2.1.3.1 General Stratigraphy and Lithology below the Bell Canyon

As stated previously, the Precambrian basement near the site is projected to be about 5,545 m (18,200 ft) below the surface (Keesey 1976, Vol. II, Exhibit No. 2), consistent with information presented by Foster in 1974. Ages of similar rock suites in the region range from about 1.14 to 1.35 billion years.

A detailed discussion of the distribution of Precambrian rocks in southeastern New Mexico and Texas can be found ~~in this application~~ in ***CCA*** Appendix GCR ~~(Section 3.3.1)~~. Figure 3.4-2 in ***CCA*** Appendix GCR provides a structure contour map of the Precambrian. The basal Paleozoic units overlying Precambrian rocks are clastic rocks commonly attributed either to the Cambrian Bliss sandstone or the Ellenberger Group (Foster 1974, ***p.*** 10), considered most likely to be Ordovician in age in this area. The Ordovician System comprises the Ellenberger, Simpson, and Montoya Groups in the northern Delaware Basin. Carbonates are predominant in these groups, with sandstones and shales common in the Simpson Group. Foster (1974, Figure 4) reported 297 m (975 ft) of Ordovician-age rocks north of the site area and extrapolated a thicker section of about 396 m (1,300 ft) at the present site (Foster 1974, Figure 5). Keesey (1976, Vol. II, Exhibit No. 2) projected a thickness of 366 m (1,200 ft) for the Ordovician System within the site boundaries.

Silurian-Devonian rocks in the Delaware Basin are not stratigraphically well defined, and there are various notions for extending nomenclature into the basin. Common drilling practice is not to differentiate, though the Upper Devonian Woodford shale at the top of the sequence is frequently distinguished from the underlying dolomite and limestone (Foster 1974, ***p.*** 18). Foster (1974, Figure 6) showed a reference thickness of 384 and 49 m (1,260 and 160 ft) for the carbonates and the Woodford shale, respectively; he estimated thickness of these units at the present WIPP site to be about 351 m (1,150 ft) (Foster 1974, Figure 7) and 52 m (170 ft) (Foster 1974, Figure 8), respectively. Keesey (1976, Vol. II, Exhibit No. 2) projected 381 m (1,250 ft) of carbonate and showed 25 m (82 ft) of the Woodford shale.

The Mississippian System in the northern Delaware Basin is commonly attributed to Mississippian limestone and the overlying Barnett shale (Foster 1974, ***p.*** 24), but the nomenclature is not consistently used. At the reference well used by Foster (1974, 25), the limestone is 165 m (540 ft) thick and the shale is 24 m (80 ft); isopachs at the WIPP are 146 m (480 ft) (Foster 1974, Figure 10) and less than 61 m (200 ft). Keesey (1976, Vol. II, Exhibit No. 2) indicates 156 m (511 ft) and 50 m (164 ft), respectively, within the site boundaries.

The nomenclature of the Pennsylvanian System applied within the Delaware Basin is both varied and commonly inconsistent with accepted stratigraphic rules. Chronostratigraphic, or time-stratigraphic, names are applied from base to top o**f** these lithologic units: the Morrow, Atoka, and Strawn (Foster 1974, ***p.*** 31). Foster (1974, Figure 13) extrapolated thicknesses of about 671 m (2,200 ft) for the Pennsylvanian at the WIPP site. Keesey (1976, Vol. II, Exhibit No. 2) reports 636 m (2,088 ft) for these units. The Pennsylvanian rocks in this area are mixed clastics and carbonates, with carbonates more abundant in the upper half of the sequence.

The Permian is the thickest system in the northern Delaware Basin, and it is divided into four series from the base to top: Wolfcampian, Leonardian, Guadalupian, and Ochoan. According to

Keesey (1976, Vol. II, Exhibit No. 2), the three lower series total 2,647 m (8,684 ft) near the site. Foster (1974, Figures 14, 16, and 18) indicates a total thickness for the lower three series of 2,336 m (7,665 ft) for a reference well north of WIPP. Foster's isopach maps of these series (Foster 1974, Figures 15, 17, and 19) indicate about 2,591 m (8,500 ft) for the WIPP site area. The Ochoan Series at the top of the Permian is considered in more detail later because the formations host and surround the WIPP repository horizon. Its thickness at DOE-2, about 3.2 km (2 mi) north of the site center, is 1,200 m (3,938 ft), according to Mercer et al. (1987, ***p.*** 23).

The Wolfcampian Series is also referred to as the Wolfcamp Formation (hereafter referred to as the Wolfcamp) in the Delaware Basin. In the site area, the lower part of the Wolfcamp is dominantly shale with carbonate and some sandstone, according to Foster (1974, Figure 14); carbonate increases to the north (Foster 1974, ***p.*** 36). Clastics increase to the east toward the margin of the Central Basin Platform. Keesey (1976, Vol. II, Exhibit No. 2) reports the Wolfcamp to be 455 m (1,493 ft) thick at a well near the WIPP site.

The Leonardian Series is represented by the Bone Spring Limestone ***or*** Formation (hereafter referred to as the Bone Spring). According to Foster (1974, ***pp.*** 35 - 36), the lower part of the formation is commonly interbedded carbonate, sandstone, and some shale, while the upper part is dominantly carbonate. Near the site the Bone Spring is 990 m (3,247 ft) thick, according to Keesey (1976, Vol. II, Exhibit No. 2).

The Guadalupian Series is represented in the general area of the site by a number of formations exhibiting complex facies relationships (Figure 2-~~5~~***9***). The Guadalupian Series is known in considerable detail west of the site from outcrops in the Guadalupe Mountains, where numerous outcrops ***are present*** and subsurface studies have been undertaken. (See, for example, ~~P.B.~~ King 1948, Newell et al. 1953, and Dunham 1972 in the ***CCA*** bibliography.)

Within the Delaware Basin, the Guadalupian Series, known as the Delaware Mountain Group, comprises three formations: Brushy Canyon, Cherry Canyon, and Bell Canyon, from base to top. These formations are dominated by submarine channel sandstones with interbedded limestone and some shale. The Lamar limestone generally tops the series, immediately underneath the Castile Formation (hereafter referred to as the Castile). Around the margin of the Delaware Basin, reefs developed when the Cherry Canyon and Bell Canyon were being deposited. These massive reef limestones, the Goat Seep and Capitan Limestones, are equivalent in time to the basin sandstone formations but were developed topographically much higher around the basin margin. A complex set of limestone-to-sandstone and evaporite beds was deposited further away from the basin, behind the reef limestones. The Capitan ~~r~~***R***eef and back-reef limestones are well known because numerous caves, including the Carlsbad Caverns, are partially developed in these rocks.

2.1.3.2 The Bell Canyon

As will be discussed in Section 2.1.3.3, the Castile is a 427-to-487-m~~eter~~(1,400-to-1,600-f~~oot~~) thick layer of nearly impermeable anhydrites and halites that isolate the Salado from the

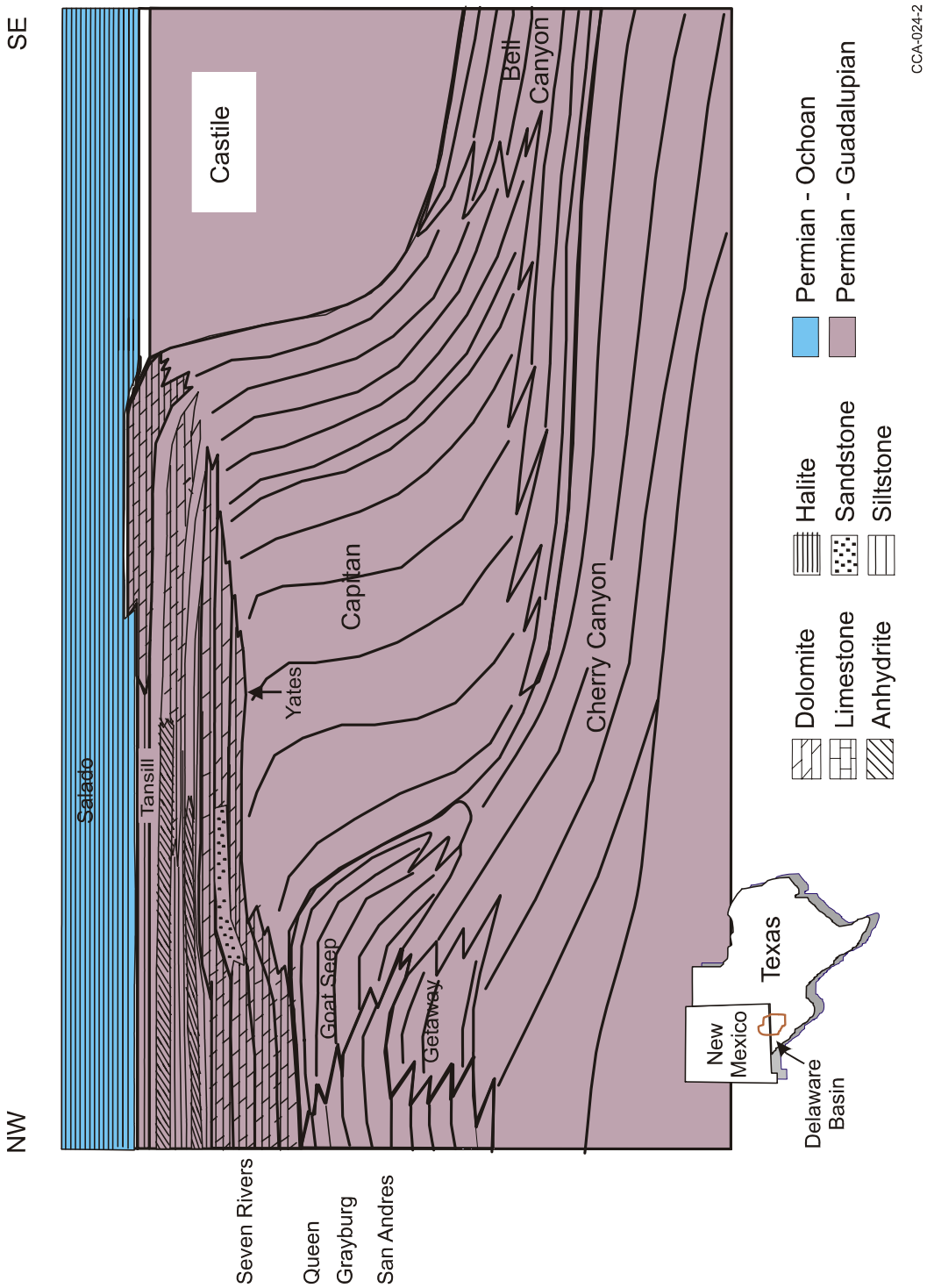


Figure 2-~~5~~9. Schematic Cross-Section from Delaware Basin (southeast) through Marginal Reef Rocks to Back-Reef Facies (based on King, ~~P.B.,~~ 1948)

deeper water-bearing rocks. This notwithstanding, the DOE is interested in the Bell Canyon because it is the first laterally continuous transmissive unit below the WIPP repository. The significance of this unit is related to the FEP in Table 2-1 for deep dissolution. In evaluating this FEP, the DOE considers the potential for groundwater to migrate from the Bell Canyon or lower units into the repository and cause dissolution. The following discussion summarizes the basic understanding of the Bell Canyon lithology. Dissolution is discussed in Section 2.1.6. Bell Canyon hydrology is presented in Section 2.2.1.2. A thorough discussion of dissolution is in ***CCA*** Appendix DEF~~(Section DEF.3.1)~~.

