Predicting Fractured Zones in the Culebra Dolomite

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Fracturing in the Culebra Dolomite Member of the Permian Rustler Formation exhibits a high degree of spatial variability in the vicinity of the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico. The WIPP is the U.S. Department of Energy's deep geological repository for transuranic and mixed wastes resulting from the nation's defense programs. The WIPP repository is located 655 m below ground surface in bedded halite of the Permian Salado Formation, which underlies the Rustler and Culebra. Culebra transmissivities (T's) in the vicinity of the WIPP vary over six orders of magnitude, with higher T's ($\log_{10}$ T (m^2/s) > -5.4) reflecting zones of well-interconnected fractures. We develop, test, and refine a conceptual model for predicting fracture zones within the Culebra. We define three regional-scale controls on Culebra fracturing, including the dissolution of salt from below the Culebra, the presence of halite above and below the Culebra, and overburden thickness. We also identify two local-scale controls on Culebra fracture zones including fracture-filling cements and localized deformation due to ductile flow of the mudstone that underlies the Culebra. The spatial distribution of the regional-scale controls is easily predicted. However, the influence of local controls can only be uniquely identified in hydraulic test data. A drilling program initiated in 2003 tests aspects of this conceptual model and leads to minor revisions of our conceptual understanding of the geologic controls on fracturing in the Culebra.

1. INTRODUCTION

Contaminant transport in aquifers is often dominated by the most conductive interconnected pathways, which typically make up only a small percentage of the total aquifer volume. In fractured rock, most flow and transport occurs in the largest aperture fractures that are well interconnected. Consequently, identifying and characterizing well-interconnected fractures, which we will refer to as fracture zones, are key goals for many contaminant transport studies. This is particularly true in the case of the Waste Isolation Pilot Plant (WIPP), the U.S. Department of Energy's underground repository for transuranic and mixed wastes near Carlsbad, NM. In the event of inadvertent human intrusion of the repository at some time in the future, the principal groundwater release

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pathway for radionuclides from the repository to the regulatory boundary (the "accessible environment") is through the Culebra Dolomite Member of the Rustler Formation. The Culebra is an 8 m thick unit that displays extensive variation in fracturing in the vicinity of the WIPP site. Characterizing the hydraulic properties of the Culebra, especially identifying fracture zones, has long been a major element of hydrogeologic investigations at the WIPP.

The Culebra is a unique fractured rock aquifer. The transmissivity of the Culebra varies over six orders of magnitude in a very small area (<1,000 km^2), an extreme level of heterogeneity that mainly reflects post-depositional processes (including fracturing), rather than depositional variations. In aquifers of this type, standard geostatistical and stochastic descriptions of aquifer heterogeneity fail due to strong spatial trends in the system. In these circumstances, meaningful quantitative models of aquifer heterogeneity require a strong conceptual connection to the underlying geologic processes that control fracturing. Because fractured rock systems like the Culebra are highly complex, this conceptual modeling process must be iterative and updated to reflect new data and understanding.

In this paper, we focus on the development of a predictive conceptual model linking Culebra fracturing with geologic processes. We first develop our current conceptual model for the spatial distribution of fracture zones in the Culebra. We then report the results of a recent drilling program conducted to verify our conceptual model. Finally, we revise our conceptual model based on our recent drilling activity.

Our current conceptual model relates fracture zones to three regional-scale factors and two local-scale controls. The regional-scale factors include dissolution of salt from the upper Salado Formation below the Culebra, proximity to halite in other units of the Rustler, and the thickness of overburden above the Culebra. The local-scale controls are structural deformation of the Culebra above the underlying ductile mudstone and the history of dissolution and precipitation of sulfate fracture-filling cements. Six wells have been drilled since 2003 to test our hypotheses. The evidence provided by those wells supports our conceptual model and leads to further refinements in our understanding. Drilling along the margin of the Salado dissolution zone suggests that the Salado dissolution margin is more complex than a simple line or zone, as previously represented [*Powers et al.*, 2003]. Some holes drilled in areas adjacent to the dissolution margin encountered high transmissivity, but did not show clear evidence of dissolution. This result is likely due to the absence of fracture-filling sulfate cements in the areas near the Salado dissolution zone and may also reflect an extensional stress field along the dissolution margin. In addition, the discriminating function (interval thickness) used to delineate upper Salado dissolution is known to have some limitations because of unevaluated small depositional variations. Additional wells are planned to continue testing of our conceptual model.

2. CULEBRA HYDROGEOLOGY

The Culebra is a thin (~8 m thick), regionally persistent marker bed within the Rustler Formation (Figure 1) that occupies an area greater than 25,000 km^2 [*Holt*, 1997]. Because the depositional margins of the Culebra have been removed by erosional processes [*Holt and Powers*, 1988], the original depositional extent of the Culebra is unknown. It is likely that the Culebra originally occupied an area approaching 100,000 km^2 [*Holt*, 1997]. Because the scale of the Culebra depositional system is so large, facies tracts within the Culebra depositional system are at a scale much larger than the general WIPP study area, which is less than

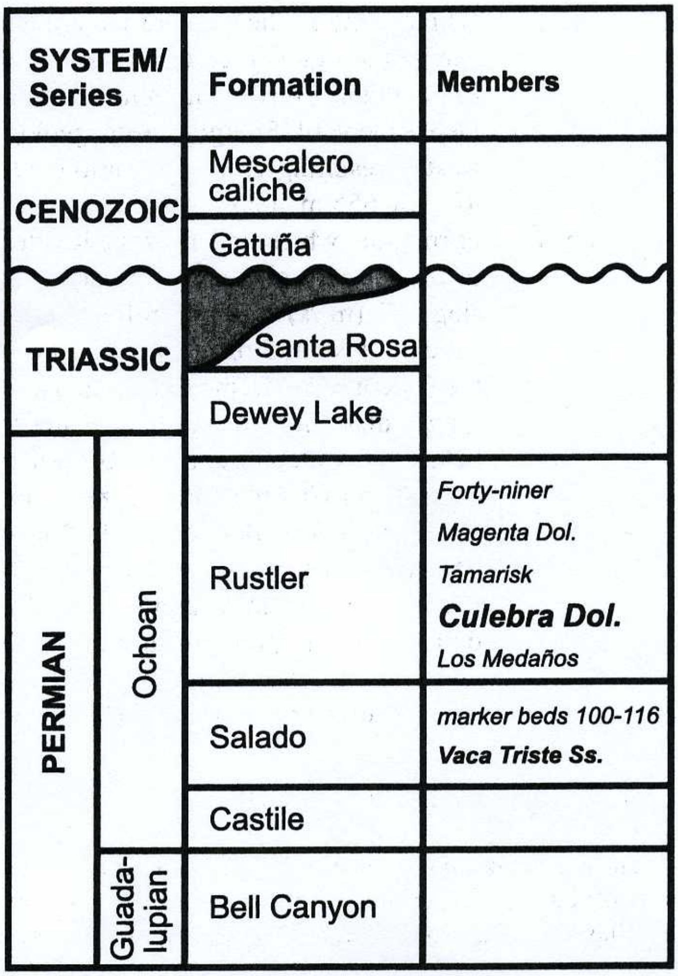

Figure 1. General stratigraphic column for the study area, showing the formations described in the text. The Culebra Dolomite Member of the Rustler Formation is emphasized. The scale of this figure does not represent unit thicknesses.

