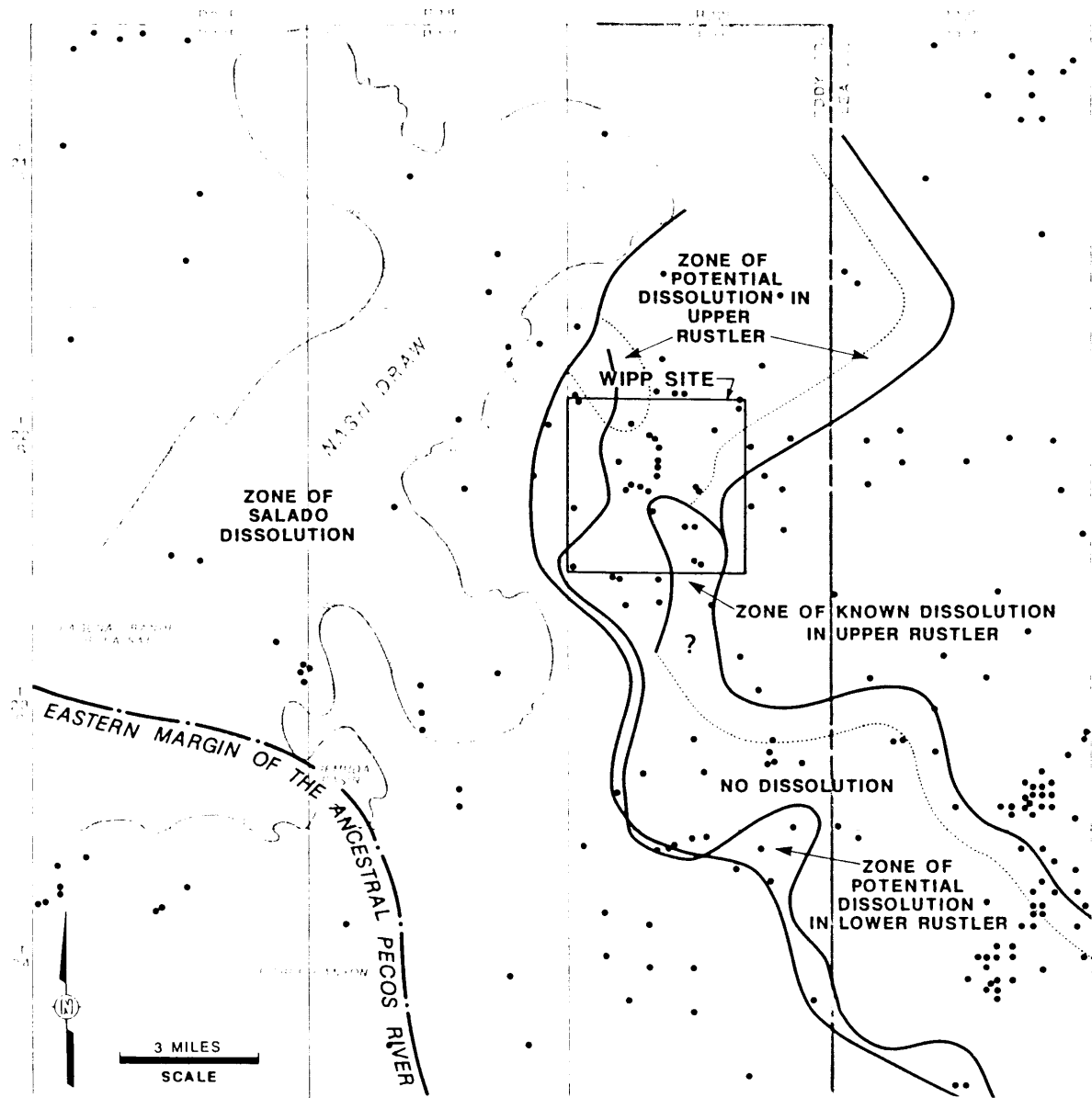


EXPLANATION

• DRILL HOLES

CONTOUR INTERVAL = 100 FEET

Figure 22. Isopach of overburden for the Culebra Dolomite Member (from Holt and others, in prep.).



EXPLANATION

• DRILL HOLES

Figure 23. Distribution of Rustler and Salado dissolution near the WIPP site (from Holt and others, in prep.).

limited, data from hydrologic testing near this zone of potential dissolution do not show the high transmissivity values expected from an area where dissolution has occurred.

Most of the deeper dissolution of Rustler and Salado evaporites in the vicinity of the WIPP site occurred in response to the hydrologic regime of the ancestral Pecos River. Outcrops of ancestral Pecos River gravels indicate that the Cenozoic stream level was at least 650 ft higher than the present Pecos River and over 200 ft higher than the equivalent freshwater head within the Culebra east of the WIPP site, where the lowest measured transmissivities are found. The ancestral Pecos hydrologic system was capable of recharging the Rustler and the underlying Salado. The dissolution pattern within the Salado and Rustler near the WIPP site originated in response to this hydrologic system. Dissolution progressed northward from the ancestral Pecos system.

The modern Pecos River is not hydrologically capable of recharging the Rustler or Salado Formations, so this dissolution pattern is not developing. Flow directions within Nash Draw are to the south toward the modern Pecos River (Mercer, 1983), and it is suspected that flow within the Rustler/Salado dissolution residuum is to the south or southeast. Salado halite continues to dissolve within Nash Draw and, possibly, south of the WIPP site in response to modern recharge in and around Nash Draw. Salado dissolution cannot progress northward without recharge from the south.

The primary controls on Culebra transmissivity variations are unloading, Salado halite dissolution, and Rustler halite dissolution (Figure 24). East of, and across most of, the WIPP site area, unloading is the primary cause of fracturing within the Culebra. As overburden decreases to the west, fractures increase. Within zones which penetrate the northern and southern margins of the WIPP site, possible Rustler dissolution may increase the degree of fracturing within the Culebra. Minor collapse and stress relief due to Rustler dissolution locally would enhance the fracturing. West and south of the WIPP site, Salado dissolution caused more extensive fracturing within the Culebra and is the dominant cause of fracturing. Fracturing