The Bell Canyon is known from outcrops on the west side of the Delaware Basin and from subsurface intercepts for oil and gas drilling. Several informal lithologic units are commonly named during such drilling. Mercer et al. (1987, ***p.*** 28) stated that DOE-2 penetrated the Lamar limestone, the Ramsey sand, the Ford shale, the Olds sand, and the Hays sand. This informal nomenclature is used for the Bell Canyon in some other WIPP reports.

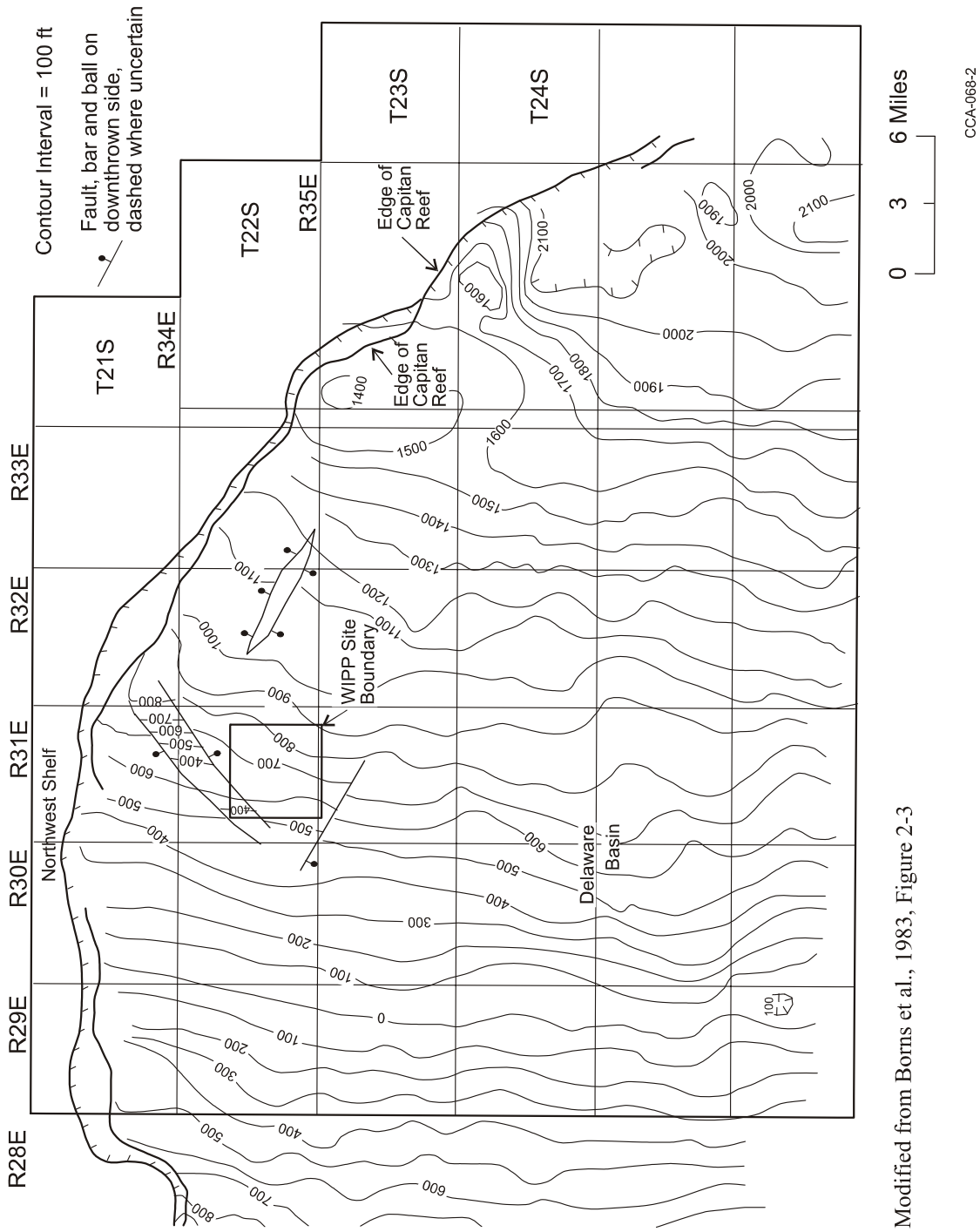
The Clayton Williams Badger Federal borehole (Section 15, T22S, R31E) intercepted 961 feet (293 meters) of Bell Canyon, including the Lamar limestone, according to Keesey (1976, Vol. II, Exhibit No. 2). Reservoir sandstones of the Bell Canyon were deposited in channels that are straight to slightly sinuous. In their 1988 paper, Harms and Williamson proposed that density currents flowed from shelf regions, cutting channels and depositing the sands.

Within the basin, the Bell Canyon- (Lamar limestone-) Castile contact is distinctive on geophysical logs because of the contrast in low natural gamma of the basal Castile anhydrite compared to the underlying limestone. Density or acoustic logs are also distinctive because of the massive and uniform lithology of the anhydrite compared to the underlying beds. In cores, the transition is sharp, as described by Mercer et al. (1987, 312) for DOE-2. A structure contour map of the top of the Bell Canyon is shown in Figure 2-~~6~~***10***. Also see ***CCA*** Appendix MASS, ~~Section MASS.18,~~ MASS Attachment 18-6, Figure 5.3-3. According to Powers et al. ***(***1978***)*** (***CCA*** Appendix GCR, 4–59)**,** this structure does not reflect the structure of deeper formations, suggesting different deformation histories. The rootless character of at least some of the normal faulting in the lower Permian suggests these are shallow-seated features.

2.1.3.3 The Castile

The Castile is the lowermost lithostratigraphic unit of the Late Permian Ochoan Series (Figure 2-~~7~~***11***) and is part of the thick layer of evaporites within the WIPP disposal system. It was originally named by Richardson (1904, ***p.*** 43) for outcrops in Culberson County, Texas.

The Castile crops out along a lengthy area of the western side of the Delaware Basin. The two distinctive lithologic sequences now known as the Castile and the Salado were separated into the Upper and Lower Castile by Cartwright (1930). Lang ~~in~~***(***1939***)*** clarified the nomenclature by restricting the Castile to the lower unit and naming the upper unit the Salado. By defining an anhydrite resting on the marginal Capitan limestone as part of the Salado, Lang in 1939 effectively restricted the Castile to the Delaware Basin inside the reef rocks.



Modified from Borns et al., 1983, Figure 2-3

Figure 2-6~~1~~10. Structure Contour Map of Top of Bell Canyon

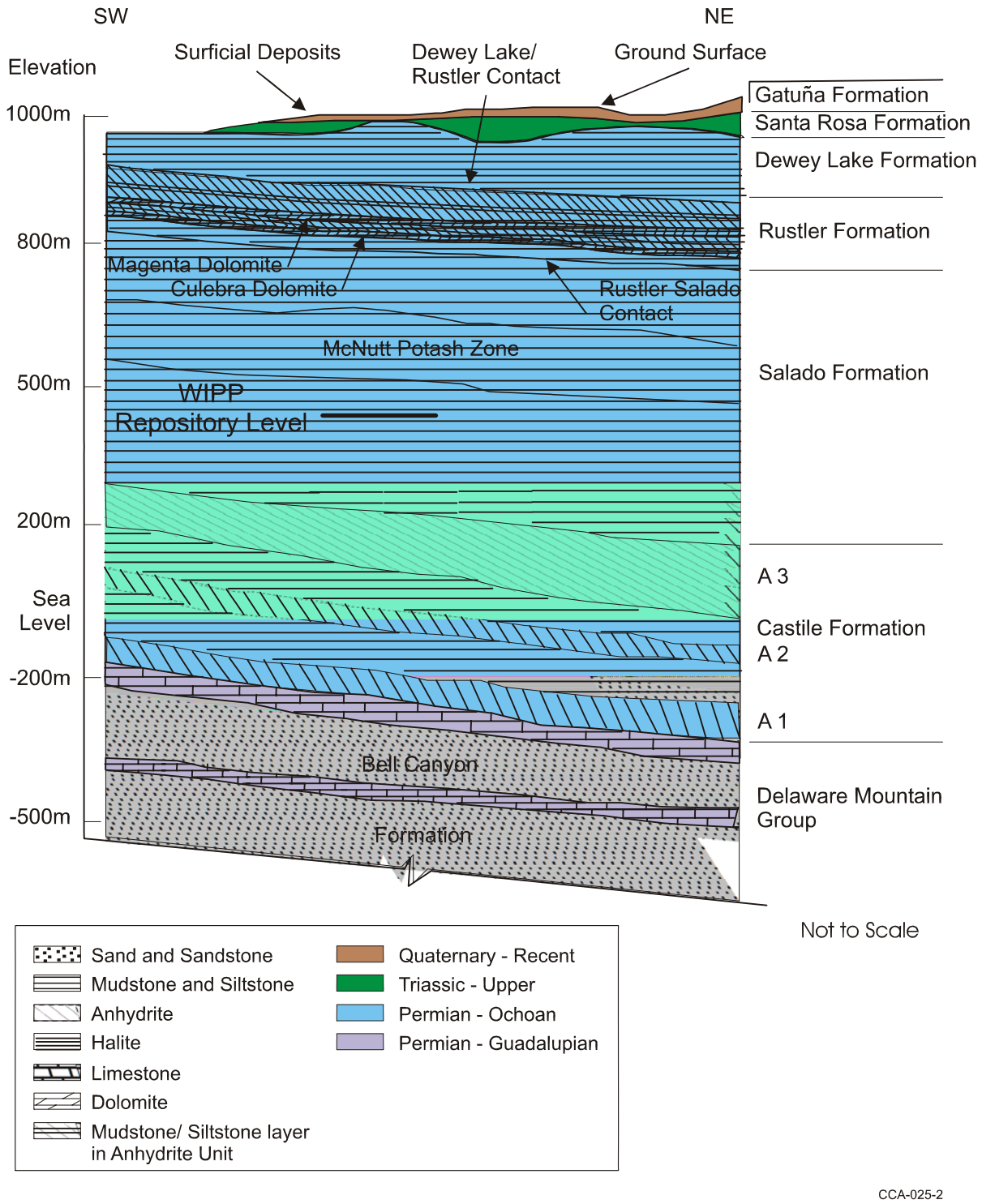


Figure 2-~~7~~11. Generalized Stratigraphic Cross Section above Bell Canyon Formation at WIPP Site