1,000 km^2 [*Holt and Powers*, 1988; *Holt*, 1997]. The vertical character of the Culebra changes little across the WIPP area [*Holt and Powers*, 1988; *Beauheim and Holt*, 1990; *Holt*, 1997]. Spatial variations in Culebra units within the WIPP area are largely confined to post-depositional features, including fractures and gypsum cements [*Beauheim and Holt*, 1990; *Holt*, 1997]. The amount of fracturing present within the Culebra has been qualitatively shown to increase from east to west across the WIPP area [*Holt and Powers*, 1988; *Beauheim and Holt*, 1990].

The Culebra consists of locally argillaceous and arenaceous, well- to poorly-indurated dolomicrite. *Holt* [1997] subdivided the Culebra into four distinct units (CU) (Figure 2), which can be identified in the subsurface across the entire WIPP area. The Culebra overlies a mudstone unit (M2 of *Holt and Powers*, 1988) across much of the WIPP area, and the lower contact undulates up to 1 m in WIPP shafts [*Holt and Powers*, 1990]. The lowermost unit (CU-4) shows evidence of syndepositional and post-depositional disruption caused by deformation of the underlying mudstone [*Holt and Powers*, 1990; *Holt*, 1997]. Bedding-plane fractures are common in CU-4 and form medium-scale (~1 m long and ~0.2 m thick) tabular blocks. The middle two Culebra units (CU-2 and CU-3) have a similar character and are often not recovered during coring. These units contain numerous open and sulfate-cemented vugs, sulfate nodules, and discontinuous interbeds of poorly indurated silty dolomite. CU-2 and CU-3 are intensely fractured with a hierarchy of superimposed block sizes resulting from the collapse of large open vugs [*Holt*, 1997]. The upper unit (CU-1) consists of well-indurated dolomite with local interbeds of silty dolomite and is dominated by bedding-plane fractures (spaced 0.1 to 0.6 m) and local subvertical fractures (spaced ~0.6 m) that bound large tabular blocks.

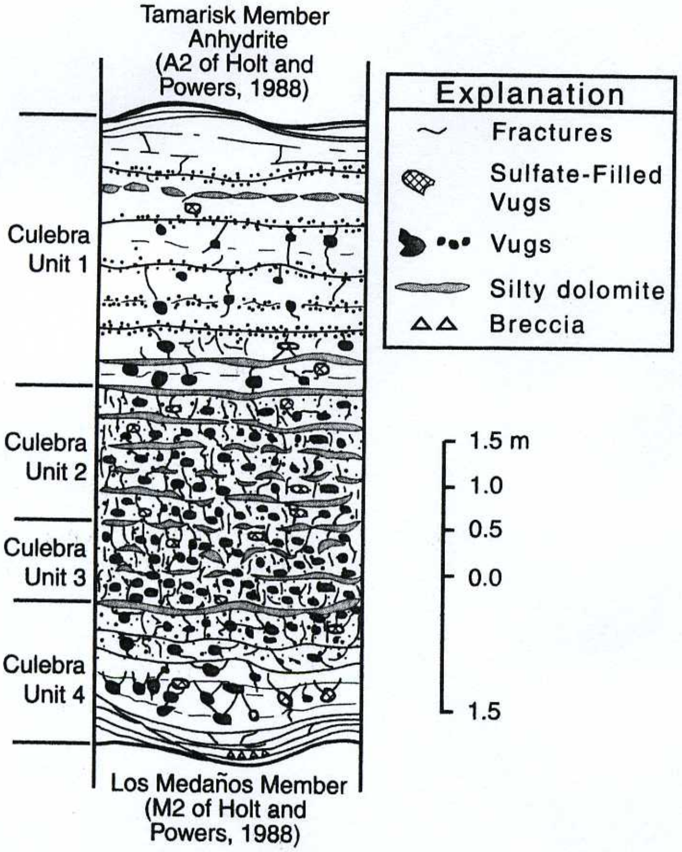

Figure 2. Culebra lithology showing representative fracture patterns (modified from *Holt*, 1997).

Near the WIPP site, the transmissivity (T) of the Culebra varies over six orders of magnitude (Figure 3). This variation appears to result from differences in the intensity of fracturing and differences in the amount (and perhaps type) of cements filling primary and secondary porosity. In general, Culebra T increases from east to west. East of the WIPP site, where the Culebra is deepest (>280 m below ground surface) and underlying evaporites of the Salado Formation have not been dissolved, the Culebra exhibits relatively few fractures, with most if not all of them filled with cements, primarily sulfate. Culebra $\log_{10}$ T (m^2/s) values in this area are typically less than –6.5. On the WIPP site itself, a wide variation in intensity and cementation of fractures is observed, and $\log_{10}$ T values range from < –6.8 to –4.0. West of the WIPP site, the Culebra is shallow (<190 m below ground surface), and in Nash Draw (Figure 4), portions of the upper Salado have been dissolved, resulting in subsidence and collapse of the Rustler Formation. Within Nash Draw, fracturing is intense, fractures are uncemented, and $\log_{10}$ T values are typically greater than –3.7.

At $\log_{10}$ T values < –5.4, Culebra hydraulic tests typically show single-porosity behavior, whereas double-porosity hydraulic behavior is observed at higher $\log_{10}$ T values. Double-porosity hydraulic behavior usually reflects the presence of interconnected, highly conductive fractures in a less conductive porous matrix, with most of the storage in the system residing in the matrix [*Gringarten*, 1987].

3. REGIONAL CONTROLS ON CULEBRA FRACTURING

We have identified three regional controls on Culebra fracturing. The areal distribution of these controls can be readily determined from outcrop, core, and geophysical log data. In the western part of the WIPP area, evaporites underlying the Culebra have been dissolved, leading to the collapse of overlying rocks and increased fracturing. In the eastern part of the study area, Rustler halite-bearing rocks overlie, underlie, and in some areas bound the Culebra. Because these halite units are very close (several meters) to the Culebra and would likely be dissolved by undersaturated Culebra waters if