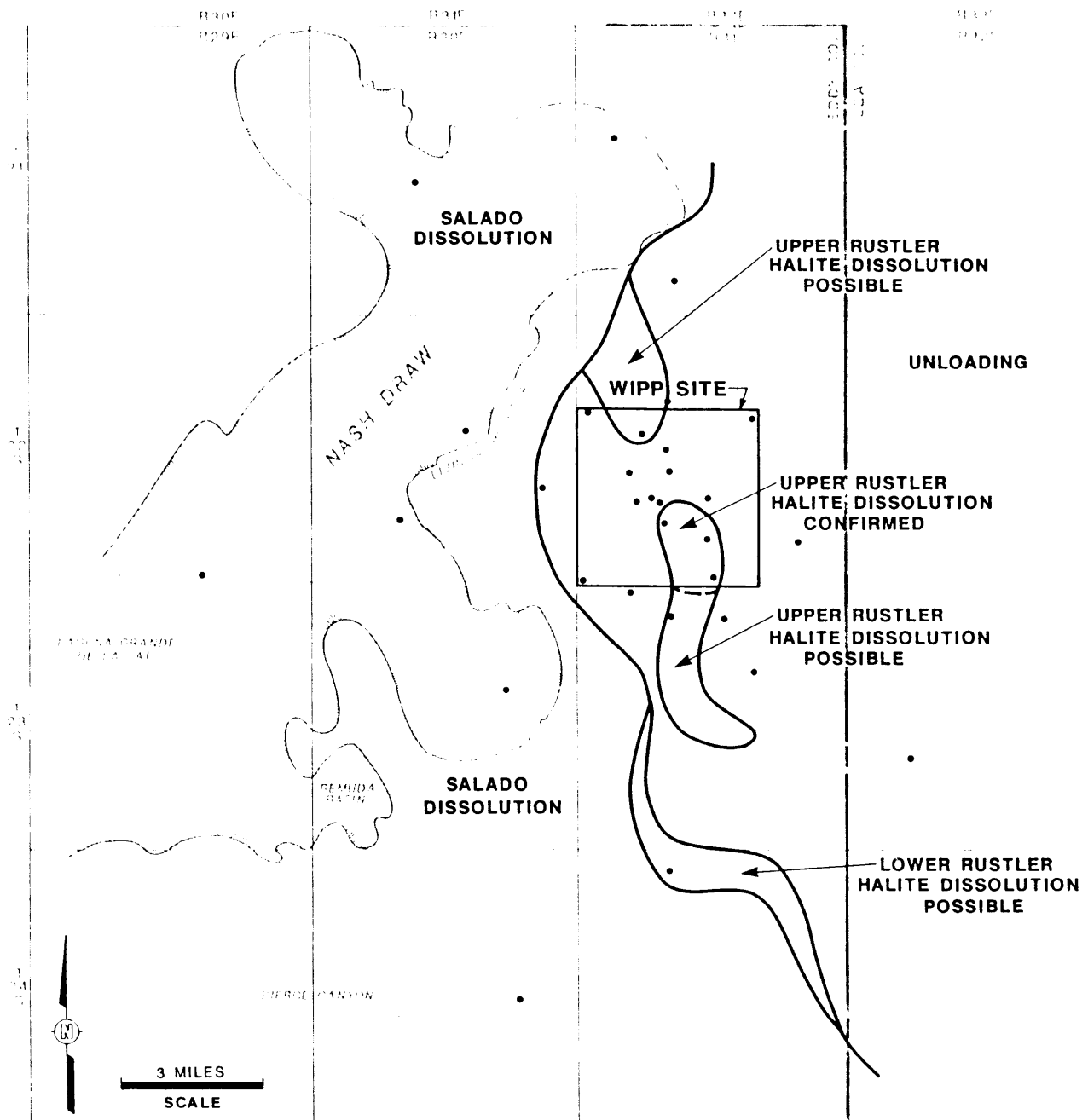
generated by Salado dissolution strongly overprints fracturing of different origin.

Culebra Conceptual Hydrogeological Model

Holt and others (in prep.) synthesized hydrologic, geochemical, and geologic data into a conceptual hydrogeological model of the Culebra summarized here.

The present hydrologic conditions within the Culebra are a relic of a previous hydrologic system. Modern flow directions are not consistent with the distribution of solutes within Culebra groundwater (Ramey, 1985), and the Culebra is not actively being recharged across the WIPP site area (Lambert and Harvey, 1987). Isotope studies of the Culebra groundwater near the WIPP site indicate that the water has been isolated from the atmosphere for at least 12 ka (Lambert, 1987; Lambert and Carter, 1987). Culebra transmissivity varies over six orders of magnitude across the WIPP site area (Mercer, 1983). This variation can be attributed to the interaction of several processes including unloading, Salado dissolution, and localized dissolution within the Rustler. These processes, particularly dissolution of Salado and possibly Rustler halite, were driven by the hydrologic regime of the Cenozoic ancestral Pecos River. As dissolution and unloading progressed, the higher Rustler transmissivities shifted to the north and east.

In summary, groundwater from the ancestral Pecos River hydrologic system accessed, dissolved, and recharged the Permian evaporites near the WIPP site. Flow through the evaporite section was dominantly north and east across the WIPP site area. Surface runoff increased, and westerly-draining tributaries progressively removed overburden from the evaporite section, including the Culebra. Strain associated with differential unloading provided pathways for groundwater into existing gypsum-filled fracture networks and generated new fractures. Along the margins of the river, Salado halite dissolved and the overlying rocks collapsed to generate additional fractures and permeability in the Culebra. Where halite was dissolved from the Rustler, fractures were more abundant and contributed to a higher transmissivity. As the regional base level dropped, flow in the



EXPLANATION

- DRILL HOLES

Figure 24. Primary controls on Culebra transmissivity (from Holt and others, in prep.).

Culebra reversed, and the system began to drain back out toward its earlier recharge areas. Even if permeability is continuing to develop within the Culebra because Culebra groundwater may be undersaturated with respect to gypsum, the hydrologic system is not likely to change rapidly across the WIPP area without a significant change in regional base level.

Six hydrogeologic zones are identified within the Culebra in the vicinity of the WIPP site (Figures 25, 26). The zones were delineated on the basis of transmissivity, amount of overburden, degree of hydraulic confinement, presence or absence of gypsum pore-fillings, and dissolution of underlying Salado halite (Figure 11). These zones progressed eastward in response to progressive unloading and dissolution driven by the ancestral Pecos hydrologic system. The hydrologic conditions which allowed this process to take place in the Cenozoic are no longer active.

Tamarisk Member

The Tamarisk Member of the Rustler Formation (Figure 12) consists of a mudstone (M-3/H-3), laterally equivalent to halite, sandwiched between two anhydrites (A-2 and A-3) (Holt and Powers, 1988). The anhydrite units act as confining beds (Confining Beds 3 and 4 of Holt and others, in prep.), while the mudstone (Water-Producing Unit 3 [WPU-3]) is the least productive of the Rustler water-producing units. Halite (H-3) is the dominant rock type in this stratigraphic position east of the WIPP site (Holt and Powers, 1988).