Through detailed studies of the Castile, Anderson et al. (1972) introduced an informal system of names that is widely used and included in many WIPP reports. The units are named from the base as anhydrite I (A1), halite I (H1), anhydrite II (A2), etc. The informal nomenclature varies through the basin from A3 up because of complexity of the depositional system. The Castile consists almost entirely of thick beds of two lithologies: (1) interlaminated carbonate and anhydrite***,*** and (2) high-purity halite.

In the eastern part of the Delaware basin, the Castile thickness ~~is commonly~~ ***ranges from about*** ~~427~~***299*** to ~~487~~ ***616 m*** ~~meters~~ (~~1,400~~ ***980*** to ~~1,600~~ ***2,022*** ft) ~~thick~~ (derived from ***Powers et al. 1996, Figure 5.3-1; see also*** Borns and Shaffer 1985, Figures 9, 11, ***and*** 16 ***for an earlier range based on fewer drillholes***). ***At DOE-2, the Castile is 301 m (989 ft) thick.*** The Castile is thinner in the western part of the Delaware Basin, and it lacks halite units.

Anderson et al. (1978***)*** and Anderson ***(***1978, Figures 1, 3, 4, ***and*** 5) correlated geophysical logs throughout the WIPP region, interpreting thin zones equivalent to halite units as dissolution residues. Anderson et al. (1972, ***p.*** 81) further attributed the lack of halite in the basin to its removal by dissolution. A structure contour map of the top of the Castile is reported in Figure 4.4-6, ***CCA*** Appendix GCR based on seismic data gathered for site characterization. In addition, Borns et al. (1983) prepared a seismic time structure of the middle Castile for identifying deformation. This map is shown in Figure DEF-2.2 in ***CCA*** Appendix DEF. ***Powers et al. (1996; Figures 5.2-1, 5.2-2, and 5.2-3) provide comparative figures of the elevations of the top of the Bell Canyon, top of Anhydrite 2 (of the Castile), and top of Anhydrite 3 (of the Castile), respectively, based on geophysical log data from oil and gas wells.***

For borehole DOE-2, a primary objective was to ascertain whether a series of depressions in the Salado ~~2 miles (3.3 kilometers)~~ ***3.3 km (2 mi)*** north of the site ***center*** was from dissolution in the Castile and related processes, as proposed by Davies ***(1984, p. 175)*** in his doctoral thesis ~~(1984, 175)~~. Studies have suggested that these depressions were not from dissolution but from halokinesis in the Castile (see, for example, Borns 1987). Robinson and Powers (1987, ***pp.*** 22 and 78) interpreted one deformed zone in the Castile ***in the western part of the Delaware Basin*** as partly caused by synsedimentary, gravity-driven, clastic deposition and suggested that the extent of dissolution may have been overestimated by previous workers. No Castile dissolution is known to be present in the immediate vicinity of the WIPP site. The process of dissolution and the resulting features are discussed later in this chapter. See ***CCA*** Appendix DEF, Section DEF.3 for a more in-depth discussion of the study of dissolution in the Castile.

In Culberson County, Texas, the Castile hosts major native sulfur deposits. The outcrops of Castile on the Gypsum Plain south of White's City, New Mexico, have been explored for native sulfur without success, and there is no reported indication of native sulfur anywhere in the vicinity of the WIPP.

In part of the area around the WIPP, the Castile has been significantly deformed and there are pressurized brines associated with the deformed areas; borehole ERDA-6 encountered both deformation and pressurized brine. WIPP-12, 1.6 km (1 mi) north of the site center, revealed lesser Castile structure, but it also encountered a zone of pressurized brine within the Castile. Castile deformation is described and discussed in Section 2.1.5 and in ***CCA*** Appendix DEF,

which detail structural features. Pressurized brine is described in Section 2.2.1, which details the area's hydrology.

Where they exist, Castile brine reservoirs in the northern Delaware Basin are believed to be fractured systems, with high-angle fractures spaced widely enough that a borehole can penetrate through a volume of rock containing a brine reservoir without intersecting any fractures and therefore not produce brine. They occur in the upper portion of the Castile (Popielak et al. 1983). Appreciable volumes of brine have been produced from several reservoirs in the Delaware Basin, but there is little direct information on the areal extent of the reservoirs or the interconnection between them. The presence of a pressurized brine pocket is treated in the conceptual model of WIPP as discussed in Section 6.4.8.

The Castile continues to be an object of research interest unrelated to the WIPP program as an example of evaporites supposedly deposited in deep water. Anderson (1993, p***p***. 12-13) discusses alternatives and contradictory evidence. ***Becker et al. (2002) presented a data set yielding a total Pb/U isochron age of 251.5 ± 2.8 million years (Ma) for calcite from the Castile and inferred that the Permo-Triassic boundary could be younger than this date. This discussion contrasts with other data regarding age of the Salado, Rustler, and Dewey Lake Formations (see later sections), including evidence that later formations yield slightly older radiometric ages.*** Although these discussions and a resolution might eventually affect some concepts of Castile deposition and dissolution, this issue is largely of academic interest and bears no impact on the suitability of the Los Medaños region for the WIPP site. Additional discussion of Castile deformation and the associated WIPP studies appears in Section 2.1.6.1 and ***CCA*** Appendix DEF. The Castile is included in the conceptual model as described in Section 6.4.8. As shown in Appendix ***PA, Attachment*** PAR, ~~in~~ Table PAR-~~49~~***43***, no stratigraphic or lithologic parameters are of importance for this unit. Important hydrological parameters are discussed subsequently.

The EPA questioned DOE's geologic and geophysical basis for the probability (i.e., eight percent probability) of intercepting pressurized brine in the Castile Formation beneath the WIPP disposal panels, and therefore required this distribution to be revised (to a uniform distribution with a range of 0.01 to 0.6) in Performance Assessment Verification Testing (PAVT) (Docket A-93-02, Item II-I-25). The formation of Castile brine pockets as a result of Castile deformation was described in the CCA, and although DOE's discussion of the distribution and nature of fractures in the Castile was limited, parameters were modified to include larger Castile brine pockets in the PAVT. Further information on this topic is contained in EPA Technical Support Document for Section 194.14: Content of Compliance Certification Application, Section IV.C (Docket A-93-02, Item V-B-3), EPA Technical Support Document for Section 194.23: Parameter Justification Report (Docket A-93-02, Item V-B-14), and EPA Technical Support Document for Section 194.23: Review of TDEM Analysis of WIPP Brine Pockets (Docket A-93-02, Item V-B-30).

2.1.3.4 The Salado

The Salado is of interest because it contains the repository horizon and provides the primary natural barrier for the long-term containment of radionuclides. The following section provides basic information regarding the genesis and lithology of the Salado. Subsequent sections discuss

Salado deformation, Salado dissolution, and Salado hydrology. ***CCA*** Appendix GCR provides detailed information about the Salado from early site characterization studies.

The Salado is dominated by halite, in contrast to the underlying Castile. The Salado extends well beyond the Delaware Basin, and Lowenstein (1988, ***p.*** 592) has termed the Salado a saline "giant."

While the Fletcher Anhydrite Member, which is deposited on the Capitan ***R***eef rocks, is defined by Lang (1939; 1942) as the base of the Salado, some investigators consider that the Fletcher Anhydrite Member may interfinger with anhydrites normally considered part of the Castile. The Castile-Salado contact is not uniform across the basin, and whether it is conformable is unresolved. Around the WIPP site, the Castile-Salado contact is commonly placed at the top of a thick anhydrite informally designated A3; the overlying halite is called the infra-Cowden salt and is included within the Salado. Bodine (1978, ***pp.*** 28 **-** 29) suggests that the clay mineralogy of the infra-Cowden in ERDA-9 cores changes at about 4.6 m (15 ft) above the lowermost Salado and that the lowermost clays are more like Castile clays. At the WIPP site, the DOE recognizes the top of the thick A3 anhydrite as the local contact for differentiating the Salado from the Castile and notes that the distinction is related only to nomenclature and has no relevance to the performance of the WIPP disposal system.

The Salado in the northern Delaware Basin is broadly divided into three informal members. The middle member is known locally as the McNutt Potash Zone (hereafter referred to as McNutt) or ***M***ember, and it includes 11 defined potash zones, 10 of which are of economic significance in the Carlsbad Potash District. The lower member and the upper member remain unnamed. The WIPP repository level is located below the McNutt in the lower member. Figure 2-~~8~~***12*** shows details of the Salado stratigraphy near the excavated regions. Elements of this stratigraphy are important to the conceptual model. The conceptual model for the Salado is discussed in Section 6.4.5. The thicknesses used in the model are given in Appendix ***PA, Attachment PAR***, Table PAR-~~57~~***49***.