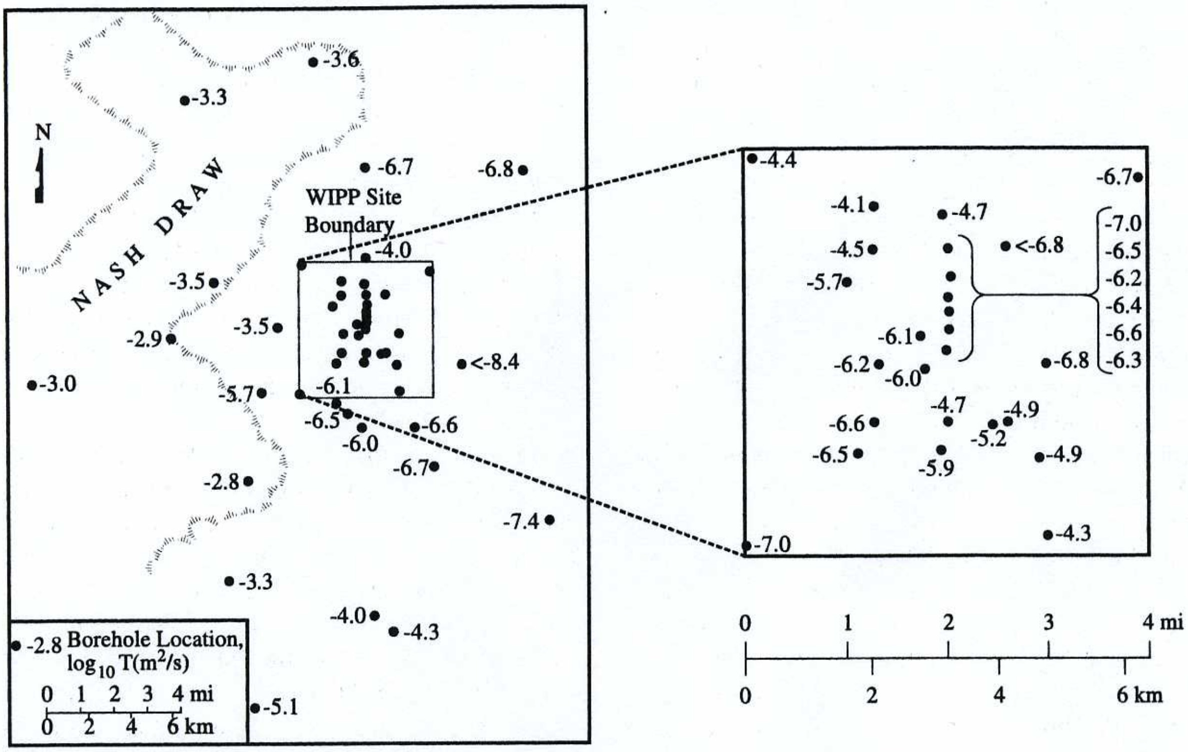

Figure 3. Culebra transmissivity values in the vicinity of the WIPP.

Culebra T were high, their presence suggests that Culebra fracturing is limited. Throughout the WIPP area, overburden thickness is a metric for two different controls on Culebra fractures: (1) fracture apertures are limited by overburden thickness and (2) erosion of overburden leads to stress-relief fractures. Structural deformation of the Culebra may also influence fracturing, but the effects of structural deformation cannot currently be separated from overburden influences.

3.1. Dissolution of Underlying Salt

To the west of the WIPP site, dissolution of the upper Salado and subsidence of the overlying strata, including the Rustler Formation, have formed a trough known as Nash Draw (Figure 4). The surface expression of Nash Draw covers approximately 400 km^2, with as much as 100 m of relief from the edge of the draw to its center. Culebra $\log_{10} T$ (m^2/s) values are –3.6 or greater at all tested wells in Nash Draw, and core, where recovered, shows extensive fracturing.

Dissolution of the upper Salado can be inferred from abrupt changes in contours of the thickness of the upper Salado and lower Rustler derived from geological and geophysical log analysis [*Powers et al.*, 2003]. (Over 1,000 oil, gas, and potash exploration holes have been drilled in the Delaware Basin in the vicinity of the WIPP site.) Along the edge of Nash Draw at Livingston Ridge, the section from the top of the Culebra to the base of the Vaca Triste Sandstone Member within the Salado Formation thins from approximately 190 m to less than 150 m over lateral distances of 200 – 400 m (Figure 5).

The upper Salado may also have been dissolved in smaller areas where either no surface expression formed or the subsidence was masked by deposition of overlying sediments. Two areas have been identified where lesser degrees of thinning of the Culebra-Vaca Triste interval occur with no obvious surface expression. These areas appear to be connected to Nash Draw and are inferred to be dissolution re-entrants (Figures 4 and 6).

The dissolution margin outside of the obvious physical extent of Nash Draw is illustrated south of SNL-12 (Figure 4; line C-D) by a cross section of geophysical logs (Figure 7). The geophysical logs are interpreted based on natural gamma signatures, which are persistent across large areas in the Delaware Basin. The geophysical logs have been arranged with the base of the Culebra along a horizontal line. The lower Rustler is dominated by clastic sediments that are responsible for higher natural gamma that decreases upward. The contact between the Rustler and the Salado is distinctive and has been marked with a heavy dashed line and labeled. Thickening of the lower Rustler at the NE end (D) of the cross section is a consequence of halite beds present in the unit. The base of the Vaca Triste has also been marked with

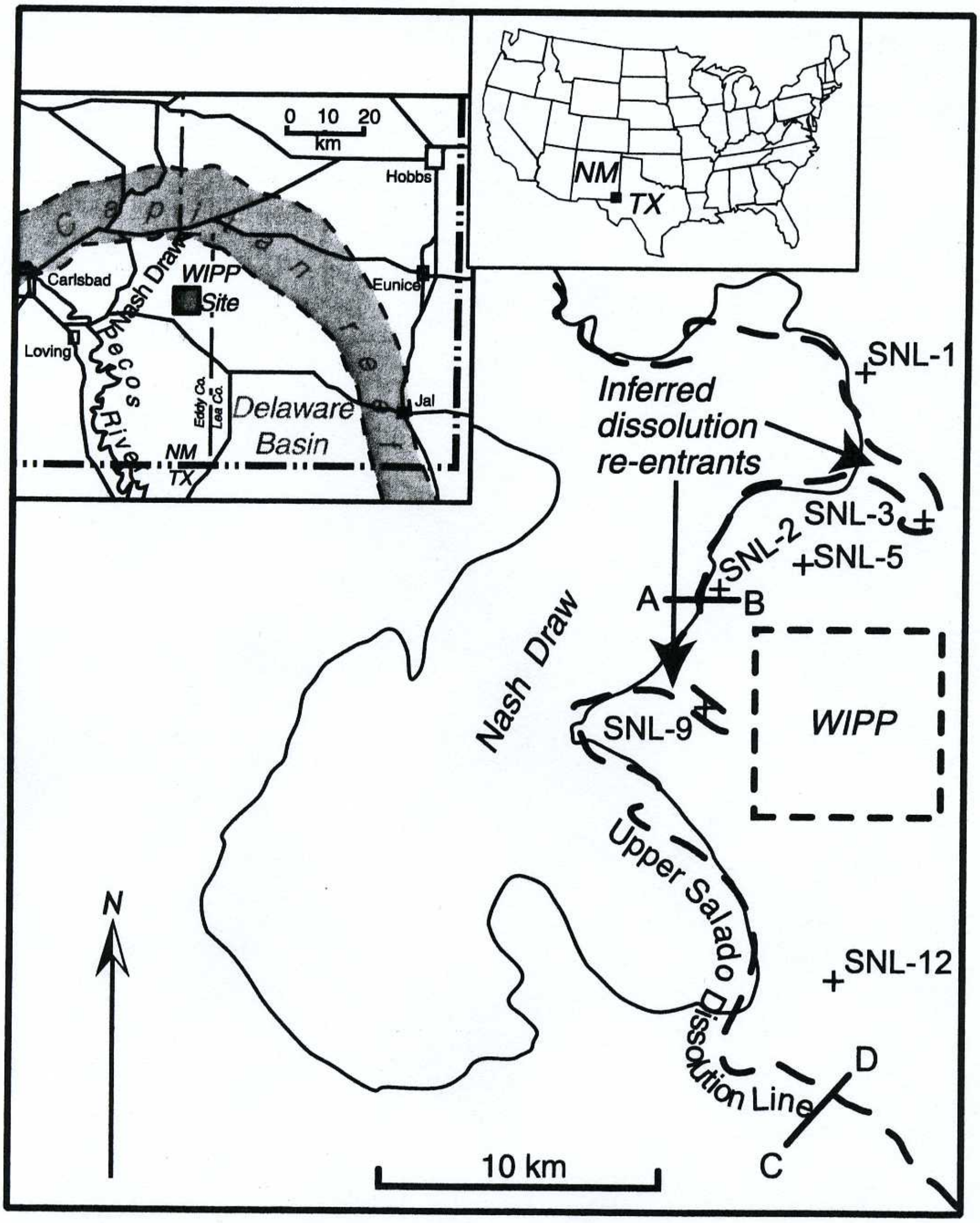

Figure 4. Outline of surface expression of Nash Draw (solid black line), showing the relationship of inferred upper Salado dissolution (heavy dashed line) to Nash Draw. Recent wells (SNL-1, etc.) were located to test hydraulic properties and geological factors in the area of WIPP. The geological cross section through Livingston Ridge shown in Figure 5 is located along line A-B. The geophysical log cross section in Figure 7 is located along line C-D.

a heavy dashed line and labeled to illustrate the interval used as an indicator of upper Salado dissolution. Lighter dashed lines follow individual gamma signatures that closely parallel the Vaca Triste because they were all deposited in a low-relief salt pan. Beds of the upper Salado are truncated against the base of the Rustler, as marked on the cross section. Several of the units near the top thin across the log cross section.