Less is known about the hydraulic properties of the Tamarisk than about those of the other Rustler members. No hydraulic tests of the Tamarisk anhydrites (A-2 and A-3) have ever been performed because of apparent low transmissivity. Hydraulic tests of the Tamarisk claystone have been attempted at only four locations: H-3b3 (1984 unpublished field notes), DOE-2 (Beauheim, 1986), H-14 (Beauheim, 1987), and H-16 (Beauheim, 1987). Drillstem and/or pulse tests failed at all four locations, as the transmissivities were apparently too low to measure over a period of several days. Based on similar tests performed successfully on the unnamed lower member at H-16, Beauheim (1987) concluded

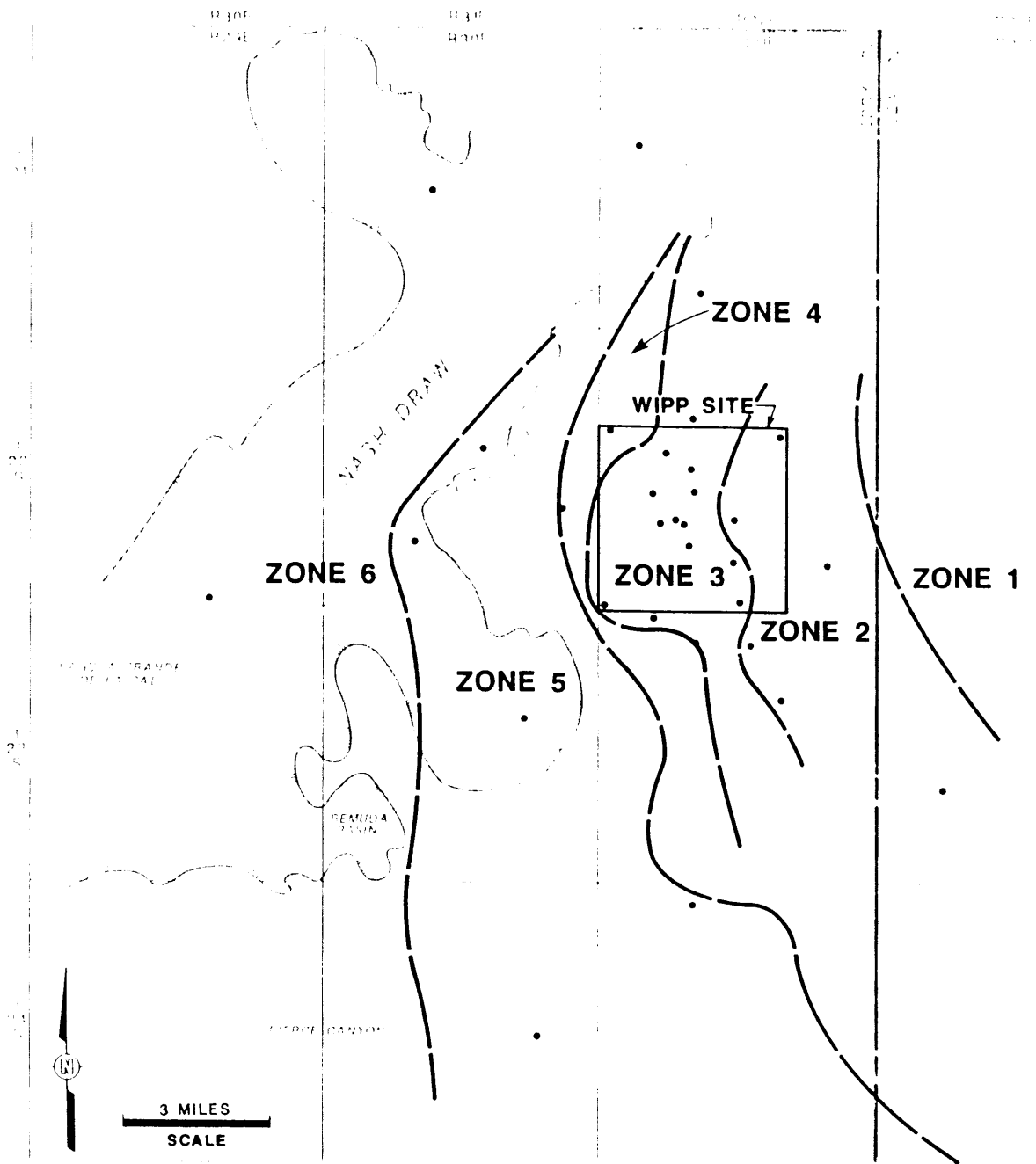
that the transmissivity of the Tamarisk claystone is likely 10^{-5} ft²/day or less. The transmissivity of the Tamarisk claystone might be expected to be greater west of the WIPP site in Nash Draw where dissolution of the upper Salado and Rustler has occurred, but no direct measurements have been made in this area. The transmissivities of the Tamarisk anhydrites in Nash Draw have probably been increased by dissolution and subsidence-induced fracturing.

No measurements of the undisturbed hydraulic head within the Tamarisk claystone have ever been made, due to low transmissivities. Fluid pressures have been measured within the Tamarisk interval of H-16 since August 1987 (Stensrud and others, 1988a, 1988b), but the pressure did not stabilize before the pressure began responding to the construction of the nearby air-intake shaft.

The Tamarisk claystone consists of mostly mudstone and claystone with minor amounts of siltstone (Holt and Powers, 1988). Gypsum occurs as fibrous fracture fillings, nodules, and displacive crystals (Holt and Powers, 1988). The nodules and displacive crystals of gypsum are primary and attest to the lack of circulating groundwaters since the Permian (Holt and others, in prep.). The fibrous fracture-filling gypsum may have developed without an external source of fluid as the dewatering of the clays within the unit could provide sufficient fluid for the relocation of sulfate. Holt and Powers (1988) report collapse of A-3 in core from boreholes H-11 and H-3 and attribute this collapse to dissolution of small amounts of halite from this interval. This suggests at least a temporary vertical hydraulic connection between the M-3/H-3 interval and other water-bearing units in the Rustler. The timing and nature of this possible connection cannot be determined with the limited data available.