Within the Delaware Basin, a system is used for numbering the more significant sulfate beds within the Salado, designating these beds as marker beds (MBs) from ~~MB100~~***MB 100*** (near the top of the formation) to ~~MB144~~***MB 144*** (near the base). The system is generally used within the Carlsbad Potash District as well as at and around the WIPP site. The repository is located between MB 139 and MB 138.

In the central and eastern part of the Delaware Basin, the Salado is at its thickest, ranging up to about 600 m (2,000 ft) thick and consisting mainly of interbeds of sulfate minerals and halite, with halite dominating. The thinnest portions of the Salado consist of a brecciated residue of insoluble material a few tens-of-feet thick, which is exposed in parts of the western Delaware Basin. The common sulfate minerals are anhydrite ($CaSO_4$), gypsum ($CaSO_4 \cdot 2H_2O$) near the surface, and polyhalite ($K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$). They form interbeds and are also found along halite grain boundaries. Isopach maps of various intervals of the Salado above the repository horizon have been provided to assist in understanding regional structure. These are Figures 4.3-4 to 4.3-7 in ***CCA*** Appendix GCR. A structure contour map of the Salado can be found in ***CCA*** Appendix GCR (Figure 4.4-10***)***.

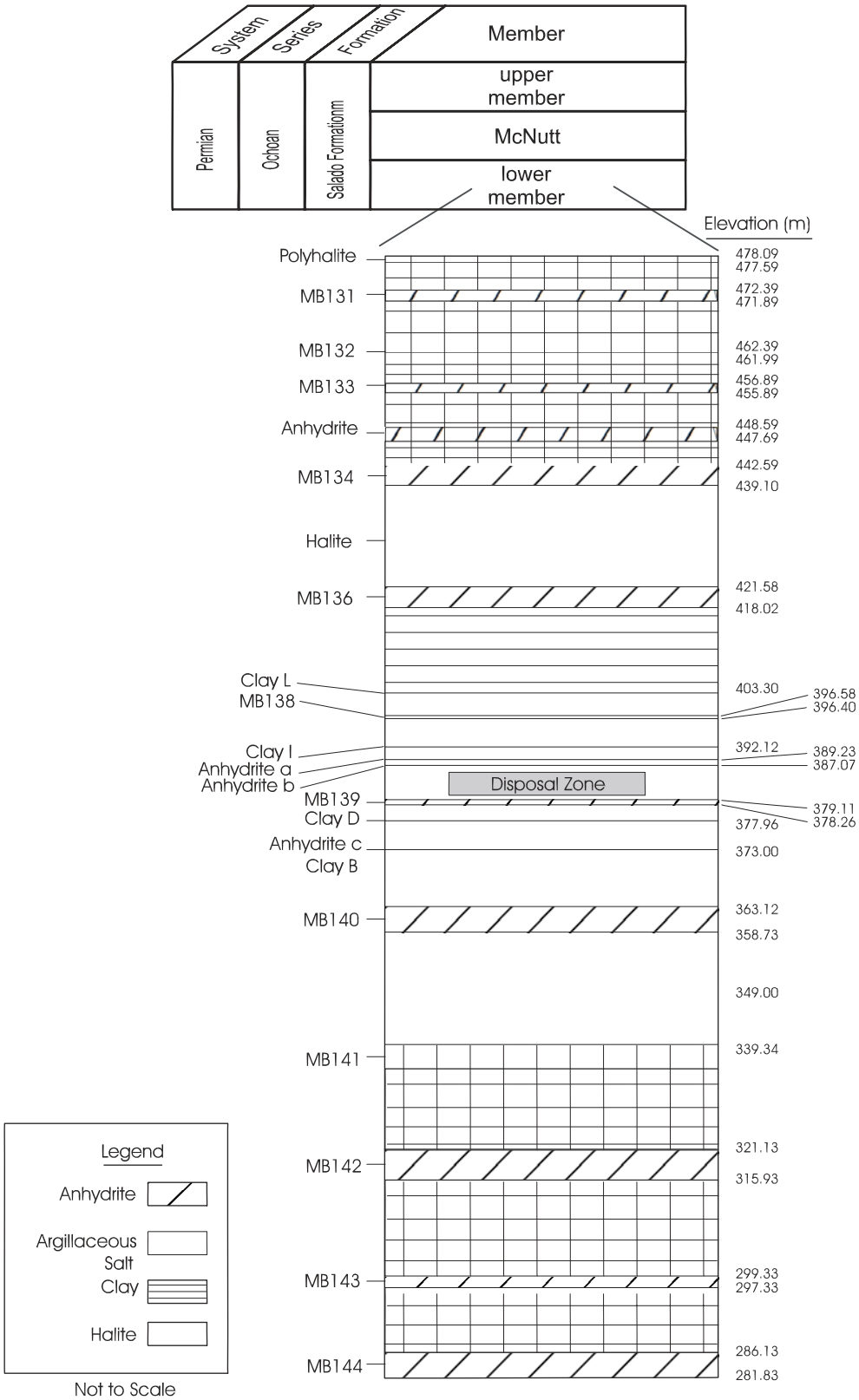


Figure 2-~~8~~*12*. Salado Stratigraphy *in the Vicinity of the WIPP Disposal Zone*

Table 2-2. Chemical Formulas, Distributions, and Relative Abundances of Minerals in the Castile, Salado, and Rustler Formations

Mineral	Formula	Occurrence and Abundance
Amesite	$(Mg_4Al_2)(Si_2Al_2)O_{10}(OH)_8$	S, R
Anhydrite	$CaSO_4$	CCC, SSS, RRR (rarely near surface)
Calcite	$CaCO_3$	S, RR
Carnallite	$KMgCl_3 \bullet 6H_2O$	SS
Chlorite	$(Mg,Al,Fe)_{12}(Si,Al)_8O_{20}(OH)_{16}$	S, R
Corrensite	mixed-layer chlorite and smectite	S, R
Dolomite	$CaMg(CO_3)_2$	RR
Feldspar	$(K,Na,Ca)(Si,Al)_4O_8$	C, S, R
Glauberite	$Na_2Ca(SO_4)_2$	C, S (never near surface)
Gypsum	$CaSO_4 \bullet 2H_2O$	CCC (only near surface), S, RRR
Halite	NaCl	CCC, SSS, RRR (rarely near surface)
Illite	$K_{1-1.5}Al_4[Si_{7-6.5}Al_{1-1.5}O_{20}](OH)_4$	S, R
Kainite	$KMgClSO_4 \bullet 3H_2O$	SS
Kieserite	$MgSO_4 \bullet H_2O$	SS
Langbeinite	$K_2Mg_2(SO_4)_3$	S
Magnesite	$MgCO_3$	C, S, R
Polyhalite	$K_2Ca_2Mg(SO_4)_4 \bullet 2H_2O$	SS, R (never near surface)
Pyrite	FeS_2	C, S, R
Quartz	SiO_2	C, S, R
Serpentine	$Mg_3Si_2O_5(OH)_4$	S, R
Smectite	$(Ca_{1/2},Na)_{0.7}(Al,Mg,Fe)_4(Si,Al)_8O_{20}(OH)_4 \bullet nH_2O$	S, R
Sylvite	KCl	SS

Legend:

C = Castile
S = Salado
R = Rustler
3 letters = abundant
2 letters = common
1 letter = rare or accessory

In the vicinity of the repository, authigenic quartz (SiO_2) and magnesite ($MgCO_3$) are also present as accessory minerals. Interbeds in the salt are predominantly anhydrite with seams of clay. The clays within the Salado are enriched in magnesium and depleted in aluminum (Bodine 1978, ***p.*** 1). The magnesium enrichment probably reflects the intimate contact of the clays with brines derived from evaporating sea water, which are relatively high in magnesium.

Powers et al. (***Chapter 7 of CCA*** Appendix GCR~~, Chapter 7~~) studied the geochemistry of the rocks in the vicinity of the disposal system. A partial list of minerals found in the Delaware Basin evaporites, together with their chemical formulas, is given in Table 2-2. The table also indicates the relative abundances of the minerals in the evaporite rocks of the Castile, Salado, and Rustler. Minerals found either only at depth, removed from influence of weathering, or only near the surface, as weathering products, are also identified.

Although the most common Delaware Basin evaporite mineral is halite, the presence of less soluble interbeds (dominantly anhydrite, polyhalite, and claystone) and more soluble admixtures (for example, sylvite, glauberite, kainite) has resulted in chemical and physical properties of the bulk Salado that are significantly different from those of pure halite layers contained within it. In particular, the McNutt, between ~~MB116~~ ***MB 116*** and ~~MB126~~ ***MB 126***, is locally explored and mined for potassium-bearing minerals of economic interest. Under differential stress, interbeds (anhydrite, polyhalite, magnesite, dolomite) may fracture while, under the same stress regime, pure halite would undergo plastic deformation. Fracturing of relatively brittle beds, for example, has locally enhanced the permeability, allowing otherwise nonporous rock to carry groundwater. Some soluble minerals incorporated in the rock salt can be radiometrically dated, and their dates indicate the time of their formation. The survival of such minerals is significant, in that such dating is impossible in pure halite or anhydrite.

Liquids were collected from fluid inclusions ***in the Salado halite*** and from seeps and boreholes within the WIPP drifts. Analysis of these samples indicated that there is compositional variability in the fluids that shows the effects of various phase transformations on brine composition. The fluid inclusions belong to a different chemical population than do the fluids emanating from the walls. It was concluded that much of the brine is completely immobilized within the salt and that the free liquid emanating from the walls is present as a fluid film along intergranular boundaries, mainly in clays and in fractures in anhydrites. Additional information can be found in ***CCA*** Appendix GCR, Sections 7.5 and 7.6.

Early investigators of the Salado recognized a repetitious vertical succession or cycle of beds in the Salado: clay - anhydrite - polyhalite - halite and minor polyhalite - halite. Later investigators described the cyclical units as clay - magnesite - anhydrite or polyhalite or glauberite - halite - argillaceous halite capped by mudstone. Lowenstein (1988, ***pp.*** 592 **-** 608) defined a depositional cycle (Type I) consisting of (1) basal mixed siliciclastic and carbonate (magnesite) mudstone, (2) laminated to massive anhydrite or polyhalite, (3) halite, and (4) halite with mud. Lowenstein also recognized repetitious sequences of halite and halite with mud as incomplete Type I cycles and termed them Type II cycles. Lowenstein (1988, ***pp.*** 592 **-** 608) interpreted the Type I cycles as having formed in a shallowing upward, desiccating basin beginning with a perennial lake or lagoon of marine origin and evaporating to saline lagoon and salt pan environments. Type II cycles are differentiated because they do not exhibit features of prolonged subaqueous deposition and also have more siliciclastic influx than do Type I cycles.

