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ADVANCES IN DEPOSITIONAL MODELS OF THE PERMIAN RUSTLER FORMATION, SOUTHEASTERN NEW MEXICO

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Abstract.—The Permian Rustler Formation in southeastern New Mexico was deposited in complex depositional environments that ranged from saline marine lagoon to salt pan-mudflats with subaerial exposure. Two significant transgressive freshening events deposited thin carbonate beds, each about 8 m thick. The Culebra Dolomite Member is the more permeable of the carbonate units. One of the geological factors influencing permeability is the presence or absence of halite cements in both fractures and other porosity. These cements underlie halite in the halite pan to mudflat deposits in a higher unit, and they confirm an earlier prediction that diagenetic halite would fill Culebra porosity near the depositional center. The Magenta Dolomite Member follows the basic Culebra pattern, with halite-filled porosity in a drillhole nearer the depositional center.

Cores recently obtained corroborate interpretations that mudstones in the Rustler were generally deposited without significant halite, or it was removed by syndepositional dissolution; they are not residues after later dissolution of halite. A laminar gray claystone underlying the Culebra is continuous across the study area, overlying mudflat as well as halite pan deposits. It indicates that the underlying mudstones are not dissolution residues. The uppermost mudstone-halite bed of the Rustler in a new drillhole shows a division between lower halite pan deposits and upper mudflat deposits that is also reflected in more distal mudflat deposits of the entire unit. These findings increase confidence that mudstones will yield additional information about the history of the mudflat to halite pan beds of the Rustler. One new core from the Tamarisk Member shows brecciation consistent with earlier predictions that halite has been dissolved in a limited area within this unit. The lower Rustler now reveals wider distribution of halite cements, which are not easily distinguished in available geophysical logs.

These data help refine ideas about the effects of halite cements and dissolution on porosity and on geochemistry of water or brine recovered from Rustler carbonates. Halite in these units also limits vertical Culebra recharge by limiting permeability, and its very presence indicates that little fresh water can be percolating into and through halitic beds.

OBJECTIVES

Drilling and coring for new monitor wells for the Waste Isolation Pilot Plant (WIPP) (Fig. 1) since 2003 provide new data on the current distribution of halite in the Permian Rustler Formation (Fig. 2) and the extent to which halite may have been dissolved from parts of the Rustler since it was deposited. These data are of significance because 1) halite in a unit affects hydraulic properties, 2) dissolution has been presumed to affect hydraulic properties of Rustler units, and 3) knowledge of the current distribution and history of halite distribution can be used to guide or bound some aspects of hydrologic modeling, including long-term infiltration where halite is present.

Our objectives in this article are limited, however. We will 1) describe some of the new data on halite occurrences and other selected sedimentologic features that bear on original halite distribution, 2) relate halite distribution to depositional facies models we previously described, and 3) evaluate recent concepts of limited halite dissolution based on data from these new drillholes. Finally, we will discuss briefly some of the significance of these findings to hydrogeology of Rustler units.

The Rustler and the Culebra Dolomite Member (Fig. 2) of the Rustler have been studied extensively in the northern Delaware Basin because the Culebra is important for assessing how well WIPP will isolate transuranic and mixed radioactive waste from U.S. defense programs. Hypothetical release scenarios that have some likelihood of occurring at WIPP involve drillholes that penetrate and connect the Culebra, radioactive waste enclosed by the Permian Salado Formation, and deeper pressurized brine in the Permian Castile Formation. If plugs in such a well fail after WIPP is closed, transport of waste through the Culebra to the regulatory boundary may occur. Quantitative models of this transport require knowledge of the spatial distribution of Culebra hydraulic properties, which are controlled by depositional and post-depositional processes that affect the Rustler and underlying Salado Formation (e.g., Holt et al., 2005; Powers et al., 2003). Halite cements that reduce permeability and porosity have been hypothesized to occur in the Culebra where halite overlies or bounds the unit (e.g., Holt, 1997). The occurrence of halite in Rustler units that overlie or bound Rustler water-bearing units is an important factor that must be evaluated (Holt et al., 2005), and we focus on halite and its distribution in this article.

INTRODUCTION TO THE RUSTLER FORMATION

Regional Setting and Stratigraphy

The Rustler Formation is the uppermost of three formations (Fig. 2) of late Permian, or possibly earliest Triassic, age in southeastern New Mexico and west Texas in which evaporite mineralogies are a significant component. The Rustler has been recognized historically as part of the Ochoan Series of Permian age (e.g., Lucas and Anderson, 1993). It seems likely that the Permo-Triassic boundary is in the lower Dewey Lake Formation based on regional relationships (Schiel, 1988, 1994; Powers and Holt, 1999, 2000), but no direct evidence of radiometric ages exist

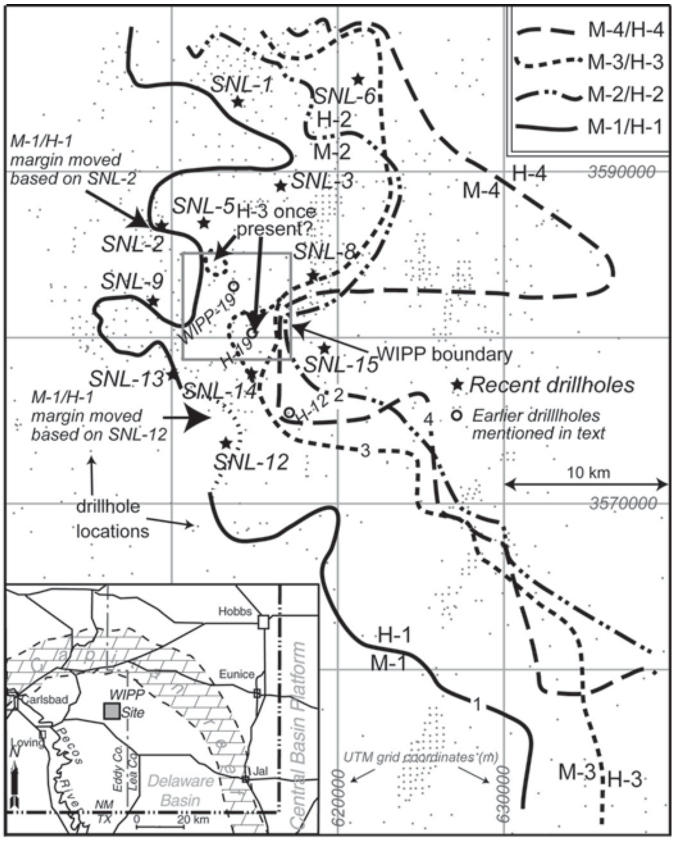

FIGURE 1. Location and area of interest. The halite margins for each of the informal mudstone-halite (M-#/H-#) units have been mapped on the basis of shafts, cores, and geophysical logs around the WIPP site area. See Figure 2 for stratigraphic information. Recent drillhole locations (star symbols) are shown relative to the margins, and earlier drillholes mentioned in the text are also shown here. A key to lines representing halite margins is shown in the upper right corner. Modified from Powers et al. (2003).