Magenta Dolomite Member

Holt and others (in prep.) include the Magenta within their hydrostratigraphic subdivision of the Rustler as Water Producing Unit 4 (WPU-4). The Magenta is confined by A-3 and A-4 of Holt and Powers (1988) which are equivalent to Confining Beds 4 and 5 of Holt and others (in prep.). The Magenta is a fine-



EXPLANATION

- DRILL HOLES

Figure 25. Hydrogeologic zones defined for the Culebra Dolomite Member (from Holt and others, in prep.). Zone characteristics are listed in Table 1.

CHARACTERISTICS OF CULEBRA HYDROGEOLOGIC ZONES

<p>ZONE 1</p> <ul style="list-style-type: none"> • Confined • Deeply Buried • Few Fractures, Most Gypsum Filled • Vugs Filled with Anhydrite • Modern Transmissivity < 0.01 ft²/day 	<p>ZONE 4</p> <ul style="list-style-type: none"> • Confined • Overburden Greatly Decreased • Abundant Open Fractures • Vugs Open/Collapsed • Modern Transmissivity < 10-100 ft²/day
<p>ZONE 2</p> <ul style="list-style-type: none"> • Confined • Overburden Slightly Decreased • More Fractures, Most Gypsum Filled • Anhydrite Vug Fillings Altering to Gypsum • Modern Transmissivity 0.01-10 ft²/day 	<p>ZONE 5</p> <ul style="list-style-type: none"> • Confined, Leaky • Overburden Usually Small • Dissolution of Underlying Halite Increases Fracturing • Fractures Very Abundant, Open • Vugs Open/Collapsed • Modern Transmissivity 10-1000 ft²/day
<p>ZONE 3</p> <ul style="list-style-type: none"> • Confined • Overburden Significantly Decreased • Abundant Fractures, Some Gypsum Filled • Vugs Open or Filled with Gypsum • Modern Transmissivity < 1->10 ft²/day 	<p>ZONE 6</p> <ul style="list-style-type: none"> • Unconfined • Overburden Minimal • Collapsed due to Salado Dissolution • No Gypsum • Fractures and Breccia Abundant • Vugs Open/Collapsed • Modern Transmissivity >1000 ft²/day

Table 1. Characteristics of Culebra Hydrogeologic Zones.

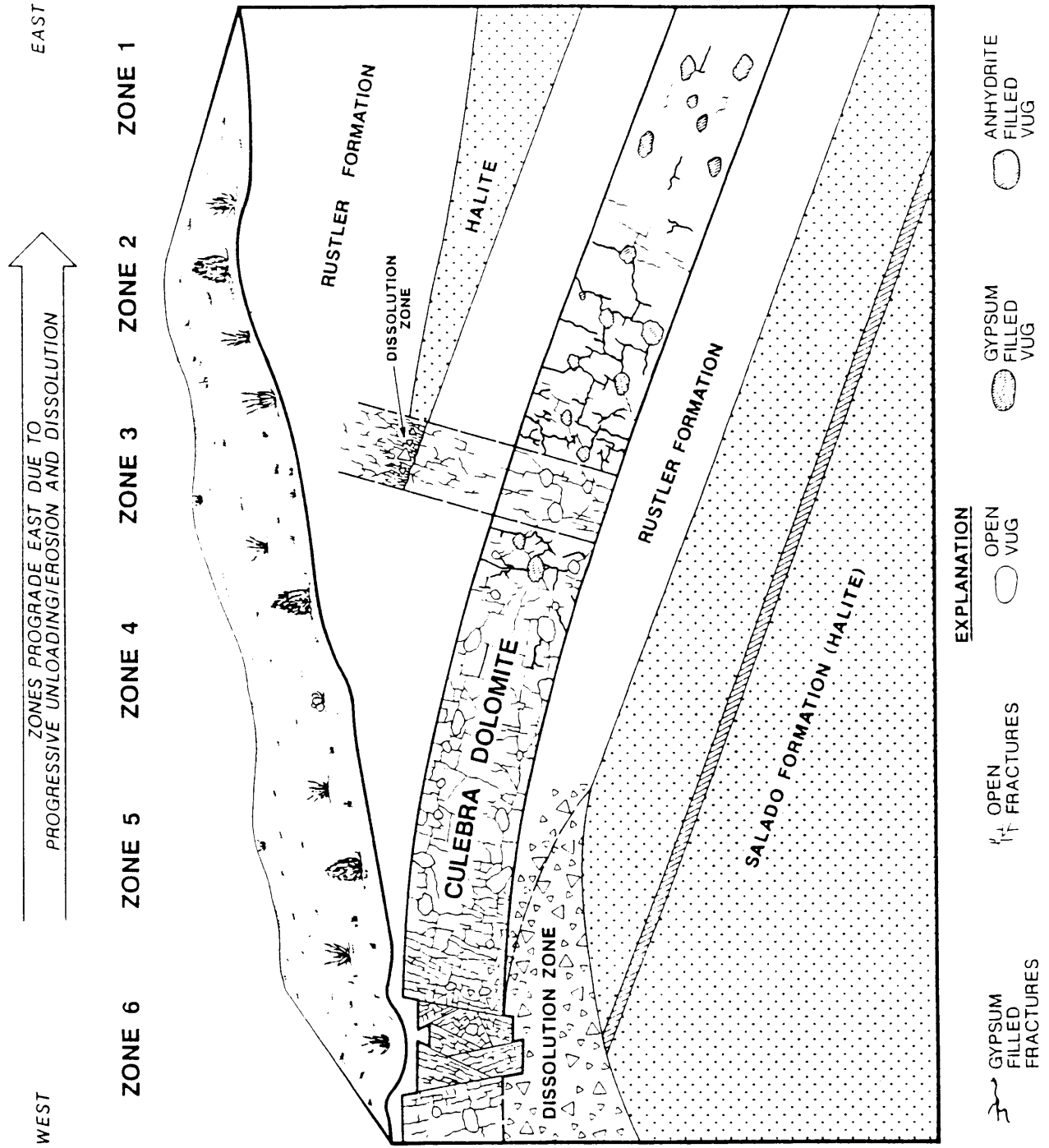


Figure 26. Conceptual cross-section of the Culebra hydrogeologic zones showing the distribution of features (from Holt and others, in prep.).

grained, gypsiferous, arenaceous dolomite (Holt and Powers, 1988).

Hydraulic tests of the Magenta dolomite at 16 locations (Mercer, 1983; Beauheim, 1986, 1987) yield transmissivity values generally less than or equal to 0.1 ft²/day (Figure 27). Higher values of transmissivity, 0.3 and 1.0 ft²/day, are found at H-6a and H-9a, respectively. The two highest values of Magenta transmissivity, 375 and 53 ft²/day, are found in Nash Draw at WIPP-25 and WIPP-27, respectively, where dissolution of the upper Salado has caused collapse and fracturing of the overlying Rustler.