Without cores from this area, the processes that contribute to the truncation cannot be fully evaluated. Certainly some depositional truncation is possible. Some Rustler lithofacies thicken to the east in response to syndepositional subsidence in that area [*Powers and Holt*, 2000], and upper Salado could have been truncated in the process. Other areas near the syndepositional subsidence zones, however, do not show this relationship. We hypothesize that the truncation is related to

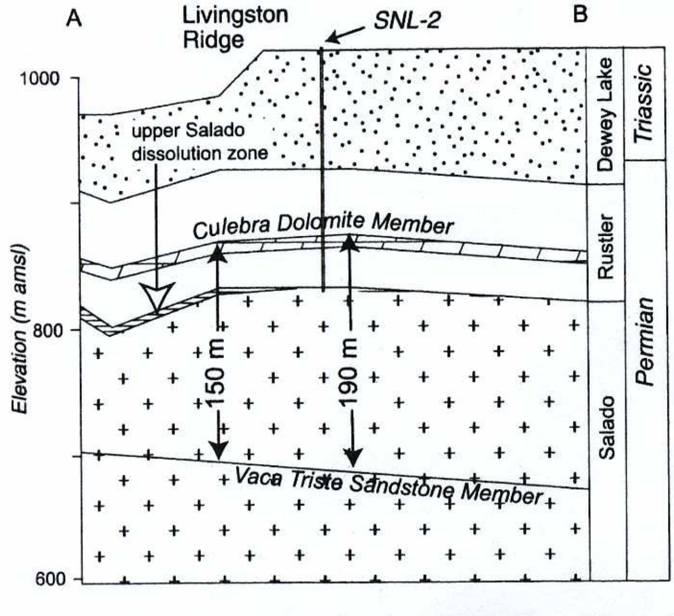

Figure 5. Cross section across the edge of Nash Draw (Figure 4, line A-B) shows thinning of the Culebra-Vaca Triste interval. SNL-2 was located near the interpreted margin of dissolution to test hydraulic properties of the Culebra and obtain geological information regarding upper Salado dissolution.

dissolution of the upper Salado rather than deposition. This is consistent with findings along Nash Draw and along a zone that continues from Nash Draw to the southeast, through the area of the cross section.

In addition to dissolution of the upper Salado, dissolution of halite may also have occurred in the Rustler Formation in certain areas. Halite was deposited within portions of the mudstone facies tracts in the three nondolomite members of the Rustler – the Forty-niner, Tamarisk, and Los Medaños Members (Figure 8). The Culebra is directly underlain by claystone of the Los Medaños Member. East of the WIPP site, halite is found in this claystone unit (designated M2/H2). Although evidence of post-depositional dissolution of this halite (H2) has not been found, some dissolution may have occurred along the present-day halite margin, resulting in Culebra subsidence and fracture zones. This is most likely to have occurred where vertical hydraulic gradients are downward across the Culebra and halite is absent in the M3/H3 interval.

3.2. Proximity to Rustler Halite Units

Halite margins are also important because the presence of halite in mudstones above and below the Culebra can be construed as evidence for the absence of fracture zones. We conceptualize fracture zones as being associated with increased groundwater flow through the Culebra. Culebra groundwater salinity varies widely, with densities ranging from 1,000 to 1,150 kg/m^3, but the salinity is everywhere below saturation with respect to halite where it has been tested. Higher fluid densities (>1,100 kg/m^3) are found in areas of low Culebra T (no fracture zones) close to or within the areas where halite is present in the Rustler above and/or below the Culebra. The high fluid densities are probably caused by slow advection of pore waters from the mudstones and/or diffusion of halite into the Culebra, accompanied by very slow Culebra groundwater movement [*Kröhn and Schelkes*, 1996]. If fracture zones were present, allowing rapid flow, the diffusion

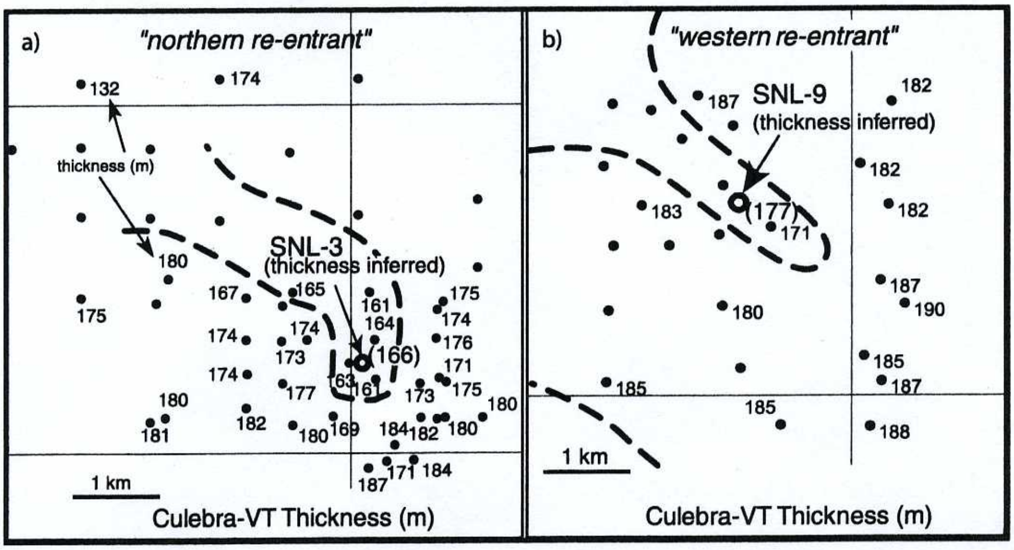

Figure 6. Dissolution re-entrants (see also Figure 4) inferred from thinning of Culebra-Vaca Triste interval were tested by drilling SNL-3 (a) and SNL-9 (b). Inferred thickness of the Culebra-Vaca Triste interval for these drillholes is shown in parentheses in italic type. Neither hole was drilled to the Vaca Triste, and the inferred thicknesses are based on comparing shorter intervals across the Rustler-Salado contact to nearby drillholes. Although SNL-3 and SNL-9 are each inferred to show some thinning of the upper Salado, it is less than in adjacent drillholes. Neither drillhole displayed significant brecciation or fracturing above the upper Salado.