from the Dewey Lake in southeastern New Mexico. The fauna already described from the Rustler is limited (e.g., Donegan and DeFord, 1950; Croft, 1978).

The Rustler was deposited over a large area in west Texas and southeastern New Mexico. Prominent features in this area known to affect deposition of pre-Rustler formations were the Delaware Basin-Central Basin Platform-Midland Basin complex (Fig. 1). Rustler facies changes and increasing thickness southeast and east of WIPP are evidence that a subsiding depositional center still existed in the eastern Delaware Basin while some of the Rustler was deposited (Holt and Powers, 1988).

Within the study area in southeastern New Mexico, five distinct members of the Rustler have been named and described (Fig. 2) (Vine, 1963; Powers and Holt, 1999). Holt and Powers (1988) also found it useful to designate informal names for beds within formal members of the Rustler, and these are also used here (Fig. 2). The lowermost member, the Los Medaños, is dominated by siliciclastics, but it has significant portions of halite, halite-cemented siliciclastics, and sulfate. The Culebra Dolomite and Magenta Dolomite Members are mostly dolomite and dolomite-sulfate mixtures, respectively. The Tamarisk and Forty-niner have similar patterns of mudstone-halite facies sandwiched between sulfate beds. The five significant sulfate beds of the Rustler have been informally named A-1 through A-5, from lowest to highest (Fig.2). Four mudstone-halite intervals representing mudflat to halite pan environments are informally designated M-1/H-1 through M-4/H-4, from bottom to top.

Background Studies

Although general stratigraphic relationships and lithologies for the Rustler in this area have been established since Vine's work (1963), few sedimentologic details were described, even from cores, prior to mapping of the Rustler in three large-diameter (~ 6 m) shafts at the Waste Isolation Pilot Plant (WIPP) (Holt and Powers, 1984, 1986, 1990). The two main, but little known, earlier reports are the shaft descriptions by Gard (1968) for Project Gnome and the Rustler core descriptions from the southern Delaware Basin provided by Eager (1983). Rustler sedimentological features and facies relationships were recorded and interpreted in detail at WIPP shafts and from cores, and geophysical logs provided further evidence to evaluate the extent to which halite had been dissolved from Rustler units after deposition (e.g., Holt and Powers, 1988, 1990, 1993; Lowenstein, 1987; Powers and Holt, 1990, 1999, 2000). To avoid much repetition, we have reduced later text citations of this extensive background material.

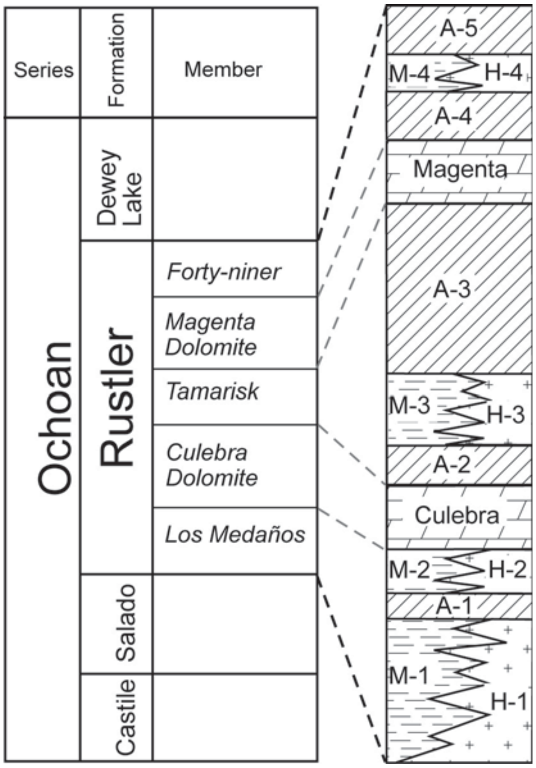

FIGURE 2. Stratigraphic relationships of Upper Permian formations, formal members of the Rustler Formation, and informal units (after Holt and Powers, 1988). The Los Medaños was described based on a type section in one of the WIPP shafts and named by Powers and Holt (1999). The chart is not scaled to unit thicknesses.

The Rustler represents a complex set of depositional environments (e.g., Holt, 1997; Holt and Powers, 1988, 1990, 1993; Lowenstein, 1987; Powers and Holt, 1990, 1999, 2000). For this article, one of the more relevant facies relationships is that developed from the halite pan to mudflat environments, as described in most detail for the Rustler by Holt and Powers (1988) and Powers and Holt (1990, 2000). Halite pan facies commonly display bedded halite with muddy interbeds, solution planes parallel to bedding, and corrosion surfaces on halite crystals due to temporary fresh water influx. Saline mudflat facies developed adjacent to the halite pan and contain sulfate nodules, some displacive and incorporative halite, and smeared intraclasts developed after syndepositional dissolution of halite from bedded halitic mudstone (Holt and Powers, 1988; Powers and Holt, 2000). Distal mudflat facies show evidence of subaerial exposure and subaqueous clastic deposition, including pedogenic cutans, bedding, cross-cutting bedding, and channels with intraclasts (Holt and Powers, 1988; Powers and Holt, 2000). Most of the halite in the Rustler was deposited directly in the halite pan, or it precipitated from groundwater as phreatic zone cements in sediments underlying the halite pan and adjacent saline mudflat. We use these facies relationships as context for describing and interpreting lateral and vertical relationships of halite that are important for understanding the hydrology of the Rustler and Culebra Dolomite.