From detailed mapping of the Salado in the air intake shaft (AIS) at WIPP, Holt and Powers (1990a, ***pp. 2-26***) ~~constructed~~ ***interpreted depositional cycles of the Salado*** ~~a more detailed sedimentological analysis of Salado depositional cycles, similar in broad aspects to the Type I cycle of Lowenstein. Argillaceous halites and halitic mudstone at the top of many depositional cycles were interpreted by Holt and Powers (1990a, 3 – 26)~~ in terms of modern features such as those at Devil's Golf Course at Death Valley National Monument, California. The evaporative basin was desiccated, and varying amounts of insoluble residues had collected on the surface through surficial dissolution, eolian sedimentation, and some clastic sedimentation from temporary flooding caused from surrounding areas. The surface developed local relief that could be mapped in some cycles, while the action of continuing desiccation and exposure increasingly concentrated insoluble residues. Flooding, most commonly from marine sources, reset the sedimentary cycle by depositing a sulfate bed.

The details available from the shaft demonstrated the important role of syndepositional water level to water table changes that created solution pits and pipes within the halitic beds while they were at the surface. Holt and Powers (1990a, Appendix F) concluded that passive halite cements filled the pits and pipes, as well as less dramatic voids, as the water table rose. Early diagenetic to synsedimentary cements filled the porosity early and rather completely with commonly clear and coarsely crystalline halite, reducing the porosity to a very small volume according to Casas and Lowenstein (1989).

Although Holt and Powers (1990a) found no evidence for postdepositional halite dissolution in the AIS, dissolution of the upper Salado halite has occurred west of the WIPP. Effects of dissolution are visible in Nash Draw and at other localities where gypsum karst has formed, where units above the Salado such as the Rustler Formation ~~(hereafter referred to as the Rustler)~~, Dewey Lake Redbeds ~~(hereafter referred to as the Dewey Lake)~~, and post-Permian rocks have subsided. Dissolution studies are summarized in ***CCA*** Appendix DEF, Section DEF.3. ***The dissolution margin of upper Salado halite (see Figure 2-13), based on changes in thickness of the interval from the Culebra dolomite to the Vaca Triste Sandstone Member of the Salado, has been interpreted in detail by Powers (2002a, 2002b, 2003a), Holt and Powers (2002), and Powers et al. (2003). Powers (2002a, 2002b, 2003a) examined data from additional drillholes and noted that the upper Salado dissolution margin appears relatively narrow in many areas, and it directly underlies much of Livingston Ridge. The hydraulic properties of the Culebra correlate in part with dissolution of halite from the upper Salado (Holt and Yarbrough 2002; Powers et al. 2003), and the relationships are further described in Section 2.2.1.4.1.2.***

Within Nash Draw, Robinson and Lang (1938, p***p.*** 87-88) recognized a zone equivalent to the upper Salado but lacking halite. Test wells in southern Nash Draw produced brine from this interval, and it has become known as the brine aquifer. Robinson and Lang ***(1938)*** considered this zone a residuum from dissolution of Salado halite (see Section 2.1.6.2). Jones et al. (1960) remarked that the residuum should be considered part of the Salado, though in geophysical logs it may resemble the ~~Lower~~ ***lower*** Rustler. The approximate eastern limit of the residuum and brine aquifer lies near Livingston Ridge (the eastward margin of Nash Draw) and is marked by a thickening of the Salado (see Section 2.1.6.2.2).

At the center of the site, Holt and Powers (1984, p***p.*** 4-9) recognized clasts of fossil fragments and mapped channeling in siltstones and mudstones above the halite; they considered these beds to be a normal part of the transition from the shallow evaporative lagoons and desiccated salt pans of the Salado to the saline lagoon of the ***l***ower Rustler. Although some Salado halite dissolution at the WIPP may have occurred before deposition of the Rustler clastics, this process was quite different from the subsurface removal of salt from the Salado in more recent time that caused the residuum and associated brine aquifer in Nash Draw. ~~Where the Salado halite is buried at depths greater than about 1,000 feet (approximately 300 meters), physical evidence for large-scale dissolution (for example, postdepositional accumulation of insoluble residues, brecciation from differential collapse, and mass removal) is not observed.~~

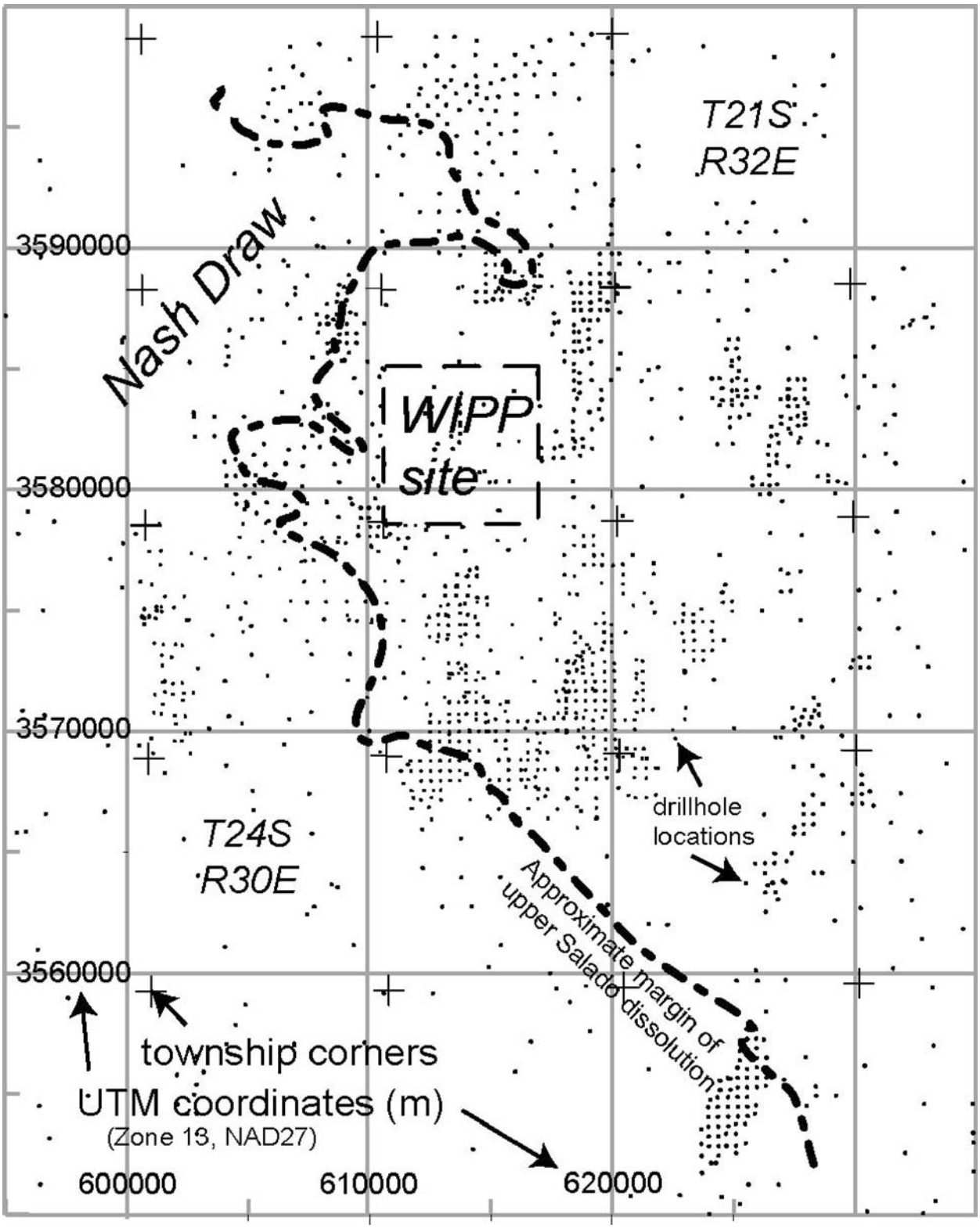


Figure 2-13. Dissolution Margin for the Upper Salado

Geochronological investigations provide a means to confirm the physical evidence indicating that little or no rock-water interactions have occurred in the Salado at the WIPP since the Late Permian Period. Radiometric techniques provide a means of determining the approximate time of the latest episode of regional recrystallization of evaporite minerals, which can be inferred as the approximate time of the latest episode of freely circulating groundwater. Radiometric dates for minerals of the Salado are available from mines and boreholes in the vicinity of the WIPP (Register and Brookins***,*** 1980, p***p***. 30-42; Brookins***,*** 1980, p***p***. 29-31; Brookins, et al. 1980, p***p***. 635-637; Brookins, 1981; and Brookins and Lambert, 1987, p***p***. 771-780). The distribution of dates shows that many of the rubidium-strontium (Rb-Sr) isochron determinations on evaporite minerals, largely sylvite (214 ± 14 million years ago), are in good agreement with potassium-argon (K-Ar) determinations on pure polyhalites (198 to 216 million years ago). (Potassium-argon ages for sylvite are significantly younger than Rb-Sr ages for the same rocks because of the loss of radiogenic argon. Radiogenic strontium, as a solid, is less mobile than argon and therefore the Rb-Sr isochron method is preferred for sylvite.) ***Renne et al. (1998) sampled langbeinite crystals from the Salado and obtained Ar-39/Ar-40 plateau ages of 251 ± 0.2 Ma and 251 ± 0.4 Ma.*** Clay minerals have both Rb-Sr and K-Ar ages significantly older (390 ± 77 million years [Register, 1981]) than the evaporite minerals, presumably reflecting the detrital origin of the clays.