Between 1979 and 1981, stabilized water levels were measured in 13 wells completed to the Magenta (Richey, 1987b). The elevations of these stabilized water levels can be compared to estimated freshwater-head elevations (Figure 28) calculated using borehole-fluid-density (or specific-gravity) data (Mercer and others, 1981; Dennehy and Mercer, 1982; Mercer, 1983; Lambert and Robinson, 1984; Richey, 1986, 1987a). The contours of the freshwater heads indicate a southwesterly flow direction within the Magenta in the northern portion of Nash Draw, and a generally westward flow direction toward Nash Draw over the rest of the region. Holt and others (in prep.) concluded that the flow directions of the Magenta (Figure 28) were not significantly influenced by fluid density variations.

The hydraulic head at H-6a (Figure 28) seems anomalously low compared to that at surrounding wells, and it causes a flexure in the contour lines across the northern portion of the WIPP site. The low head at H-6a may be related to drainage into dissolution cavities in the upper Rustler, such as those encountered at WIPP-33 (Sandia and USGS, 1981) about a half mile southwest of H-6. If so, it may be a relatively localized perturbation in the Magenta potentiometric surface, and may not affect heads as far to the east as is indicated on Figure 28.

Freshwater heads (Figure 28) at DOE-2, H-14, and H-16 were estimated from pressure measurements. The pressures measured at DOE-2 and H-14 (Beauheim, 1986, 1987) represent upper bounds on the stabilized

formation pressures, while the pressure measured at H-16 reflects drainage from the Magenta into the nearby WIPP shafts since 1981 (Beauheim, 1987). With these caveats, the estimated freshwater heads at DOE-2, H-14, and H-16 agree qualitatively with the pattern of freshwater heads derived from the water-level data.

The Magenta was originally deposited as clastic gypsum and carbonate grains in well developed strata (Holt and Powers, 1988). Upon shallow burial, the gypsum clastic component was at least partly replaced by anhydrite and sulfate cements developed between clastic grains, probably as overgrowths on existing sulfate (Holt and Powers, 1988). The anhydrite has since been replaced by gypsum, and most of the clastic texture within the sulfate component of the Magenta has been erased (Holt and Powers, 1988). Porosity within the Magenta is primarily intergranular and formed by the dissolution of gypsum (Holt and others, in prep.). In those areas which originally contained abundant clastic gypsum, small open vugs have developed. Fracture porosity is less common, and the fractures are often filled with gypsum. Disruption and fracturing from unloading and dissolution have apparently been less effective in the Magenta than in the Culebra.

Forty-niner Member

The Forty-niner Member of the Rustler Formation (Figure 12) is composed of two anhydrite and/or gypsum units (A-4 and A-5 of Holt and Powers, 1988) separated by a siltstone, mudstone, and claystone interbed (M-4). The anhydrite/gypsum units act as confining beds (Confining Beds 5 and 6 of Holt and others, in prep.), while the claystone is a water-producing unit (Water-Producing Unit 5). M-4 is stratigraphically equivalent to halite (H-4) east of the WIPP site.

M-4 has been hydraulically tested at only four locations: DOE-2 (Beauheim, 1986), H-3d (Beauheim and others, in prep.), H-14 (Beauheim, 1987), and H-16 (Beauheim, 1987). Transmissivities reported for the claystone are 2.5×10^{-3} to 1.1×10^{-2} ft²/day at DOE-2, 3.9×10^{-3} ft²/day at H-3d, 3.0×10^{-2} to 7.1×10^{-2} ft²/day at H-14, and 5.0×10^{-3} to