Rustler Hydrogeology Studies

Holt et al. (2005) established the basic relationship between Culebra hydraulic properties and three geological factors affecting the Culebra. Two geological factors (Culebra overburden thickness and whether upper Salado halite has been dissolved) account for most of the variation in Culebra transmissivity. We do not address these factors further in this article.

Holt et al. (2005) examined a third factor, of lesser impact on the variation of Culebra transmissivity, that relates to the presence of halite cements in the Culebra along the depositional margin of halite (H-3) in the Tamarisk (Figs. 1, 2). Although the margin of H-3 has been mapped with reasonable consistency, Holt and Powers (1988) also concluded there may have been outliers that were dissolved. Beauheim and Holt (1990) outlined tracts where H-3 may have been dissolved. Powers et al. (2003) described the basic distribution of halite in Rustler members in terms of approximate margins or lateral limits of halite in each of the four mudstone-halite (M-#/H-#) units (Figs. 1, 2). Halite/mudstone facies tracts of the Rustler are principally controlled by depositional processes, with limited post-depositional dissolution of these halites.

There is considerable history of relating the hydraulic properties of the Rustler to dissolution of halite from the upper Salado as well as from the Rustler. Mercer (1983, figure 13), for example, showed the extent of halite in each Rustler member. The prevailing notion at the time was that, beyond the margin of halite, the halite had been dissolved from the unit, leaving a "dissolution residue" of mudstone. In some reports, summaries of these beds simply reported "dissolution residue" (e.g., Sandia National Laboratories and U.S. Geological Survey, 1978). Details of the maps of the extent of halite, shown as halite margins, continue to be revised with additional data (Powers et al., 2003; see DISCUSSION); the bigger difference is the interpretation of halite distribution as dominated by deposition and syndepositional processes.

SOME NEW RUSTLER HALITE FACIES DETAILS

Halitic Rustler units have been described previously and assigned to facies tracts that were deposited in salt pan to saline mudflat environments with laterally equivalent mudflat environments without halite. The margin of halite for each of the mudstone-halite units in the Rustler has previously been mapped and recent drillhole locations are displayed with respect to the margins (Fig. 1).

Halite Distribution of the Lower and Middle Los Medaños Member

The lower and middle Los Medaños Member of the Rustler is the most difficult unit in which to determine a halite margin. Halite was deposited in a mudstone-halite unit (M-1/H-1) as a lenticular body with the thicker areas east and southeast of the WIPP site area. Within the areas more recently cored, M-1/H-1 ranges from halite with some mudstone interbeds (Fig. 3A) to bedded to conglomeratic siltstones and sandy siltstone (Fig. 3B). Some cores show smeared intraclast textures interpreted as evidence of syndepositional dissolution of halite from bedded halitic mudstones deposited around the margins of the salt pan (Powers and Holt, 2000). The margin of halite formed from these environments is complicated by syndepositional dissolution of halite.

Halite in the lower to middle Los Medaños is not restricted to the M-1/H-1 unit. WIPP shafts and earlier cores displayed halite cements, halite fracture fillings, and even halite pseudomorphs of fossil fragments. These diagenetic forms of halite generally correspond areally to the distribution of halite in the overlying H-1 salt pan, reflecting brine infiltration. At SNL-2 (Fig. 2), however, siltstones and sandstones below the M-1/H-1 stratigraphic position are well cemented by halite, and this appears to be beyond the limits of the halite pan. The halite pan deposits may have been reduced in area by syndepositional dissolution without affecting the lower cements. Another alternative is that dense phreatic brine aquifers within the depositional environment extended beyond the salt pan margins displacing fresher water from the mudflat environment. A third, unlikely alternative is that cementation occurred much later due to diffusive or advective transport of halite from the Salado. We are unable to test these alternatives at this time.

Mudstone-Halite 2 (M-2/H-2) of the Upper Los Medaños Member

Understanding the uppermost Los Medaños is critical for understanding the deposition of the Culebra and development of its hydraulic properties.

The mudstone-halite (M-2/H-2) unit that underlies the Culebra has been described previously from cores, shafts, and geophysi-

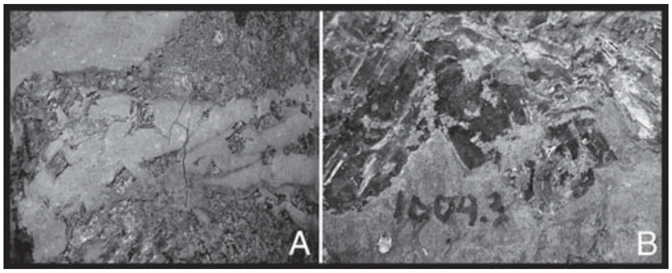

FIGURE 3. A. Halite with mudstone interbeds within M-1/H-1 from drillhole SNL-8 at a depth of 1012.7 ft (308.7 m) below ground level. The core width in the photo is 10 cm. B. Upward view of displacive halite in clastic beds from the M-1 portion of the unit from drillhole SNL-8 at a depth of 1004.2 ft (306.1 m). The width of photographed core in B is 4.3 cm.

cal logs from drillholes at and around WIPP. Until recently, no cores included halite (H-2), but cuttings and geophysical logs clearly show that halite is present east of WIPP.

As exposed in the type section of the Los Medaños at the WIPP site (Powers and Holt, 1999), M-2 is commonly about 3 m thick and displays two basic stratigraphic units: a lower reddish-brown mudstone or claystone unit about 2 m thick and an upper dark gray silty claystone commonly a little less than 1 m thick.

The reddish-brown mudstone has crude bedding and includes smeared intraclast textures, pedogenic cutans, and some conglomeratic zones. Fractures are often filled with fibrous gypsum. Thicker reddish-brown muddy halite and halitic mudstones (H-2) to the east are laterally equivalent to this lower reddish-brown mudstone at WIPP. Cores from two wells (SNL-15 and SNL-6) drilled in 2005 preserved bedded halite and muddy halite with thin mudstone interbeds through this interval (Figs. 1, 2). Some of these thin interbeds truncate the pre-existing thin halite beds and record fluctuating water levels in the halite pan, including periods during which the salt pan was likely subaerially exposed (Fig. 4). Pedogenic cutans and smeared intraclasts indicate subaerial exposure, soil-forming processes, and syndepositional dissolution of halite from mudstones in the areas of the mudflat along the margin of the halite pan and further upland. This reddish-brown unit represents a salt pan to mudflat facies tract with its own complicated record of brine level fluctuations.