One significantly younger recrystallization event has been identified in evaporites in the WIPP region and is a contact phenomenon associated with the emplacement of an Oligocene igneous dike (see Section 2.1.5.4). Polyhalite near the dike yields a radiometric age of 21 million years, compared to the 32- to 34-million-year age determined for the dike (Brookins, 1980, p***p***. 29-31; and Calzia and Hiss, 1978, p. 44) (this number was recalculated to 34.8 ± 0.8 million years***; CCA*** Appendix GCR, p***p***. 3 - 80). This exception notwithstanding, the results of radiometric determinations argue for the absence of pervasive recrystallization of the evaporites in the Salado in the last 200 million years. This conclusion is supported by the number of replicate determinations, the wide distribution of similarly dated minerals throughout the Delaware Basin, and the concordance of dates obtained by various radiometric methods.

The notion of extensive recrystallization of Salado evaporites has been raised again since the CCA was submitted. Hazen and Roedder (2001), reiterating some arguments presented by Roedder (1984) and O'Neill et al. (1986), suggested that halite has been extensively recrystallized by water moving through the Salado at unknown times. Stable isotope data from fluid inclusions within coarse, clear halite crystals were interpreted as signifying that modern meteoric water constituted part of the fluid inclusion. O'Neill et al. (1986) noted as well that the stable isotope data are consistent with meteoric water falling on a desiccated Salado salt pan surface. Powers and Hassinger (1985) and Holt and Powers (1990a, 1990b) interpret syndepositional dissolution pipes as a common feature of the Salado, with coarse, clear halite with large fluid inclusions formed on a desiccated salt pan. Powers et al. (2001) summarized the arguments against extensive recrystallization of Salado halite. Stein and Krumhansl (1988) found variable compositions of large fluid inclusions, and show that inclusion chemistry differs significantly from intercrystalline brines, indicating that fluid movement is very limited. Satterfield et al. (2002) also concluded that the coarse halite cements found in certain beds of the Salado are synsedimentary, based on ionic concentrations in fluid inclusions. Moreover, Beauheim and Roberts (2002) find extremely low permeability in Salado halite, showing that fluid movement, especially vertically, through the Salado is too

limited and slow to create the purported recrystallization. These findings are also consistent with indications that salt pan deposits are cemented quickly and thoroughly at shallow depths of burial (Casas and Lowenstein 1989). The conclusion that Salado halite has not been pervasively recrystallized remains sound.

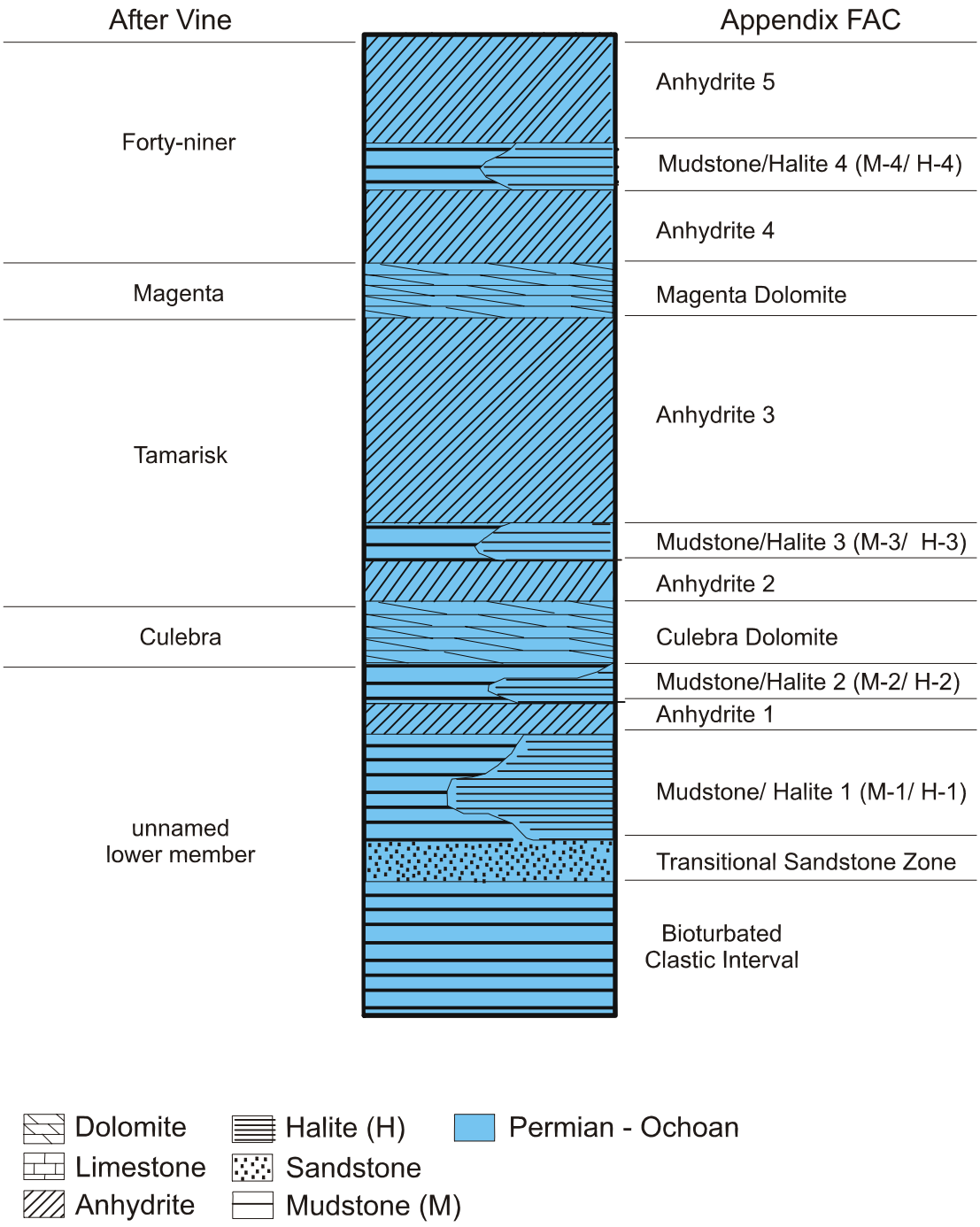
The Salado is of primary importance to the containment of waste. Because it is the principal natural barrier, many of the properties of the Salado have been characterized by the DOE, and numerical codes are used by the DOE to simulate the natural processes within the Salado that affect the disposal system performance.

Two conceptual models of the Salado are used in the performance assessment. One models the creep closure properties of the Salado and the other, the hydrological properties. The creep closure of the Salado is discussed in ***Appendix PA, Attachment*** ~~Appendix~~ PORSURF. This model uses key parameters derived from both in-situ measurements and laboratory testing on Salado core samples. Summaries of these parameters are in ***Butcher (1997).*** Appendix PORSURF Attachment 1, Table 2.

The second conceptual model is titled the Salado conceptual model and is discussed in Section 6.4.5. This model divides the Salado into two lithologic units: impure halite and Salado interbeds. The impure halite in this conceptual model is characterized entirely by its hydrological parameters as shown in Table 6-16. The interbeds are characterized by both hydrological parameters in Table 6-17 and fracture properties in Table 6-19. This latter information is needed since the model in Section 6.4.5.2 incorporates the possibility of interbed fracturing should pressures in the repository become high enough. The modeling assumptions surrounding the fracturing model are discussed in Appendix ***PA, Attachment*** MASS, Section MASS~~.~~-13.~~3.~~

2.1.3.5 The Rustler

The Rustler is the youngest evaporite-bearing formation in the Delaware Basin. It was originally named by Richardson in 1904 for outcrops in the Rustler Hills of Culberson County, Texas. Adams (1944, p. 1614) first used the names Culebra Member and Magenta Member to describe the two carbonates in the formation, indicating that Lang favored the names, although Lang did not use these names to subdivide the Rustler in his 1942 publication. Vine (1963, p. B1) extensively described the Rustler in Nash Draw and proposed the four formal names and one informal term that ~~are still~~ ***were*** used for the stratigraphic subdivisions of the Rustler. These are as follows (from the base): unnamed lower member, Culebra Dolomite Member, Tamarisk Member, Magenta Dolomite Member, and Forty-niner Member (~~Figure 2-9~~ ***Figure 2-14***). ~~Though it has been suggested by some investigators that the unnamed lower member might be named the Los Medaños Member, this nomenclature has not been formalized and is not adopted here.~~ ***Powers and Holt (1999) formalized the nomenclature for the lower Rustler, naming the Los Medaños Member for the exposures of the former "unnamed lower member" in the WIPP shafts and in boreholes in the vicinity of Los Medaños near the WIPP site. Four*** ~~Two~~ studies of the Rustler since Vine's 1963 work contribute important information about the stratigraphy, sedimentology, and regional relationships while examining more local details as well. Eager (1983) published a report on relationships of the Rustler observed in the southern Delaware Basin as part of sulfur exploration in the area. Holt and Powers (1988, Section 5.0), reproduced