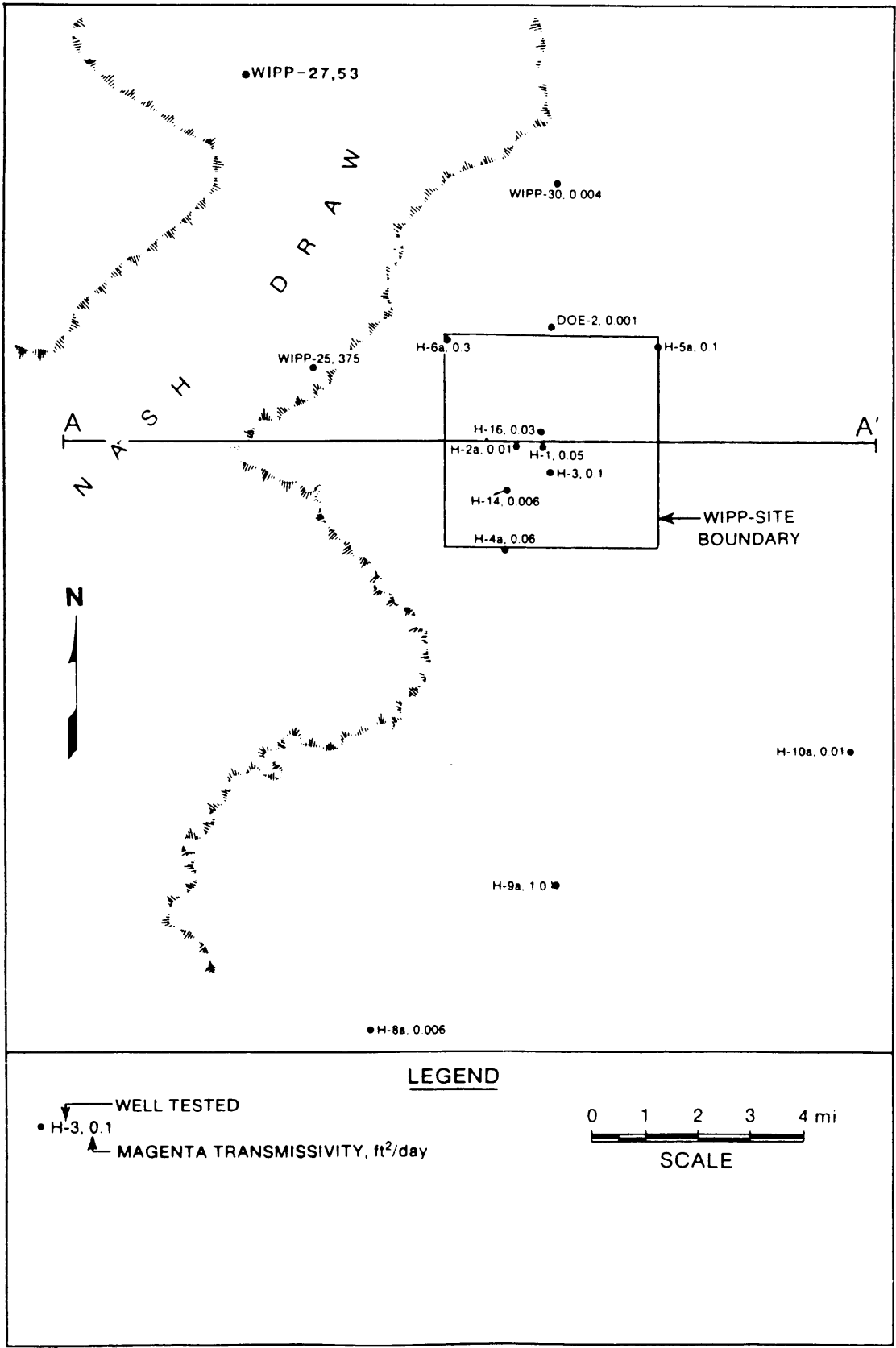


Figure 27. Transmissivity of the Magenta Dolomite Member (from Holt and others, in prep.).

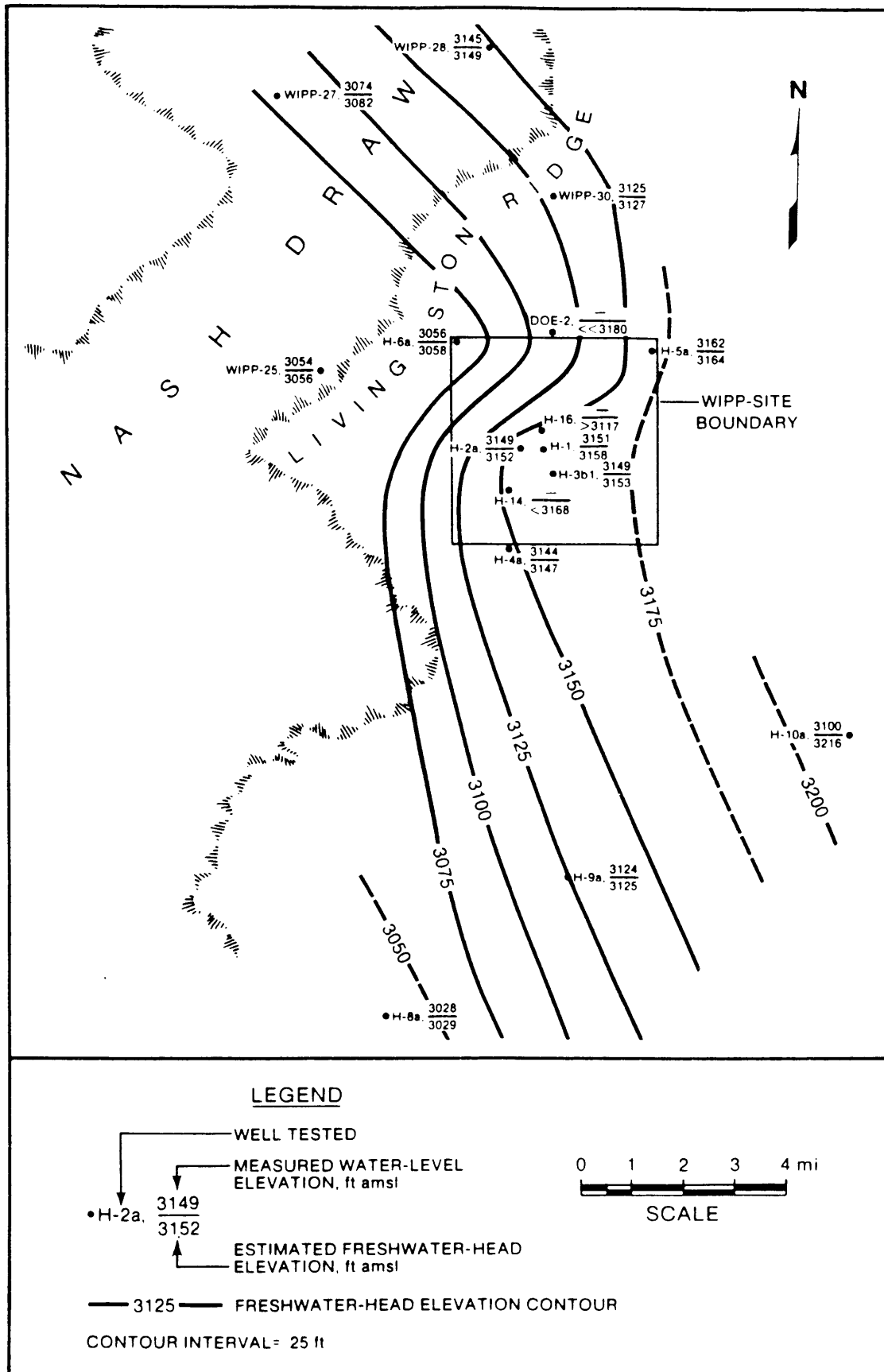


Figure 28. Measured water level and estimated freshwater head elevation, Magenta Dolomite Member (from Holt and others, in prep.).

5.6×10^{-3} ft²/day at H-16. The Forty-niner claystone might be assumed to have higher transmissivities in Nash Draw, but no direct measurements have been made in that area. Transmissivity of the unit is probably less east of the WIPP site where halite (H-4) is present.

The transmissivities of the anhydrites are very low and not measurable (Beauheim, 1987). Where present in Nash Draw, the Forty-niner anhydrites may have very high transmissivities as a result of dissolution and subsidence-induced fracturing.

Hydraulic heads of the Forty-niner claystone have been measured at wells H-3d, H-14, H-16, and DOE-2. Holt and others (in prep.) summarize these observations and estimate static fluid pressures at the midpoint of the claystone. The measurement from DOE-2 had the greatest uncertainty. The original data from DOE-2 (Beauheim, 1986) indicate that a "static" pressure 12 psi lower than that reported by Beauheim (1987) is a more accurate upper bound on the hydraulic head. Static fluid-pressure estimates for the Forty-niner claystone at H-3d, H-14, H-16, and DOE-2 have been converted to freshwater heads (Figure 29). Firm conclusions cannot be drawn from so few data, but the data are consistent with southwesterly to westerly flow towards Nash Draw. The relatively low head at H-16 may be related more to localized drainage into the WIPP shafts than to the undisturbed regional head distribution (Beauheim, 1987).