The upper gray claystone differs significantly from the lower mudstone unit. Cores of the gray claystone reveal more fine bedding (mm to cm scale laminae), and a sharp transition (generally <2 cm) to the dolomite of the overlying Culebra (Fig. 5). The gray claystone is continuous throughout the area. Recent cores of this transition show that the gray claystone continues laterally and overlies halitic mudstone and muddy halite of the reddish-brown lower bed at drillholes SNL-15 and SNL-6.

The upper gray claystone below the Culebra was deposited across the basin as water level rose, ending the halite pan environment. The gray color and fine laminae suggest that the basin water was temporarily poorly mixed. Continuity and similarity across differing facies of the underlying unit, as corroborated by the new core data, indicate that the transgression was rapid and widespread.

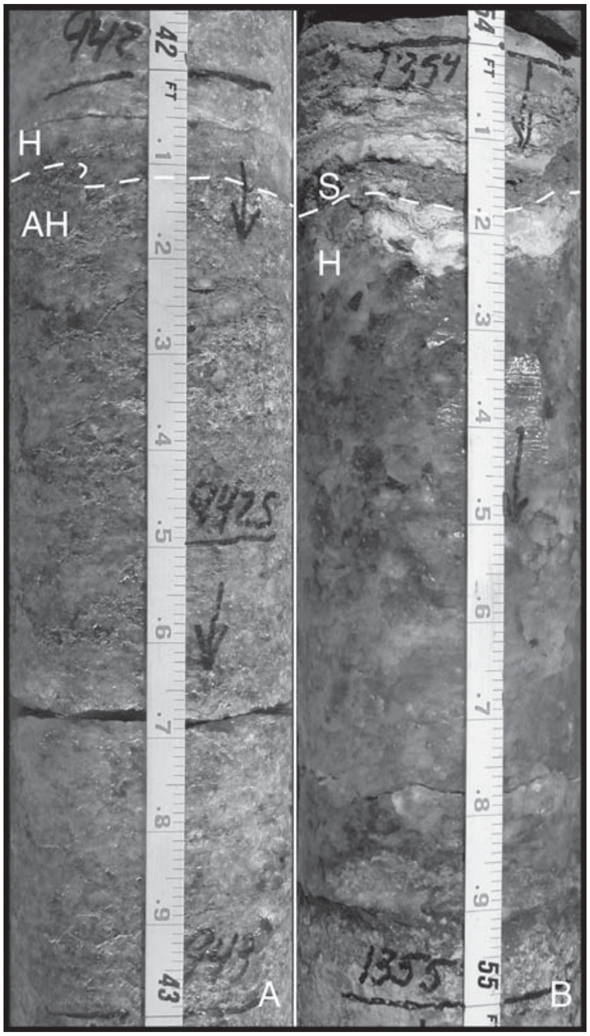

FIGURE 4. Bedded halite and thin mudstone interbeds from informal unit M-2/H-2 at SNL-15 (A) and SNL-6 (B). Depths are in feet below ground level. The core widths are 10 cm. In A, disseminated clay between coarse halite crystals (AH) increases upward to a surface at 942.1 ft (white dashed line) and is overlain by coarse, purer halite (H). In B, coarse, pure halite overlies a surface just above 1355. Near the top of this core interval, siltstone (S) overlies a corroded surface (dashed line) on the coarse halite (H).

Some halite from the reddish-brown halite pan and saline mudflats may have dissolved as this much fresher marine water invaded the northern basin. The basal Culebra is locally disturbed in some cores and WIPP shafts, showing soft sediment deformation and possible responses to modest halite solution from the underlying layer. Before detailed studies of cores and shafts (e.g., Holt and Powers, 1984; 1986; 1988), this mudstone/claystone unit was commonly considered to be part of the residue from dissolution of halite long after deposition of the overlying units. The bedding and continuity of the dark gray claystone underlying the Culebra, however, are clear indicators that it is not such a residue. The relationships also are consistent with mainly syndepositional development of textures and features in the underlying reddish-brown mudstone to muddy halite.

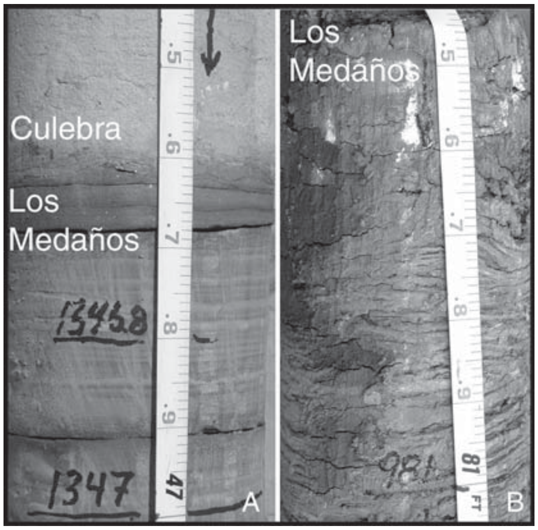

FIGURE 5. Laminar gray claystone at the contact between the Los Medaños and Culebra Dolomite Members at SNL-6 (A) and SNL-8 (B). Core widths are 10 cm. The Culebra immediately overlies the laminae and thin beds of the core of Los Medaños in photo B. Depths are in feet below the ground surface. The gray claystone extends laterally over portions of the lower M-2/H-2 with halite, showing the development as a depositional unit associated with the freshening event that led to Culebra deposition.

Halite in the Culebra Dolomite Member

The basic model for the Culebra across the northern Delaware Basin is deposition in a low-energy carbonate lagoon that established a generally stable substrate where organisms burrowed (e.g., Holt, 1997). Thin algal mats developed at times, and they were prominent at the transition to the overlying sulfate (A-2). Pores and vugs developed along bedding, and early diagenetic sulfate grew as nodules and filled much of the porosity. Anhydrite pore fillings are more abundant eastward toward the depositional center where salinity of subsequent environments was high. Holt (1997) refined this model, defining hydrogeological units and inferring that some porosity in the Culebra east of the WIPP site could be filled with halite. Two wells cored in 2005 provide the first direct evidence of such halite.