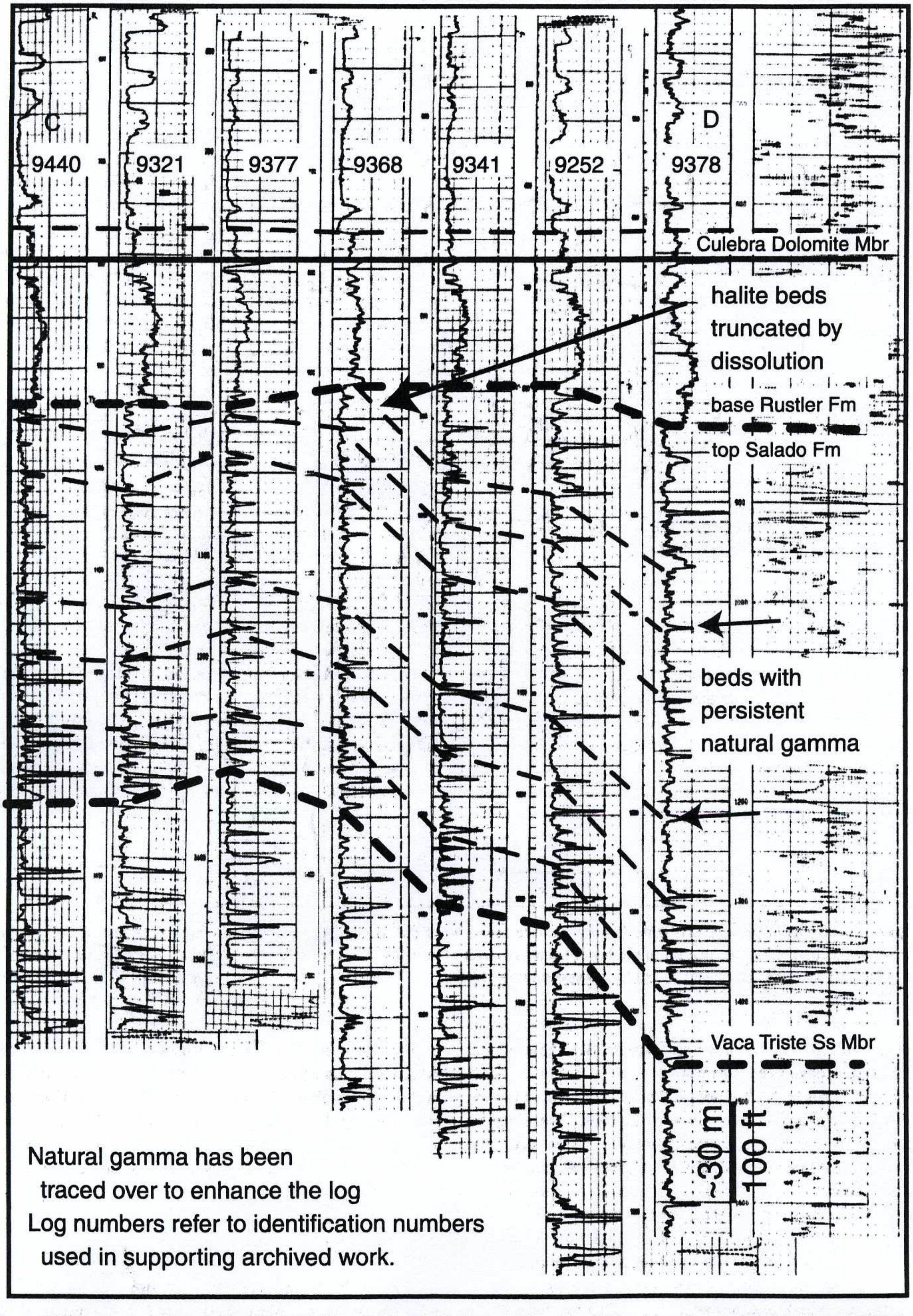

Figure 7. Natural gamma logs south of SNL-12 (Figure 4, line C-D) show stratigraphic relationships of upper Salado beds to the Rustler-Salado contact. The thickness from top of Culebra to the Vaca Triste thins dramatically to the southwest along the transect. Upper Salado beds pinch out, and they are interpreted as removed by post-depositional dissolution by analogy to other areas along Nash Draw.

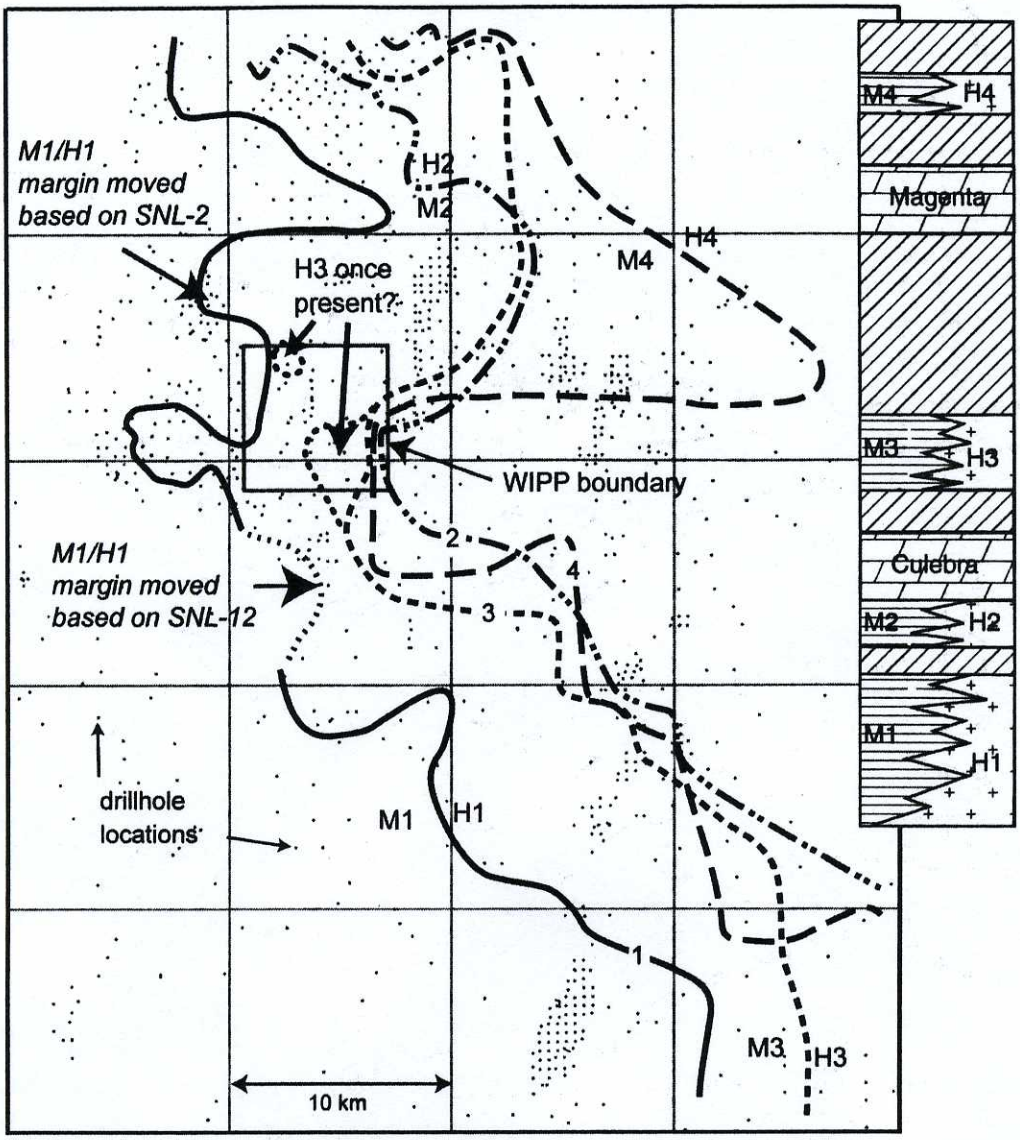

Figure 8. Margins of present-day halite in non-dolomite members of the Rustler Formation. Halite is present east of the margins. Based on recent drilling, the margin of the lower halite (H1) has been redrawn in the areas around SNL-2 (where halite cement was encountered) and SNL-12 (where no halite was encountered in M1).

gradient would be much higher, and any nearby halite would be expected to have been dissolved.