The M-4 unit (WPU-5) consists of siltstone, claystone, and locally some sandstone, all of which are cemented with halite (Holt and Powers, 1988). Porosity within M-4 is principally intergranular, resulting from the dissolution of halite cements.

Summary of Rustler Hydraulic-Head Relationships

The hydraulic-head distributions for the unnamed lower member/upper Salado, Magenta, and Forty-niner claystone (Figures 14, 28, and 29) all indicate westerly to southwesterly groundwater flow. In contrast, flow within the more transmissive Culebra appears to be largely southerly (Figure 16). These data are consistent with the

paleorecharge/modern discharge hypothesis of Lambert and Harvey (1987).

Vertical gradients within the Rustler reflect a recharge-discharge cycle and are consistent with Lambert and Harvey's (1987) hypothesis of late-Pleistocene recharge and current discharge (Holt and others, in prep.). A vertical east-west cross section through the center of the WIPP site shows the directions of the vertical hydraulic gradients between members of the Rustler (Figure 30). Where no dissolution of either upper Salado or unnamed lower member halite has occurred, from about the west-central portion of the WIPP site to the east, hydraulic gradients from the unnamed member and Magenta indicate potential fluid flow from both above and below into the Culebra. The Culebra, the most transmissive part of the Rustler in this vicinity, drains towards Nash Draw faster than the other water-producing units. The gradients toward the Culebra do not imply, however, that vertical leakage between units is significant (Holt and others, in prep.). Rather, the high hydraulic heads in the low-permeability Magenta and unnamed member demonstrate the effectiveness of the confining beds separating them from the Culebra.

The western portion of the WIPP site appears to be a transition region in which vertical hydraulic gradients change. Where the upper Salado has been dissolved, the Magenta head decreases until the unit dewateres, and gradients are downward from the Culebra to the unnamed member/upper Salado. The changes in transmissivities caused by the dissolution increased the internal drainage from each of the members to the west and southwest. Dissolution of the upper Salado combined with Rustler subsidence to fracture the Rustler confining beds, allowing increased flow between Rustler members.

Vertical hydraulic gradients between the Magenta and the Forty-niner claystone are upward in the central portion of the WIPP site, based on measurements made in holes DOE-2, H-3d, H-14, and H-16 (Beauheim, 1987). The two water-producing units are separated by an effective confining bed (A-4) in this region, which likely prevents significant leakage. The origin of the head difference between the Magenta and Forty-niner claystone is unclear, but the relative heads

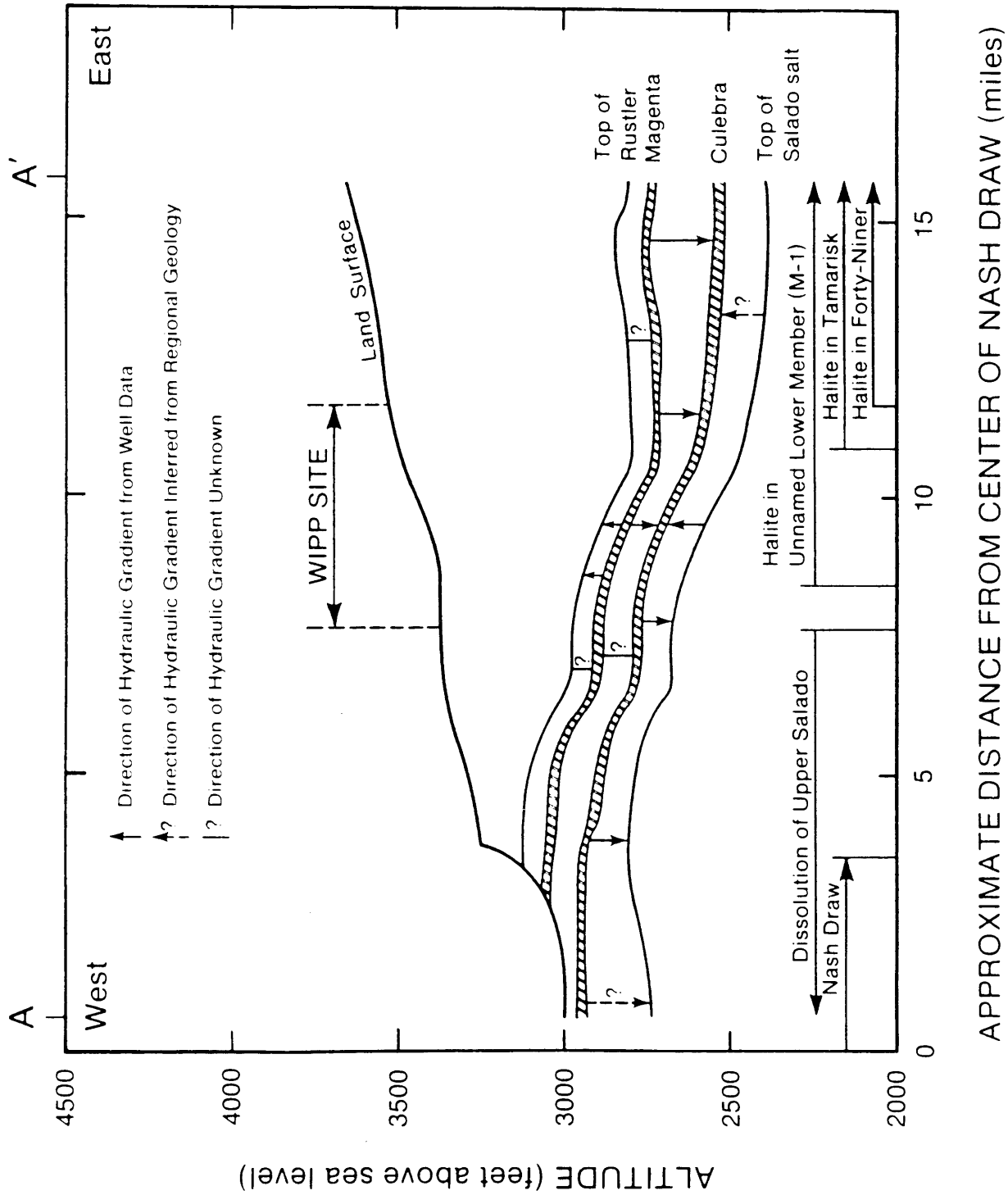


Figure 30 Vertical flow potential in the Rustler Formation (from Holt and others, in prep.).

currently prevent overlying units from recharging the Magenta. No data are available to evaluate hydraulic gradients between the Magenta and Forty-niner claystone in the region surrounding the WIPP site, such as at the J.C. Mills Ranch to the south, where portions of the Dewey Lake Formation are saturated (Mercer, 1983).