Macroscopic halite in the Culebra from SNL-15 (Fig. 6) fills fractures, occupies some irregular vuggy porosity, and cements zones of silty dolomite. At SNL-6, halite fills fine fractures. Halite and carbonate are not compatible primary deposits, and the fracture filling is clear evidence of post-depositional precipitation of the halite. The irregular pores filled by halite are similar to some sulfate nodules that are anhydrite, and the nodular sulfate within the Culebra at SNL-15 is dominated by anhydrite.

Holt (1997) suggested that halite cements and halite replacement of gypsum may have formed in Culebra sediments during the accumulation of halite in the M3/H-3 interval. Preliminary evidence suggests that this may be the case. At SNL-15, halite is found cementing irregular zones of silty dolomite. Similar zones west of the M-3/H-3 margin contain no cements and appear to be uncemented dolomite mud. Halite occupying vuggy porosity may be early diagenetic replacements of displacive gypsum nodules. Microscopic information is required, and will be developed, to test these hypotheses and illuminate the timing of this diagenetic activity in the Culebra.

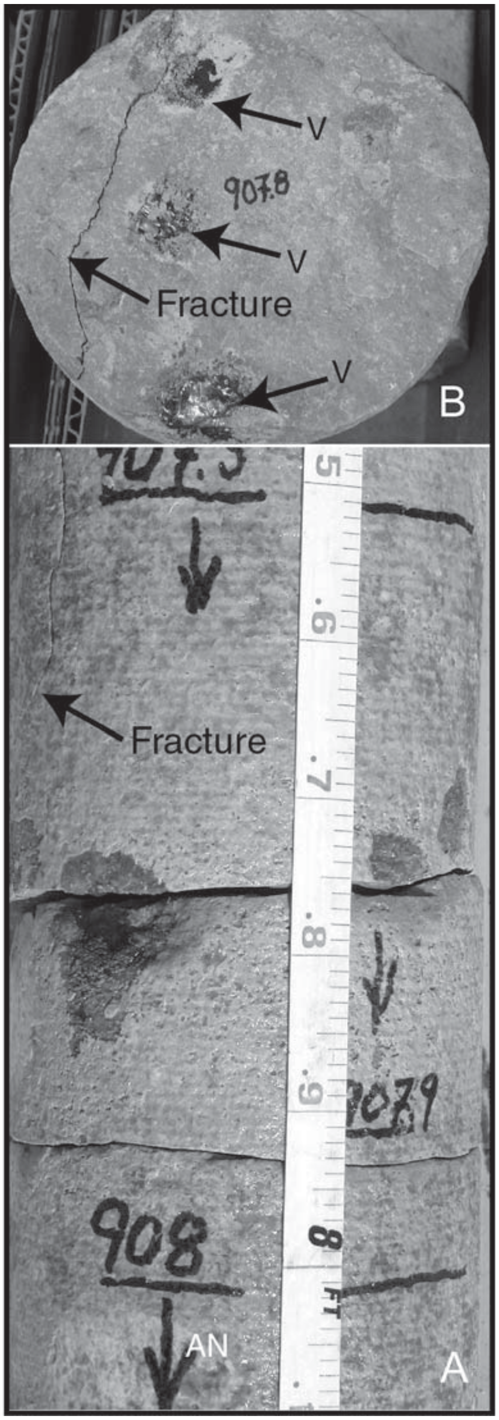

FIGURE 6. A. Core surface at 907.8 ft (276.7 m) from SNL-15 showing anhydrite vug filling (below AN) at base and narrow vertical fractures with halite. B. Halite in fractures and as silty dolomite cements and vug fillings (V) on a core cross-section from the Culebra Dolomite at a depth of 907.8 ft (276.7 m) in SNL-15. Core width is 10 cm in each photo.

Halite in the Tamarisk Member

The Tamarisk mudstone-halite (M-3/H-3) is the thickest, most diverse salt pan to mudflat facies tract represented within the Rustler. Geophysical logs from drillholes east of WIPP exhibit low natural gamma and low density or acoustic velocities characteristic of halite over an interval about 60 m thick. Some thin anhydrites and a polyhalite are distinguishable; the polyhalite was used to separate a lower (H-3a) from an upper (H-3b) subunit. Very low natural gamma indicates that H-3b is very pure halite, except for the thin anhydrites. The lower part of H-3a is also very pure halite. Upper H-3a is a persistent zone of somewhat higher natural gamma indicating a slightly argillaceous zone. The natural gamma logs indicate that H-3 has very limited insoluble content, and it is impractical to consider M-3 as the residue after dissolution of halite from H-3.

The mudstone (M-3) equivalent to H-3 is generally about 4–6 m thick in cores and shafts. Most of M-3 is reddish-brown or reddish-gray, but the uppermost part is dark gray and locally includes pyrite. The basal contact of M-3 with A-2 is locally erosional. This channeling is apparent in some shafts, and A-2 was completely eroded and replaced with conglomerate in drillhole WIPP-19 (Fig. 2). A channel near the base of M-3 in the WIPP air intake shaft was also filled with clasts. Bedding is weakly developed in M-3, and there are smeared intraclasts in some intervals.

Clasts (both of sulfates and clastics) are a significant feature of M-3. In some instances, they are rounded, graded, and deposited in channels. These are clearly erosional and depositional, and the examples in the lower part of M-3 were responses to changes in the base level of the salt pan. The channeling may be time equivalent to the argillaceous halite in upper H-3a. Base level in the halite pan likely was lowered (whether by evaporation or subsidence), increasing the gradient upland and bringing some clastics into the center of the halite pan. The higher clastic content in upper H-3a most likely signifies such a change; the time equivalence to the channeling is conjecture at this time.