Holt [1997] suggests that porosity within the Culebra may contain abundant halite cements in regions where halite occurs above and below the Culebra, based on geologic observations of other halite-bounded units in the Rustler and Salado Formations [e.g., *Holt and Powers*, 1988, 1990; *Powers and Holt*, 1990, 1999]. This hypothesis is supported by the presence of anhydrite nodules and fracture fillings in the eastern part of the WIPP area (anhydrite nodules are primary depositional features that form in the presence of high-salinity brines) and by low T ($\log_{10}$ T (m^2/s) of < -8.4) reported for a borehole east of the WIPP (Figure 3).

The halite margins in the Rustler, with the exception of M1/H1 (Figure 8), can be accurately mapped from the abundant well logs available, allowing firm predictions of where fracture zones are not likely to be present. Additional drilling and testing is planned at locations with and without halite in various Rustler units, and these tests will provide further evidence regarding the relationship between Rustler halite and Culebra T.

3.3. Overburden Thickness

The depth to the top of the Culebra decreases from over 450 m east of the WIPP to 0 m in Nash Draw, west of the WIPP. *Holt* [1997] has estimated that as much as 600 m of overburden were eroded from above the Culebra at the WIPP site during the Cenozoic. Cenozoic erosion progressed from west to east across the WIPP area. The stress relief that accompanied this erosion induced fracturing in the Culebra, particularly along bedding planes and between mechanical inhomogeneities, including vugs and sulfate nodules [*Holt*, 1997]. The degree and hydraulic significance of stress-relief fractures increase with decreasing thickness of overburden above the Culebra. Because the Culebra dips to the east, hydraulically significant fractures are more prevalent to the west. In addition to being a metric for stress-relief fracturing, overburden thickness also limits fracture apertures, which should lead to lower transmissivity where Culebra depths are great [*Beauheim and Holt*, 1990; *Holt*, 1997]. Figure 9 supports this hypothesis and suggests a strong relationship between log T and depth for Culebra locations containing both well-interconnected and poorly interconnected fractures.

Recent drilling results also indicate that unloading history is locally more complicated than would be perceived by examining depth alone. At SNL-3 (Figure 4), for example, Miocene-Pleistocene Gatuña Formation is about 20 m thick, and the erosional base of the unit is about 30 m deep. The terrain is relatively flat in the area, with Triassic formations at the surface at slightly higher elevations north and south of SNL-3. The Gatuña partially fills a paleovalley in an area previously identified more generally by *Bachman* [1985] as lateral to Nash Draw. SNL-5 (Figure 4) was drilled in an area where the paleovalley might have extended, but the Gatuña was found to be very thin, confirming that the extent and course of such paleovalleys are complex. Individual wells at comparable depth may differ in the magnitude and history of stress relief, because of such processes that are disguised by relatively flat terrain, surface dune sands, and pedogenic calcrete. However, stress relief alone does not fully explain why the Culebra is observed to be more fractured in some areas than in others.

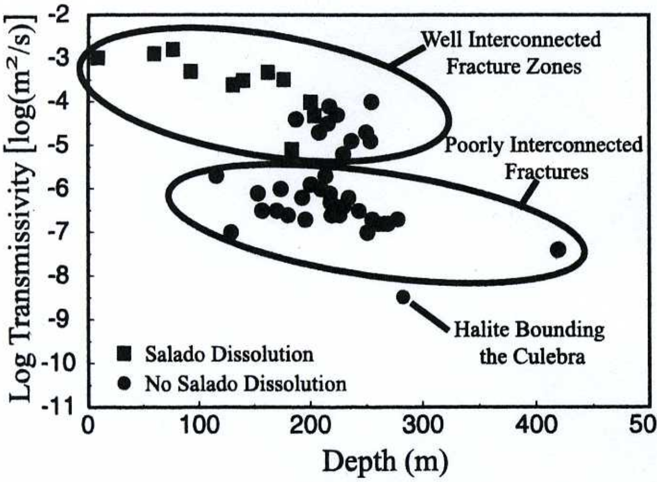

Figure 9. Log Culebra transmissivity (T) shows a strong relationship to depth. The lower field of T values is from test holes without well-interconnected fractures. The upper field is from test holes with well-interconnected fracture zones and includes places where the upper Salado has been dissolved. The lowest value occurs in a location where the Culebra is underlain by halite in the Los Medaños Member and overlain by halite in the Tamarisk Member.

4. LOCAL CONTROLS ON CULEBRA FRACTURING

While dissolution explains some fracturing and stress relief helps explain its intensity, some fracture zones have been found for which no regional-scale explanation can be adduced. Between the limit of Salado dissolution shown on Figure 4 and the M2/H2 and M3/H3 margins shown on Figure 8, 12 wells have encountered fractured, high-T conditions consistent with fracture zones, while 24 wells have encountered low-T conditions. We recognize two local-scale geologic controls on Culebra fracturing. First, the Culebra overlies a very ductile mudstone unit (M2) across much of the WIPP area, and ductile displacement of the mudstone in response to stress relief and structural deformation has led to fracturing, including localized brecciation, in the Culebra. Second, the Culebra has had a complicated history of dissolution and precipitation of sulfate fracture-filling cements, and these cements are capable of reducing the hydraulic connectivity of fractures. Pathological combinations of local structural deformation and the distribution of sulfate cements likely produce fracture zones. While we understand the mechanisms that lead to these fracture zones, we cannot uniquely identify their presence from geologic data. However, the influence of these fracture zones is easily recognized in hydraulic test data.

4.1. Local Structural Deformation

Across much of the WIPP area, the Culebra overlies a ductile mudstone unit (M2). In WIPP shafts, this mudstone displays slickensides and deformed strata consistent with post-depositional deformation [*Holt and Powers*, 1984; 1986; 1990]. The contact between the Culebra and M2 is undulatory, with an amplitude that exceeds 1 m. The Culebra shows features consistent with the accommodation of strain induced by movement in M2, including deformed strata, fracturing, and localized brecciation. Fractures produced following ductile deformation of M2 are likely to form local interconnected fracture zones. The presence of halite (H2) below the Culebra probably indicates the absence of ductile M2 deformation and attendant fracturing of the Culebra.

4.2. Sulfate Nodules and Cements

In some locations, the Culebra is fractured but the fractures are filled with sulfate cements, primarily with anhydrite or gypsum. Consequently, the distribution of high and low Culebra T may, in some areas, be related more to flow patterns that have dissolved (or precipitated) fracture fillings than to the occurrence of fracturing per se.

Sulfate minerals (gypsum or anhydrite) are found in the Culebra as nodules and as secondary cements in vugs and fractures [*Holt*, 1997]. The distribution of sulfate minerals within the Culebra exhibits a clear east to west pattern across the WIPP area [*Beauheim and Holt*, 1990; *Holt* 1997]. In the eastern part of the WIPP area, sulfate nodules consist of anhydrite in various stages of replacement by gypsum, and fractures are often filled with fibrous gypsum that may contain relict laths of anhydrite. In the central part of the WIPP area, nodules contain only gypsum, sulfate within some nodules has been removed leaving vuggy porosity, and fractures are filled with large gypsum crystals in optical continuity with gypsum in adjacent fractures and vugs (poikilotopic cements). Westward, poikilotopic cements and fracture fillings become more common, and some vugs and nodules are collapsed. In the western and southern part of the WIPP area, gypsum is rare, and open and collapsed vugs are common.