~~Figure 2-9. Rustler Stratigraphy (From Appendix FAC, Figure 3.2)~~

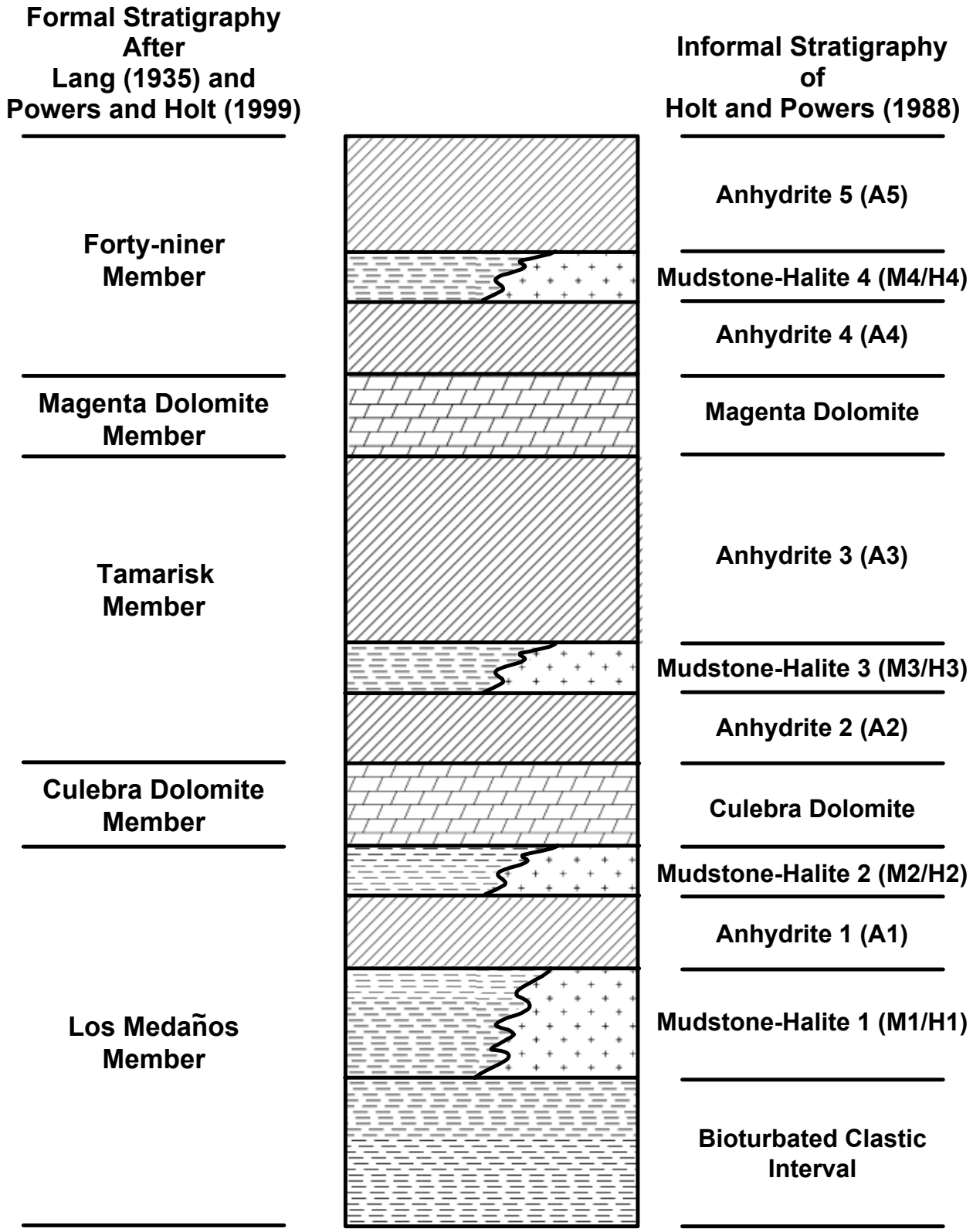


Figure 2-14. Rustler Stratigraphy

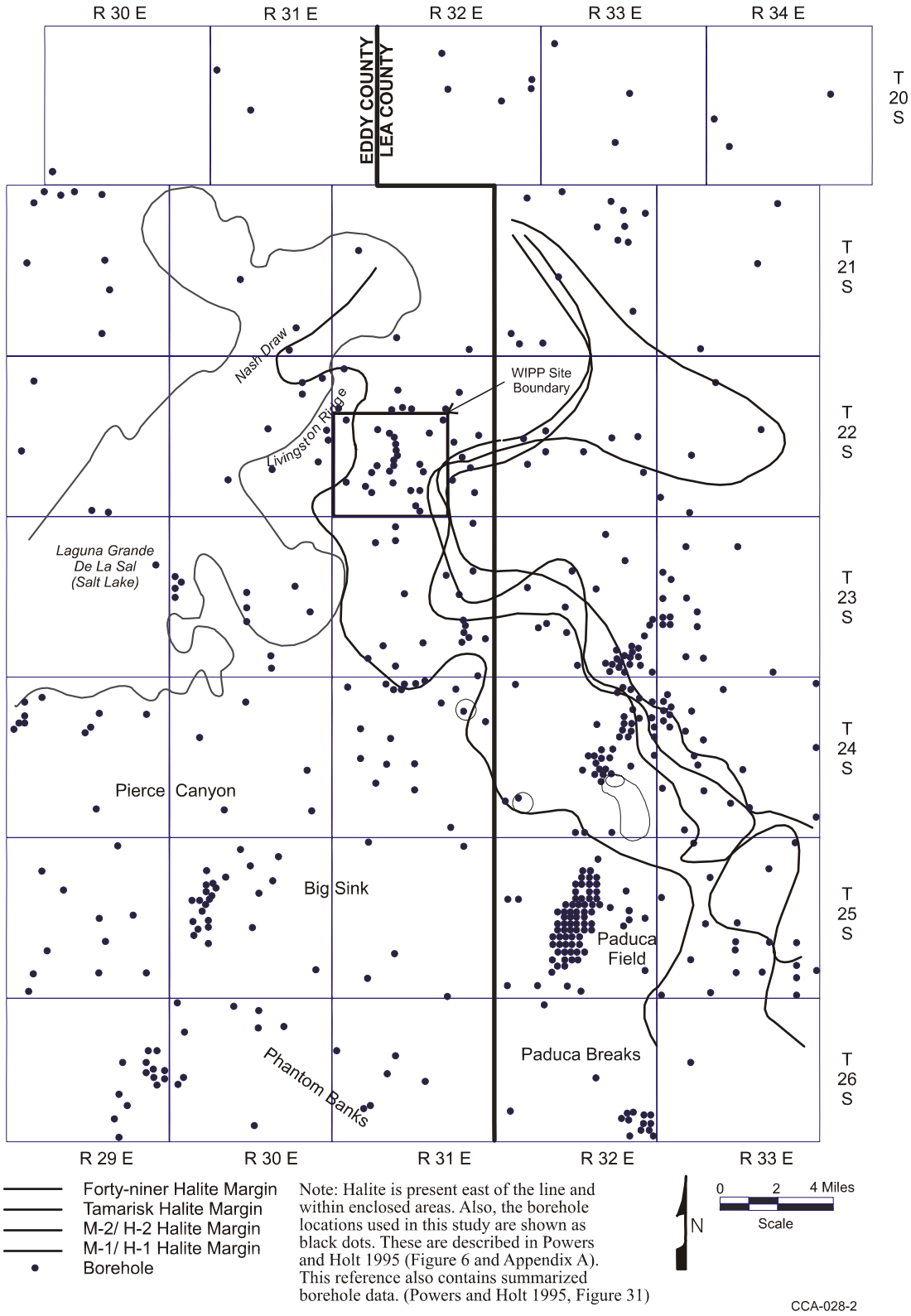
~~in this application~~ as ***CCA Appendix FAC, reported the details of sedimentologic and stratigraphic studies of WIPP shafts and cores as well as of geophysical logs from about 600 boreholes in southeastern New Mexico. Their work resulted in the more detailed subdivisions of the Rustler indicated in the right-hand column of Figure 2-14.***

The Rustler is regionally extensive; a similar unit in the Texas panhandle is also called the Rustler. Within the area around WIPP, evaporite units of the Rustler are interbedded with significant siliciclastic beds and the carbonates. Both the Magenta and the Culebra extend regionally beyond areas of direct interest to the WIPP. In the general area of the WIPP, both the Tamarisk and the Forty-***n***iner have similar lithologies: lower and upper sulfate beds and a middle unit that varies principally from mudstone to halite from west to east ~~(Figure 2-9)~~ ***(Figure 2-14)***. In a general sense, halite in the ~~unnamed lower member~~ ***Los Medaños*** broadly persists to the west of the WIPP site, and halite is found east of the center of the WIPP in the Tamarisk and the Forty-***n***iner ~~(Figure 2-10)~~ ***(Figure 2-15)*.**

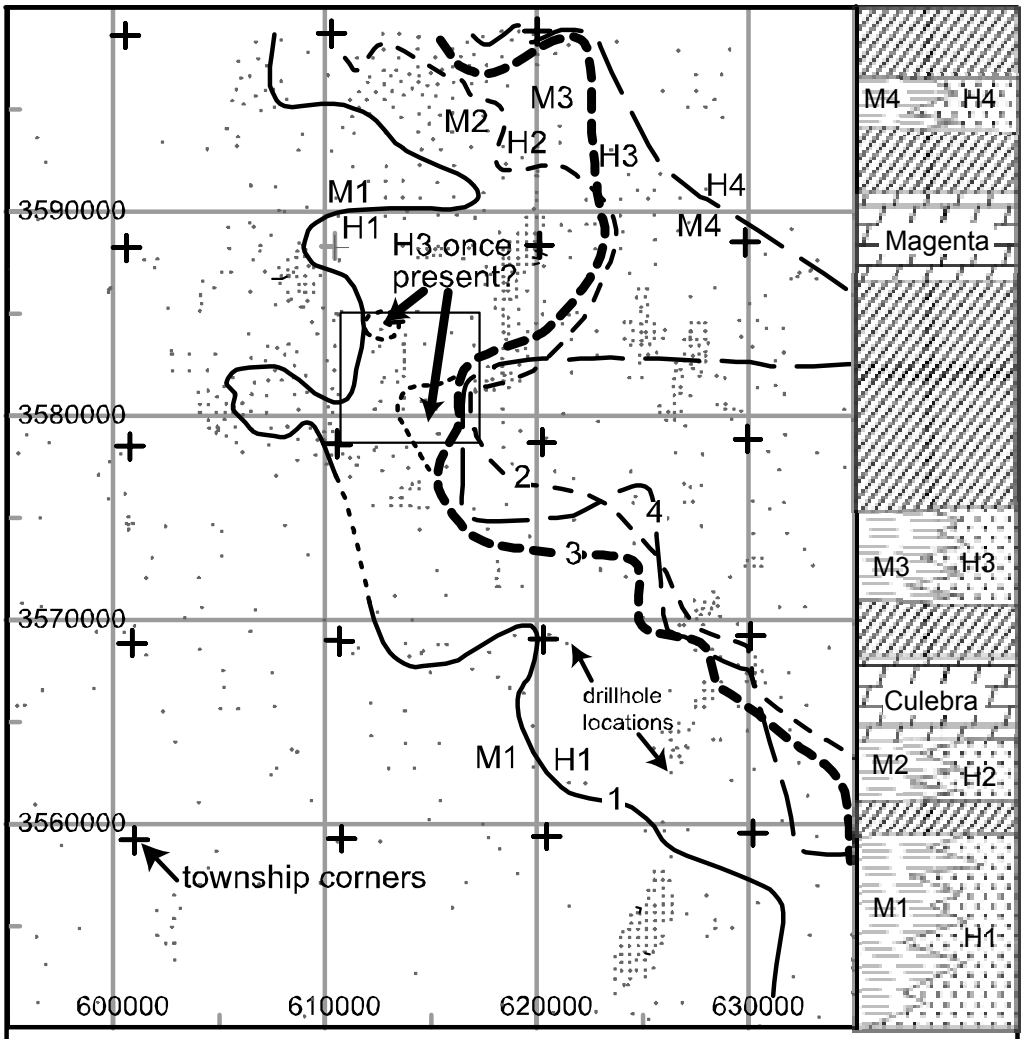
~~Two different explanations have been used to account for the halite distribution. An implicit assumption in many documents is that halite was originally deposited relatively uniformly in the noncarbonate members across southeastern New Mexico, including the WIPP site. The modern distribution resulted from dissolution of Rustler halite to the west of the site. As shown in Appendix FAC, sedimentary features and textures within WIPP shafts and cores led Holt and Powers to propose an alternative interpretation of depositional facies for the mudstone-halite units: halite was dissolved syndepositionally from mudflat facies, especially to the west, and was redeposited in a halite pan to the east.~~ ***Two different explanations have been proposed over the history of the project to account for the observed distribution of halite in the non-dolomite members of the Rustler. The earliest researchers (e.g., Bachman [1985] and Snyder [1985]) assumed that halite had originally been present in all the non-sulfate intervals of the Forty-niner, Tamarisk, and Los Medaños Members, and that its present-day absence reflected post-depositional dissolution.***