Holt (in Mercer et al., 1998) described angular clasts of sulfate in the upper part of M-3 at drillhole H-19 (Fig. 2) accompanied by brecciation of the overlying sulfate (A-3) and clast rotation. These features show significant post-depositional disruption, and the interpreted cause of the fracturing of A-3 is post-depositional dissolution of halite from the Tamarisk. Recent core from M-3 in drillhole SNL-8 exhibits features (Fig. 7) similar to those found at H-19, and the tentative interpretation is that this area along the margin of H-3 also has undergone some post-depositional dissolution of halite (H-3). At drillhole SNL-14, however, the lower part of A-3 does not appear to be extensively brecciated. The bedding and character of M-3 at SNL-14, including sulfate clasts in the lower part of M-3, are similar to other areas where little, if any, post-depositional dissolution of halite and collapse have occurred.

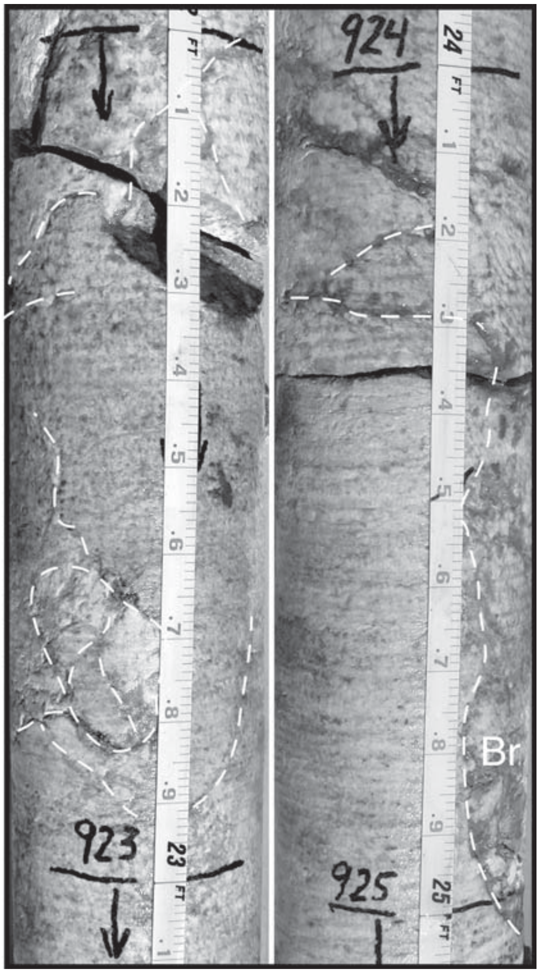

FIGURE 7. Core photographs from the lower part of A-3 in drillhole SNL-8 showing some brecciation that is likely associated with some post-depositional dissolution of halite along the original depositional margin of halite. Dashed white lines outline other less visible fracturing. Br marks a more intense zone of brecciation. Each core is 10 cm wide. Depths and scale are in feet.

The current margin of H-3 has been suggested (Holt and Powers, 1988; Beauheim and Holt, 1990) as a location where significant post-depositional halite dissolution and collapse would be found. Evidence from drillhole H-19b1 is consistent with post-depositional dissolution of halite along the H-3 margin. Preliminary evidence suggests that post-depositional dissolution of H-3 halite was more significant at SNL-8 than at SNL-14. Although these cores will be studied in more detail, it is also not clear that the features found in M-3 alone will clearly indicate the thickness of halite removed at a particular location. Holt and Powers (1988) proposed that the vertical extent of brecciation of the lower Rustler is an indicator of the thickness of halite dissolved from the upper Salado. A similar relationship might be developed for A-3.

Halite in the Magenta Dolomite Member

The Magenta is a regionally persistent unit, about 7–8 m thick, with consistent vertical features. The dominant sedimentological features of the Magenta in the northern Delaware Basin include 1) an algal-dominated section (Fig. 8A), at and above the basal transition from the underlying sulfate, 2) strongly expressed small cross-laminated bedforms (Fig. 8B), and 3) a thin nodular gypsum bed near the top of the Magenta (Fig. 8C). There is

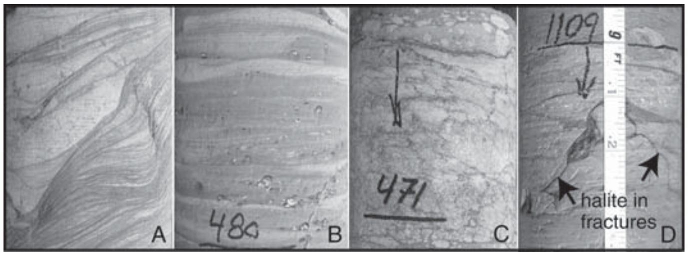

FIGURE 8. A. Algal laminae from the lower Magenta in drillhole SNL-1 at 490 ft (149.4 m). B. Cross-laminated dolomite and gypsum from the Magenta in drillhole SNL-1 at 480 ft (146.3 m). The large grains are gypsum clasts. C. Nodular gypsum near the top of the Magenta at 471 ft (143.6 m) in SNL-1. D. Halite in fractures near the top of the Magenta at 1109 ft (338 m) in SNL-6. All core widths are 10 cm.

some increase upward through the Magenta of grain size, amount of cross-laminae and ripple forms, and set size. Grains in these clastic units are about equal parts dolomite and gypsum. The Magenta formed in a relatively high energy, shallow tidal shelf to lagoon environment that did not become desiccated. The mineral assemblage and algal forms indicate a significant freshening that provided a carbonate environment for a period of time, followed by another salinity increase across the area that resulted in the formation of nodular sulfate near the top of the Magenta and the basal sulfate (A-4) in the overlying Forty-niner.

Geophysical logs and cores from recent drillholes for WIPP commonly show that there is some porosity increase across a zone up to 3 m thick that is below the upper nodular bed (e.g., Powers and Richardson, 2003, 2004). This zone is likely to be modestly fractured, but there is also some intergranular porosity evident from macroscopic examination.

Cores from drillhole SNL-6 showed that halite has filled some of the limited fracture porosity in the Magenta (Fig. 8D). The overlying Forty-niner Member (see next section) basal anhydrite (A-4) showed halite pseudomorphs after vertical gypsum crystals, as well as bedded halite in H-4, and diagenetic fluids associated with H-4 are the likely sources of the halite that fills fractures in the Magenta at SNL-6. Halite cements are likely present in interparticle porosity at SNL-6, but this remains to be confirmed by microscopic analysis.