The hydraulic gradients within and between the individual water-producing units of the Rustler are consistent with Lambert and Harvey's (1987) hypothesis that the Rustler flow systems are not at steady-state, but are instead draining, following a late-Pleistocene recharge event (Holt and others, in prep.). The most transmissive unit, the Culebra, has drained faster than the other units, leaving it relatively underpressurized at the WIPP site and east of it. The other Rustler units exhibit hydraulic gradients towards the drainage region represented by Nash Draw. West of the WIPP site, where the upper Salado dissolved and caused Rustler subsidence and fracturing, it is likely that all of the Rustler members hydraulically communicate.

Conceptual Hydrogeological Model of the Rustler

Holt and others (in prep.) proposed the following conceptual model for the development of the hydrologic zones within the Rustler. In the WIPP region, the hydrogeologic conditions in the Rustler developed concurrently with the ancestral Pecos hydrologic regime. The erosional pattern generated by the ancestral Pecos River and its tributaries was superimposed over the existing erosional surface. This erosion brought the evaporites of the Rustler and Salado close to the surface, allowing recharge from the ancestral Pecos and meteoric waters to dissolve the evaporites. Groundwater circulated and evaporites dissolved in areas adjacent to the ancestral Pecos River and its tributaries. Collapse enhanced the transmissivity within the Rustler.

Major tributaries to the ancestral Pecos River also dissolved evaporites, as erosion and later dissolution preferentially exposed the Rustler and Salado to circulating groundwater. Local solution features collapsed along these drainages and later coalesced into karst

valleys. The hydrologic regime within the evaporite section around each of these tributaries was dominated by these karst processes. Nash Draw was the closest such tributary. During the Cenozoic, it acted as a recharge point and, as climatic conditions varied, a possible discharge point for fluids moving within the Rustler.

Ancestral Pecos River deposits can be considered a record of paleohydraulic head levels. West and southwest of the WIPP (Figure 23), these deposits are higher than the modern head levels within any of the Rustler units when the effect of subsidence due to dissolution is removed. This relationship suggests that the ancestral Pecos River and its tributaries within karst valleys were capable of recharging Rustler hydrologic units during the Cenozoic.

The hydrologic systems within the Rustler across the site area were mostly passive, as no active discharge point existed. Additional recharge to the low-permeability parts of the Rustler only occurred when new porosity developed in response to fracturing caused by unloading and dissolution of evaporite cements, fracture fillings, and sedimentary features. The Rustler hydrologic units were most active near the ancestral Pecos River and its tributary hydrologic system, where dissolution and collapse enhanced the porosity and permeability within the Rustler. Passive conditions existed further away from the recharge areas, where conditions within the Rustler remained at or near steady state, and where discharge was not possible or very slow. The hydrologic conditions in the area between those clearly active and passive hydrologic zones varied with permeability, porosity, recharge rates, and discharge rates decreasing away from the active zones. The active hydrologic zones encroached upon the passive hydrologic zones as unloading, erosion, and dissolution migrated laterally away from recharge areas.

Variations in climate, the location of the ancestral Pecos River and tributary channels, and local geologic conditions controlled the rate of advance and the locations of the active zones. As a consequence, the hydraulic head potentials within the Rustler hydrologic units varied such that flow direction reversed. Paleoflow reversals dissolved and removed

evaporite minerals from those passive areas of the Rustler and increased transmissivity and potential for further discharge. As modern transmissivity variations within the hydrologic units reflect the extent of active Cenozoic zones, paleoflow directions within active Cenozoic hydrologic zones must have been parallel to the modern transmissivity distribution. The principal direction of flow has not been precisely identified.

The hydrologic units within the Rustler across the WIPP site are not being recharged today, and the flow directions indicate that Rustler hydrologic units are now draining. Therefore, modern transmissivities of these units are interpreted to reflect the maximum encroachment of Cenozoic active areas into passive areas. The modern transmissivities within Rustler hydrologic units in the vicinity of the WIPP site generally decrease away from Nash Draw, a probable Cenozoic recharge area. Modern transmissivities appear to increase where Cenozoic dissolution and collapse occurred within the Rustler and Salado. In those hydrologic units subject to fracturing during unloading (principally the Culebra, WPU-2), modern transmissivity generally is related to the amount of overburden removed by erosion. This is true in the highly transmissive zone south of the WIPP site and east of Nash Draw. Modern transmissivities may be lower than predicted in those areas where late-stage secondary pore fillings are present. At the present time, only one such location has been tentatively identified in the Rustler. It occurs within the Culebra Dolomite Member (WPU-2) west of the WIPP site.

Dewey Lake Formation

The Dewey Lake consists almost entirely of mudstone, claystone, siltstone, and interbedded sandstone. The lower Dewey Lake is characterized by locally abundant gypsum-filled fractures. The upper Dewey Lake is cemented with carbonate, and it is moist within the air-intake shaft at the WIPP (Holt and Powers, 1990). Some fractures in this zone are open, and carbonate-filled fractures become more abundant downward.

Lower in the Dewey Lake, an abrupt change of cement type was noted by Holt and Powers (1990) from carbonate to a much harder, unidentified material. Coincident with the change in cement, fractures became filled with fibrous gypsum, and no moisture was evident.

In the northern and central portions of the WIPP site, no water has been reported in the Dewey Lake in WIPP drillholes, although a zone of lost circulation associated with fractures is commonly encountered approximately 200 to 250 ft below ground surface (e.g., Mercer and others, 1987). Water has been encountered within the Dewey Lake at several drillholes near the southern WIPP site boundary, and several stock wells south of the WIPP site are possibly completed in a perched aquifer in the upper Dewey Lake (Mercer, 1983).

Dockum Group

The Dockum Group is of Late Triassic age (Figure 1). The Dockum Group occurs as an erosional wedge that pinches out westward along a north-south line through the middle of the WIPP site (Powers and others, 1978). The Dockum Group consists of calcareous interbedded sandstone, siltstone, and claystone. It is moderately well indurated to soft. It is not a hydrologically significant unit in the vicinity of the WIPP site, although it is a significant aquifer east of the WIPP site (Mercer, 1983). The Dockum Group may be recharged by precipitation in the eastern portion of the WIPP site (Mercer, 1983).

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