Beauheim and Holt [1990] and *Holt* [1997] attribute the pattern of Culebra sulfate cements to Cenozoic post-depositional processes. Fracturing due to eastward-progressing Cenozoic erosion allowed gypsum-saturated waters to replace anhydrite nodules and fill fractures with fibrous gypsum crystals as they opened [e.g., *Durnay and Ramsay*, 1973]. As erosion and fracturing continued, waters capable of dissolving gypsum fracture-fillings and nodules circulated in the Culebra, dissolving nodular and fracture-filling gypsum. Some nodules and vugs collapsed, creating additional small-scale fractures. In the western part of the WIPP area, nearly all gypsum pore-filling cements were removed. The Culebra groundwater chemistry changed, at least once, and slowly grown, poikilotopic gypsum cements filled some open fractures and pores, including vugs. In the vicinity of Nash Draw, all gypsum pore-filling cements have been dissolved, and no evidence of secondary cementation with gypsum has been observed.

4.3. Identifying Local Effects

Large-scale hydraulic tests can help us to identify well-interconnected fracture zones, even in areas dominated by local-scale effects. Numerous pumping tests have been conducted in fractured areas of the Culebra that produced observable drawdown responses in observation wells as much as 6 km from the pumping wells. The patterns of observed responses provide evidence of fracture zones in areas where they are not known to be present from direct observation. When wells that had intensely fractured cores and show high T in pumping tests show rapid, high-magnitude responses to pumping in fractured areas several kilometers away (e.g., H-3b2 in Figure 10), we infer that the pumping and observation wells are in an interconnected fracture zone.

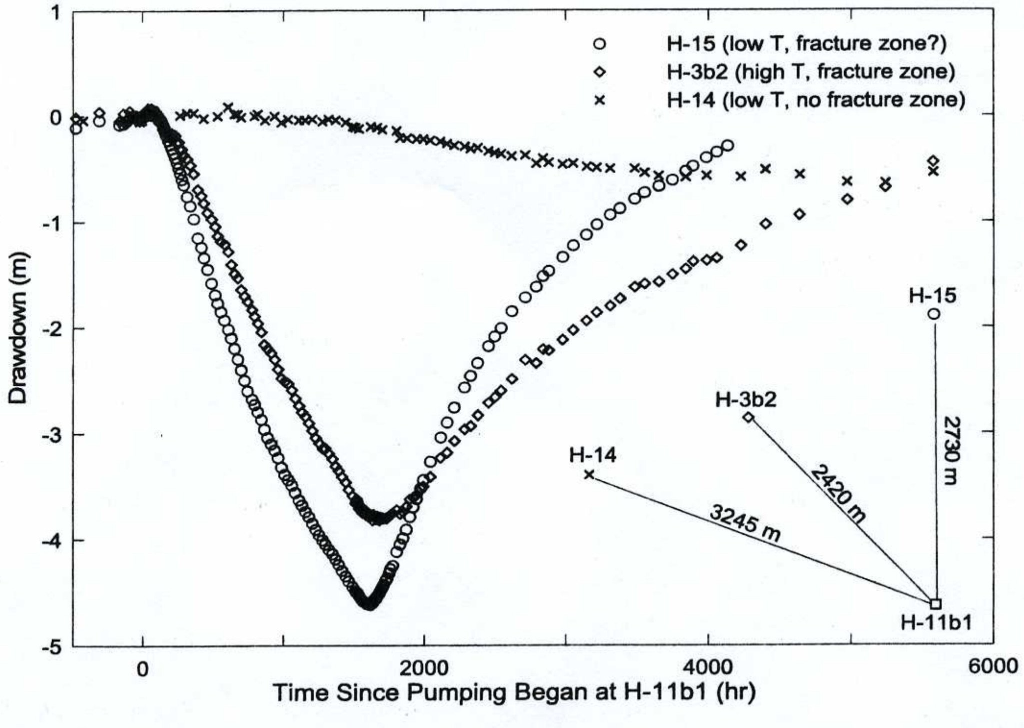

Figure 10. Drawdown responses in fractured and unfractured zones to pumping in a fractured zone.

When wells that had less-fractured core and show low T in slug tests nevertheless show rapid, high-magnitude responses (e.g., H-15 in Figure 10), we infer that fracture zones must pass near to these observation wells, although outside the radii of influence of the slug tests. Conversely, when delayed, low-magnitude responses are all that are observed (e.g., H-14 in Figure 10), we infer that fracture zones do not pass near the observation wells. These qualitative inferences have been substantiated by model simulations that cannot reproduce observed rapid, high-magnitude responses without extending high-T zones close to wells known to have low T. Similarly, high T (fracture zones) cannot be present in other locations where low-magnitude, delayed responses were observed.

5. FIELD VERIFICATION

A field program was initiated in 2003 to test our hypotheses about Culebra fracturing and provide additional information about the causes of fracturing. This program involves installing and testing wells in areas where fracture zones are expected and where they are not expected. Six new wells have been drilled and tested to date (Figure 4): two slightly past the inferred margin of Salado dissolution (SNL-1 and 2), two where Salado dissolution re-entrants had been inferred (SNL-3 and 9), one in an area where no dissolution was believed to have occurred (SNL-5), and one behind the dissolution margin (SNL-12) where the Culebra-Vaca Triste interval showed a localized thinning in a nearby drillhole.

SNL-1 (Figure 4) was drilled adjacent to the inferred margin of Salado dissolution in the northeastern arm of Nash Draw. As the Culebra was being cored, drilling fluid circulation was lost and the core barrel dropped ~0.6 m. Some of the recovered core showed evidence of larger porosity, beyond the normal vuggy porosity of the Culebra [*Powers and Richardson*, 2004a]. Core recovery was poor (presumably because of fracturing and possible dissolution), but testing revealed extremely high T. Although we have no direct information from the upper Salado at SNL-1, an initial assessment suggests that the location has been affected by upper Salado dissolution, increasing fracturing and allowing solution of the dolomite. The dissolution margin is likely not as precise as is suggested by drawing a line based on drillhole spacings, and dissolution may have locally advanced beyond the interpreted margin.

SNL-2 was installed near the margin of Salado dissolution, but where no dissolution was expected. Although no evidence of dissolution was found [*Powers and Richardson*, 2003a], this well nevertheless encountered fractured Culebra and moderately high T. We believe the fracturing may be related to tension created by subsidence along the margin of Nash Draw, creating a "skin" zone of fracturing that extends some distance beyond the region of actual dissolution.

SNL-3 and 9 were located in areas where geological/geophysical log interpretation indicated dissolution of the upper Salado had likely occurred, despite the lack of surface expression of that dissolution. SNL-3 was cored and drilled in the northern inferred dissolution re-entrant (Figures 4 and 6a). Cores across the basal Rustler and upper Salado from SNL-3 are not intensely fractured or brecciated [*Powers and Richardson*, 2004b], as might be expected from significant dissolution. Clastic beds are present, however, at the top of the Salado, including an unusual semilithified sandstone, that require further analysis for evidence of post-depositional dissolution. The Culebra is highly fractured at SNL-3 and shows high T.