Halite in the Forty-niner Member

The Forty-niner Member is a regionally persistent unit generally similar to the Tamarisk: a mudstone-halite (M-4/H-4) unit is sandwiched between sulfate beds. Geophysical logs show that halite (H-4) is present to the east and southeast of WIPP. Only two cores available earlier showed evidence of halite in the Forty-niner. Near the center of WIPP, thin sections of M-4 from drillhole WIPP-19 revealed halite cement and some displacive halite (Holt and Powers, 1988) not reported in the original basic data report (Sandia National Laboratories and U.S. Geological Survey, 1978). Drillhole H-12 (Fig. 2) encountered argillaceous halite in addition to the sequence of mudstone units (Mercer and Snyder, 1990) that are exposed clearly in WIPP shafts. On the basis of geophysical logs, Holt and Powers (1988) also interpreted a thin halite bed within the upper anhydrite (A-5) in a few drillholes southeast of WIPP.

From WIPP shafts, M-4 was subdivided into three main mapping units. The basal siltstone is bluish-gray to greenish-gray, laminar, wavy to contorted, and includes siltstone clasts. It overlies the sulfate with a sharp contact. Most of M-4 consists of reddish-brown siltstone and mudstone that variably includes laminar bedding, low-angle cross-bedding, some ripples, intraclasts, and smeared intraclasts. Channeling truncates thin bar deposits in one shaft, and some beds fine upward. Bedding can be wavy or contorted. The reddish-brown interval is generally divided about midpoint because of color and texture changes. The uppermost mudstone in M-4 is thin, bluish-gray to yellowish-gray, laminar, slightly rippled, gypsiferous, and includes flaser-like siltstone and very fine grained sandstone. The contact with the overlying sulfate bed is sharp.

The basal bluish-gray to gray siltstone with laminar bedding and slight crosscutting relationships is well preserved in SNL-6 core. Halite recovered above this basal unit at SNL-6 is about 3 m thick. The lower half is generally clear, medium to coarse halite with small amounts of reddish-brown or gray intercrystalline mudstone or claystone. The upper half is finer, more reddish-brown and argillaceous, and it displays some displacive halite and corroded crystal margins. The uppermost recovered core from this interval is mainly reddish-brown siltstone with some halite. There is a gap in the core of nearly 2 meters thickness corresponding to the upper part of the M-4/H-4 unit. Geophysical logs from a nearby oil well are consistent with the interpretation that halite dominates the lower portion of the unit. Argillaceous siltstone was recovered immediately below A-5.

At both SNL-6 and H-12, H-4 is in a stratigraphic position similar to the lower half of the reddish-brown siltstones mapped in the shafts. We suggest that the lower part of the reddish-brown mudstone in M-4 is the mudflat environment that correlates with a distinct halite pan represented by H-4 in these cores. The upper half of the reddish-brown mudstones in M-4 includes greater detail of bedding, cross-cutting, and erosion. We suggest that this represents a more energetic and distal environment to a salt pan not yet encountered in cores.

Cores of both A-4 and A-5 from SNL-6 also displayed halite pseudomorphs after gypsum. Pseudomorphs in A-4 indicate infiltration of brine from the salt pan environment of H-4, and they most likely formed at the same time and from the same brine responsible for halite infill of Magenta fractures. Pseudomorphs in A-5 are more likely to have been formed by infiltrating brines associated with the thin halite found to the southeast of SNL-6 in A-5 (Holt and Powers, 1988). These pseudomorphs, along with halite in the lower part of M-4/H-4 at this location, also testify to a lack of fresh water infiltration at this location, and they complicate any process proposed to dissolve halite from M-4 at a later time.

DISCUSSION

Rustler units with halite are now much better sampled in cores, complementing extensive and detailed descriptions from these same units in WIPP shafts. Halite formed in two ways: 1) as primary deposits in salt pan to saline mudflat environments and 2) as cements and pore or fracture fillings from brine infiltrating underlying beds, as illustrated by halite cements, fracture fillings, and mineral and fossil replacements.

Macroscopic and microscopic textural relationships suggest that gypsum and anhydrite nodules developed early in the diagenetic history of the Culebra (Holt, 1997), most likely associated with the incursion of sulfate-rich water that led to the formation of the overlying sulfate bed (A-2). Halite fills fractures and the centers of some irregular pores in the Culebra in SNL-15, indicating a later origin that we associate with salt pan deposits (H-3) that succeeded A-2. Halite pseudomorphs after gypsum in A-2 are likely to have formed at virtually the same time and the brine is likely from the same source – the H-3 salt pan. Both Culebra and A-2 continue through the depositional center to the east. There is no logical source for the brines before this halite pan was established.

The Magenta shows no macroscopic evidence of diagenesis related to the overlying sulfate (A-4), but the halite fracture fillings of Magenta at SNL-6 are likely to have crystallized from infiltrating brines associated with the halite pan (H-4). As discussed for the Culebra, halite pseudomorphs of gypsum in the sulfate bed (A-4) overlying the Magenta are interpreted as having formed at approximately the same time by brines from the same overlying halite pan (H-4). We note the halite pseudomorphs near the base of A-5 at SNL-6 are more likely related to the subsequent halite found in A-5 to the southeast of SNL-6.

If these halite fracture fillings are coeval with the accumulation of halite above the units, the fractures indicate that both carbonates were lithified significantly to fracture early in their history. These units are also fractured where halite is dissolved from the underlying Salado or from Rustler units (e.g., Holt et al., 2005), but it is now clear that some fracturing predates later halite dissolution. We do not know at this time how to differentiate these fracturing episodes once halite is dissolved from the dolomites.

Good examples of the claystone in M-2/H-2 under the Culebra from these cores are important because they confirm the interpretations already made (e.g., Holt and Powers, 1988; Powers and Holt, 1999) that the claystone is a depositional unit rather than a dissolution residue. The claystone is continuous and displays similar sedimentological features from these areas where halite (H-2) is present to areas where there is no halite, only mudstone (M-2). There is local soft-sediment deformation in this claystone (e.g., Holt and Powers, 1988). The gray claystone continuity also provides confirming evidence of the facies relationships of the halite pan to mudflat deposits that underlie the gray clay. Significant dissolution of an underlying halite after deposition of the claystone would have disrupted the claystone.