An alternative interpretation was presented by Holt and Powers (1988) following detailed mapping of the Rustler exposed in the WIPP ventilation (now waste) and exhaust shafts in 1984. Fossils, sedimentological features, and bedding relationships were identified in units that had previously been interpreted from boreholes as dissolution residues. Cores from existing boreholes, outcrops, geophysical logs, and petrographic data were also reexamined to establish facies variability across the area.

As a result of these studies, the Rustler was interpreted to have formed in variable depositional environments, including lagoon and saline playas, with two major episodes of marine flooding which produced the carbonate units. Sedimentary structures were interpreted to indicate synsedimentary dissolution of halite from halitic mudstones around a saline playa and fluvial transport of more distal clastic sediments. The halite in the Rustler, by this interpretation, has a present-day distribution similar to that at the time the unit was deposited. Some localized dissolution of halite may have occurred along the depositional margins, but not over large areas. Hence, the absence of halite in Rustler members at the WIPP site more generally reflects non-deposition than dissolution.



~~Figure 2-10. Halite Margins in the Rustler~~



Explanation

M#, H# indicate mudstone and halitic facies on each side of estimated halite margin (numbered line on map) for stratigraphic intervals as indicated in the column to the right (key on Figure 2-14).

UTM coordinates (m) for Zone 13 (NAD27) are provided for easting and northing.

Two zones within the WIPP site boundary ("H3 once present?") indicate where halite may have been present west of the current boundary of H3 (marked by ▬▬▬▬).

Figure 2-15. Halite Margins for the Rustler Formation Members

This hypothesis was tested and refined by subsequent investigations (e.g., Powers and Holt 1990, 1999, 2000; Holt and Powers 1990a) and is now considered the accepted explanation for the present-day distribution of halite in the Rustler. Powers and Holt (1999) thoroughly described the sedimentary structures and stratigraphy of the Los Medaños as part of the procedure for naming the unit. This shows the basis for interpreting the depositional history of the member and for rejecting significant post-burial dissolution of halite in that unit. Powers and Holt (2000) further describe the lateral facies relationships in other Rustler units, especially the Tamarisk, developed on sedimentologic grounds, and rejected the concept of broad, lateral dissolution of halite from the Rustler across the WIPP site area.

As discussed in Section 2.2.1.4, regional Culebra transmissivity shows about six orders of magnitude variation across the area around the site and about three orders of magnitude across the site itself. Although some investigators have called attention to the ~~correlation~~ ***broad relationship*** between the distribution of halite in the Rustler and variations in Culebra transmissivity and have attributed the variation to fracturing resulting from postdepositional dissolution of Rustler halite (see, for example, Snyder~~,~~ 1985, p. 10; and ***CCA*** Appendix DEF, Section DEF-3.2***),*** ~~,Holt and Powers' work~~ ***CCA*** Appendix FAC ***and Powers and Holt 1990, 1999, 2000***) largely rule out this explanation. Variations in transmissivity of the Culebra ~~(Beauheim and Holt 1990) have also been~~ were correlated qualitatively to the thickness of overburden above the Culebra (see discussion in Section 2.1.5.2), the amount of dissolution of the upper Salado, and the distribution of gypsum fillings in fractures in the Culebra ***(Beauheim and Holt 1990). Subsequently, Holt and Yarbrough (2002) and Powers et al. (2003) related the variation in Culebra transmissivity more quantitatively to overburden thickness and dissolution of upper Salado halite.*** The DOE believes that variations in Culebra transmissivity are primarily caused by the relative abundance of open fractures in the unit, which may be related to each of these factors. As discussed in Section 6.4.6.2 and Appendix ***PA, Attachment*** TFIELD, uncertainty in spatial variability in the transmissivity of the Culebra has been incorporated in the PA.

In the region around the WIPP, the Rustler reaches a maximum thickness of more than 152 m (500 ft) (Figure 2-~~11~~***16***), while it is about 91 to 107 m (300 to 350 ft) thick within most of the WIPP site. Much of the difference in Rustler thickness can be attributed to variations in the amount of halite contained in the formation. Variation in Tamarisk thickness accounts for a larger part of thickness changes than do variations in either the ~~unnamed lower member~~ ***Los Medaños*** or the Forty-***n***iner. Details of the Rustler thickness can be found in ***CCA*** Appendix GCR, 4-39 to 4-42 and Figure 4.3-8. See also ***CCA*** Appendix FAC.

Much project-specific information about the Rustler is contained in ***CCA*** Appendix FAC. The WIPP shafts were a crucial element in Holt and Powers' 1988 study, exposing features not previously reported. Cores were available from several WIPP boreholes, and their lithologies were matched to geophysical log signatures to extend the interpretation throughout a larger area in southeastern New Mexico. These data are included in ~~Appendix II to~~ ***CCA*** Appendix FAC, ***Appendix II***.

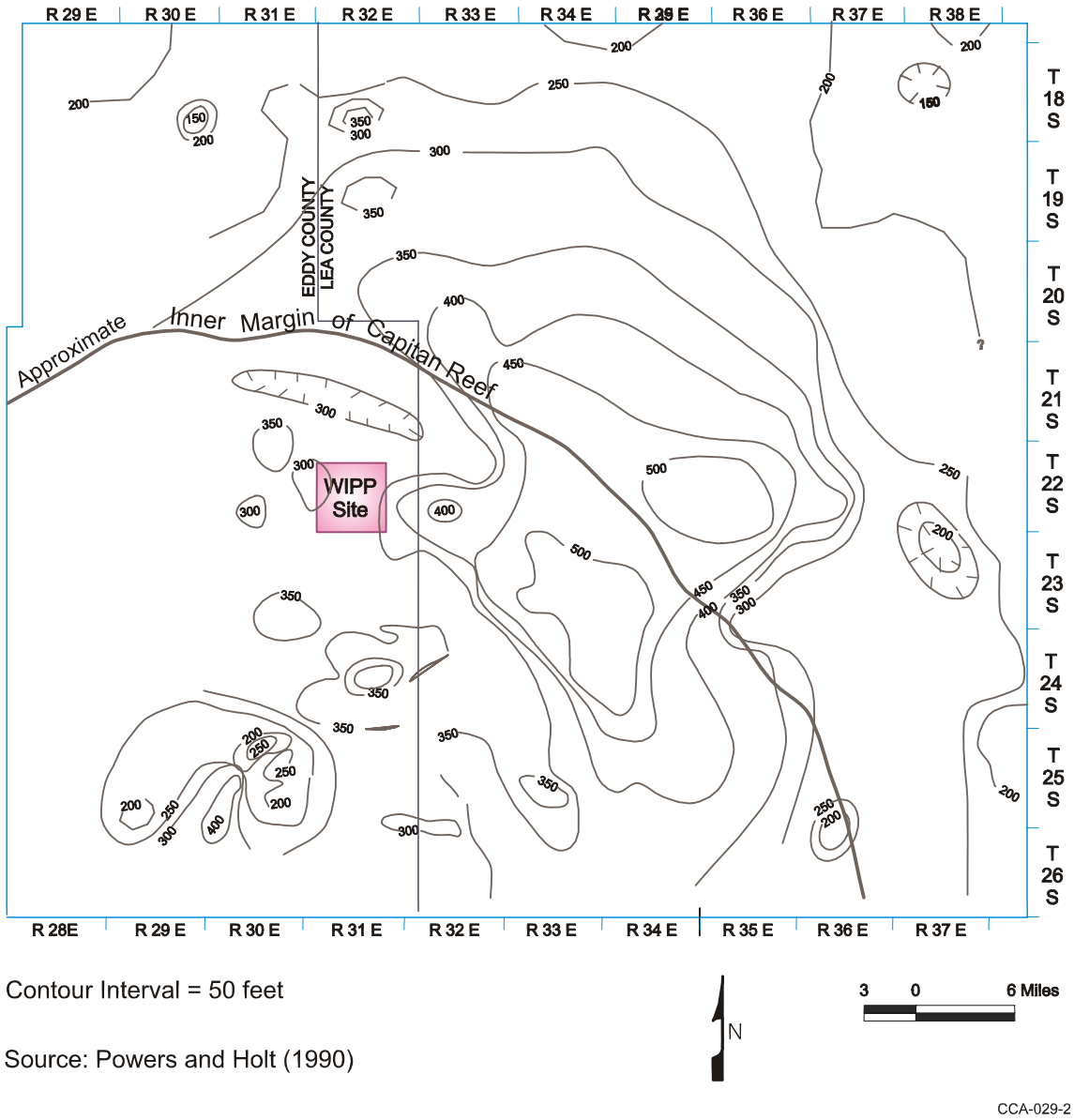


Figure 2-~~11~~*16*. Isopach Map of the Entire Rustler