SNL-9 was drilled in the inferred re-entrant west of the WIPP site (Figures 4 and 6b). Coring and drilling into the upper Salado at SNL-9 did not provide evidence of significant post-depositional dissolution of halite, although the Culebra is highly fractured and shows high T. The contact rocks are well preserved, and the cores revealed a sharp contact [*Powers and Richardson*, 2003b] consistent with an erosional surface found elsewhere. At this time, we cannot be sure if a re-entrant in fact exists near SNL-9. If a re-entrant is present, it probably differs in areal extent from, and is more complex than, what was inferred. Future well testing should help resolve how well connected the fractures at SNL-9 are to fractured locations in Nash Draw.

SNL-5 (Figure 4) was drilled in an area where no Salado dissolution was expected. SNL-5 encountered significant lower Rustler halite and was not deepened into the upper Salado [*Powers and Richardson*, 2004c]. The Culebra showed less fracturing than in any of the other holes, and testing showed low T characteristic of poorly interconnected Culebra fractures.

SNL-12 was located behind the indicated Salado dissolution margin (Figure 4) and adjacent to an oil well where the Culebra-Vaca Triste interval is thin relative to surrounding wells. SNL-12 shows halite in the upper Salado and undisturbed basal Rustler that indicate little, if any, dissolution of the upper Salado [*Powers and Richardson*, 2004d]. The Culebra at SNL-12, however, is much thicker (~13 m) than is common, and the upper part is unusually oolitic. Despite the apparent absence of significant dissolution, SNL-12 encountered fractured Culebra and high T. At SNL-12, cores did not recover any halite beds or halite cemented intervals from the Los Medaños. While recovery was not complete, some intervals indicate some disturbance of sedimentary structures. At this time, we have not analyzed the cores to determine if sufficient halite has been dissolved from this interval to alter Culebra hydraulic properties.

6. REVISED CONCEPTUAL MODEL OF RE-ENTRANTS

The absence of clear evidence in cores of dissolution in the two wells (SNL-3 and SNL-9) drilled in inferred dissolution re-entrants suggests that our original conceptualization of the re-entrants may have been overly simplified. The re-entrants were defined on the basis of small amounts (~10 m) of thinning (Figure 6) of the interval between the Culebra and Vaca Triste shown on geophysical well logs. This thinning was interpreted as reflecting dissolution of the upper Salado, which would presumably lead to subsidence of the overlying strata and fracturing of the Culebra. It was interpreted as extending more or less linearly along fronts 100 m (or more) wide.

The process by which the dissolution occurs, however, may be important in understanding the geometry of the re-entrants. At one time, most of the primary and secondary porosity in the Rustler was probably cemented with gypsum and/or halite. This condition still prevails east of the WIPP site. Close to Nash Draw, gypsum cements in Culebra fractures have been dissolved by relatively fresh water, resulting in moderately high T. Combined with downward hydraulic gradients to the Los Medaños (present today from the western edge of the WIPP site out to Nash Draw), water progressively dissolved the halite cements in the Los Medaños and then attacked the halite at the top of the Salado. These fluids ultimately moved into Nash Draw. This process prograded from the edge of Nash Draw to the east, establishing dissolution re-entrants to Nash Draw. These re-entrants are probably not as linear or as regular as the re-entrants delineated on Figures 4 and 6. Once established, the dissolution process fed on itself, as dissolution of Salado halite caused subsidence and increased permeability in the Culebra and Los Medaños, allowing still more water to reach the halite. The spatial distribution of Nash Draw re-entrants is likely highly complex, reflecting a complicated history.

Predicting the position of dissolution re-entrants to Nash Draw may not be straightforward, as shown by our overestimation of how much thinning would be evident at SNL-3 and SNL-9. However, while Culebra T may be highest directly over dissolution pathways, it would still be high in a wider region around Nash Draw and its re-entrants, where gypsum cements are absent from the Culebra.

In terms of predictive indicators, we conclude that the absence of halite cements in the lower Los Medaños should correlate with high Culebra T (fracture zones). Unfortunately, halite cements in clastic rocks, unlike distinct halite beds, are difficult if not impossible to resolve from geophysical logs, reducing the utility of this indicator except in areas where core data are available.

7. SUMMARY

In this paper, we develop, test, and revise a conceptual model for predicting fractured zones in the Culebra Dolomite Member of the Rustler Formation, which is the most transmissive unit overlying the WIPP underground repository. The Culebra is a highly heterogeneous, fractured aquifer with over six orders of magnitude variation in transmissivity in a small area (<1,000 km^2). Unlike most sedimentary aquifers that are dominated by depositional variability, this heterogeneity is mainly caused by post-depositional processes.

Our conceptual model for predicting Culebra fracturing includes three regional-scale controls and two local-scale controls. Regional-scale processes can be predicted from existing outcrop, core, and geophysical logs and include the dissolution of salt from below the Culebra, the proximity to Rustler halite units, and Culebra overburden thickness. West of the WIPP site, halite rocks from the Salado have been dissolved, leading to collapse of the overlying Rustler and increased fracturing in the Culebra. East of the WIPP, Rustler halite units overlie, underlie, and bound the Culebra. These halite units are within a few meters of the Culebra and would be dissolved if Culebra T were high. Additionally, the Culebra may contain halite cements in these areas. Therefore, we expect few fracture zones in areas where these Rustler halite units are present. Overburden thickness is a metric for two different controls on Culebra fracturing. First, variations in overburden thickness primarily reflect variable erosion in the WIPP area. Much of the fracturing in the Culebra is the result of erosional stress-relief. Second, fracture apertures are limited by lithostatic pressures which increase with overburden thickness. Both the amount of fracturing and degree of fracture interconnection are expected to increase where the Culebra is shallow.

Local controls on Culebra fracturing include the precipitation and dissolution of fracture-filling cements, which can reduce the interconnection of fracture zones, and localized structural deformation resulting from ductile deformation of the mudstone that underlies the Culebra. Because fracture interconnection is difficult to observe in cores and geophysical logs, the direct influence of these smaller scale controls is difficult to establish using geologic information alone. However, well-interconnected fracture zones resulting from these processes are readily identified using hydraulic test data.

In 2003, a field program was initiated to test our hypotheses for Culebra fracturing. Six wells have been installed and tested to date. Two wells were drilled next to the Salado dissolution margin, two wells were drilled within inferred Salado dissolution re-entrants, and two wells were drilled into areas where no Salado dissolution was expected. The four wells drilled to test the Salado dissolution margin showed that the margin is more complex than previously thought. Some holes drilled in areas adjacent to the dissolution margin encountered high transmissivity but did not show clear evidence of dissolution. High T at these locations cannot be attributed to depositional variations and is likely due to increased fracturing in a narrow region east of the Salado dissolution margin. Also, the connectivity of open fractures along the dissolution margin is not limited by fracture-filling sulfate cements. In addition, these data suggest that the discriminating function (interval thickness) used to delineate upper Salado dissolution may have some limitations where thinning in the Salado is small. The two wells drilled further east of the Salado dissolution margin showed the influence of local-scale controls on fracturing.

Additional wells are proposed near the margins of present-day halite in the Rustler and where simulation of hydraulic tests indicates high T must be present. Still other wells are proposed in areas where halite is present below the Culebra and low T is expected, to verify our conceptual model. Core is being taken in all new wells to identify features in overlying and underlying strata that might be related to Culebra fracturing. Once all of the proposed wells have been installed, large-scale tests will be performed by pumping at some of the new high-T wells for 30 days to see if the responses observed at surrounding wells suggest the existence of interconnected fracture zones.

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