Stratigraphic and sedimentologic details of M-3/H-3 and M-4/H-4 in these wells also provide confirming evidence of the facies relationships in contrast to a notion of extensive dissolution of halite. Details of stratigraphic relationships in the mudstones, such as the break in the middle of the reddish-brown portion of M-4, are expressed in wells such as SNL-6, where a lower halite is overlain by an upper mudstone. The salt pan to mudflat environments were significantly altered at that time, probably by a significant reduction in the halite pan brine body by evaporation or subsidence; the more distal parts of the mudflats reflect the change as well. The mudflat deposits will continue to yield more insights as confidence grows that subtle changes in their stratigraphy, sedimentologic features, and even color are significant.

The halite facies tract (H-3) in the Tamarisk has undergone some post-depositional dissolution, with the current halite margin (Fig. 2) farther east than when deposition ended (Beauheim and Holt, 1990, figure 24; Powers, 2003). Mercer et al. (1998) described evidence of brecciation of the overlying A-3 from drillhole H-19b1 within this general area. Macroscopic evidence from wells SNL-14 and SNL-8, drilled west of the margin of H-3, vary. SNL-8 seems to indicate some post-depositional dissolution of H-3 in the form of brecciation of A-3, while A-3 is little disturbed in SNL-14. At this time, we infer that SNL-8 is in an area with some dissolution (Fig. 9) and SNL-14 is not. More detailed investigations will be undertaken to verify these results.

Finding halite in the mudstone-halite units of the Rustler in some wells requires adjusting the halite margins (Fig. 9). Powers et al. (2003) had previously adjusted the margin of H-1 around SNL-12 after the cores failed to reveal halite. The largest difference is in the northeastern map area (Fig. 9), where halite encountered in SNL-6 push the margins of H-3 and H-4 farther west. The line is not exact; geophysical logs from oil and gas wells will be examined, but some areas are not heavily drilled.

It is not appropriate to construct lines marking the limits of halite in the Magenta and Culebra based on only one and two occurrences, respectively. Brine infiltration might extend halite

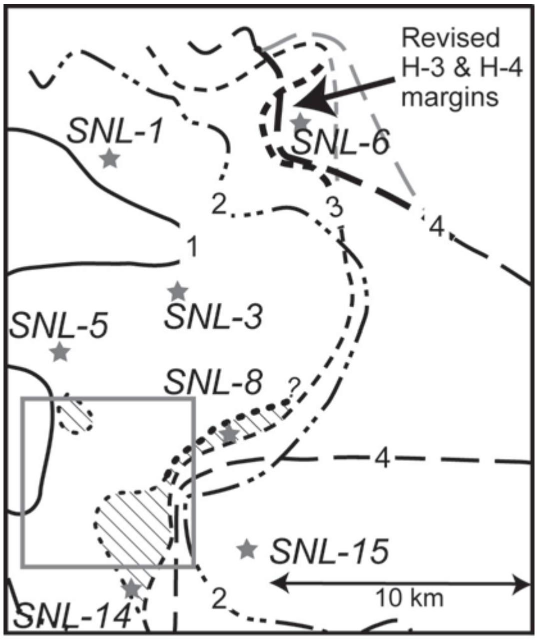

Figure 9. A simplified version of Figure 2 shows revisions to the area of likely halite dissolution from H-3 (area with diagonal lines) and to the H-3 and H-4 margins in the vicinity of SNL-6. See Figure 1 for a key to lines and margins. Line weights have been reduced in areas where they have not been modified. Gray lines show original positions for modified segments.

beyond the margin of halite in the overlying halitic beds. On the other hand, synsedimentary dissolution that removes halite from the saline mudflat to halite pan edges may also remove earlier halite from the underlying beds.

Earlier testing showed that Culebra transmissivity varies over several orders of magnitude, decreasing to the east (Beauheim and Ruskauff, 1998). SNL-15 was drilled and completed in an area east of WIPP expected to have very low transmissivity based on earlier testing. SNL-15 will be tested to determine hydraulic properties, with the tests expected to validate very low values. SNL-6 yields very little water, and the well is expected to behave like SNL-15. The porosity of the Culebra at these locations appears to be very limited; it is now clear that halite-filled fractures are a factor in the low transmissivity. Nearby wells such as SNL-8 lack halite; testing there may help resolve the effects of halite.

Further modeling of the Culebra and other hydrogeological units in the vicinity of WIPP will likely be undertaken in the future. The halite in various Rustler units, including the Culebra and Magenta, are clear evidence that vertical infiltration is now limited in these units. Furthermore, sodium-chloride brines in the Culebra near WIPP are likely derived from halite pore and fracture fillings. Brine has commonly been assumed to be derived in part from dissolution of overlying or underlying halitic units. It is possible that this process occurs in some locations, but halite in the Culebra and limits on vertical infiltration lead to the inference that an initial source of brine within the Culebra is from the Culebra itself.

CONCLUSIONS

Recent drilling and coring results for the Rustler continue to provide additional details regarding the depositional and diagenetic history of the formation along with important hydraulic properties for the Culebra in regions not previously tested. Halite is a significant part of the Rustler, and more detailed coverage of the extent of halite, particularly now in the carbonate units at SNL-15 and SNL-6, provides additional evidence for both the infiltration of brine from later halite pans and the effects of halite (and sulfate) plugging of porosity eastward from WIPP. Halite margins in H-3 and H-4 are tentatively revised in the recently drilled northeastern area (Fig. 9), and will be refined with evidence from industry drilling in the area.

Cores from mudstone-halite beds in these drillholes provide confirming evidence of the hypothesis that these are laterally equivalent facies reflecting mainly depositional processes, including syndepositional dissolution. Some of the cores show detailed evidence of changes in the halite pan extent, which can be correlated with subtle sedimentologic changes in the more distal mudflats. Such data provide confidence that the mudflats can yield additional details of changes in depositional environments.

The margins of halite beds have been anticipated as the most likely areas for post-depositional dissolution (Holt, 1997; Beauheim and Holt, 1990), and H-3 (above the Culebra) appears to be the main unit with some marginal dissolution. New drillhole SNL-8 indicates evidence of such dissolution, and that area is now included in the zone of probable H-3 dissolution.

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