Geological Factors Related to the Transmissivity of the Culebra Dolomite Member, Permian Rustler Formation, Delaware Basin, Southeastern New Mexico

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ABSTRACT.—The Culebra Dolomite Member of the Permian Rustler Formation in southeastern New Mexico has been tested hydraulically at 42 sites, yielding reliable transmissivity (T) values. The T values show a strong relationship to depth with contributions from two additional factors: dissolution of halite from the upper part of the underlying Salado Formation, and distribution of halite in the Rustler.

Three maps related to these factors improve our understanding of the processes involved in creating the T distribution. An elevation map of the Culebra shows the general regional eastward dip, which contributes to the depth factor, and two northwest–southeast-trending anticlines. Along the eastern margin of Nash Draw (a closed depression formed by dissolution and erosion), elevation contours are disrupted where the Culebra subsided as halite was removed from the upper Salado Formation. A map of the thickness between the Culebra and an upper Salado unit reveals pronounced decreases identified as the margin of dissolution of upper Salado halite. The dissolution margin underlies, and is the apparent control for, the escarpment on the eastern margin of Nash Draw. Rustler halite margins on the third map mainly indicate limits to saline facies tracts; they are also the most likely location for any post-depositional dissolution.

The geologic data on these maps can be used to develop a quantitative model for predicting Culebra T. The data have also been used to select drilling and hydraulic-testing locations for an extensive field program, beginning in 2003.

INTRODUCTION

The Culebra Dolomite Member of the Permian Rustler Formation (Fig. 1) in southeastern New Mexico has been intensively studied for nearly 30 years to determine its hydraulic properties. In the vicinity of the Waste Isolation Pilot Plant (WIPP) (Fig. 2), the Culebra has little significance for water production, but it is the dominant water-bearing unit above the Salado Formation, where radioactive waste is being stored for the WIPP. Its hydraulic properties are important parameters for estimating the probability of release of radionuclides from the WIPP to the boundaries of the controlled area over the next 10,000 years.

In the area of study (Fig. 2), Culebra transmissivity (T) varies over at least 6 orders of magnitude (e.g., Beauheim and Ruskauff, 1998). Across the study area, Culebra T values generally increase from east to west. Following several studies of Rustler geology as it relates to the hydrology of the Culebra (Holt and Powers, 1988, 2002; Beauheim and Holt, 1990; Powers and Holt, 1993; Holt, 1997), a detailed conceptual hydrogeological model for Culebra T has emerged. Unlike most geologic units, where heterogeneous hydraulic properties are attributable to depositional variations, spatial variability in Culebra T is primarily due to post-depositional processes (Holt, 1997).

The Culebra is a fractured dolomite (Holt and Powers, 1988), T in the Culebra is primarily due to fractures, and the amount of fracturing has been qualitatively shown to increase from east to west across the study area (Holt and Powers, 1988; Beauheim and Holt, 1990). Four regional-scale geologic processes have been postulated to account for the observed variations. Beauheim and Holt (1990) suggest that fracturing from erosion/unloading processes is a primary control on Culebra T, and Powers and Holt (1995) indicate that as much as 600 m of overburden might have been removed owing to Cenozoic erosion at the WIPP

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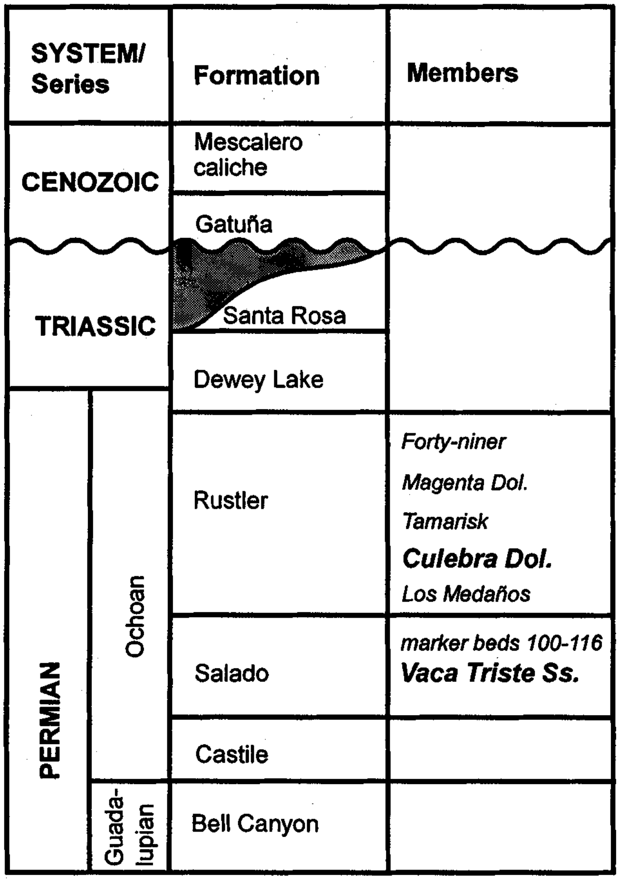

Figure 1. General stratigraphic column for the study area, showing formations described in the text. The Culebra Dolomite Member and the Vaca Triste Sandstone Member are emphasized because they are dominant features of later figures. The Los Medaños Member was named by Powers and Holt (1999) to replace the informal term "unnamed lower member" in common use. The scale of this figure does not represent unit thicknesses.

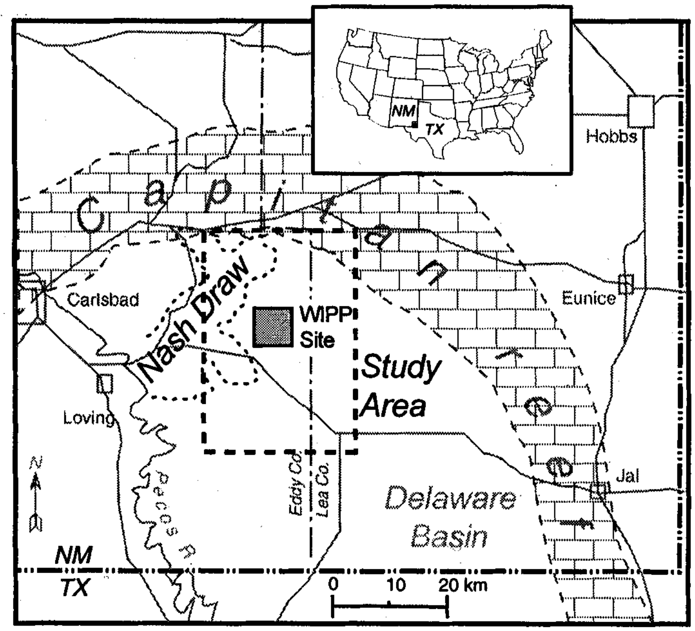

Figure 2. General location map of the study area, illustrating important features.

site. Structural deformation, including gravity foundering of the underlying Castile Formation and Cenozoic tilting of the Delaware Basin (Borns and others, 1983), also might have contributed to Culebra fracturing. In the western part of the study area (Nash Draw), halite from the Salado Formation has been dissolved, further fracturing the Culebra and, in some areas, resulting in collapse that lengthens the Culebra section (Holt and Powers, 1988; Beauheim and Holt, 1990; Powers and Holt, 1995; Holt, 1997). In the eastern part of the study area, halite directly underlies the Culebra (Holt and Powers, 1988). Holt (1997) suggests that halite cements in these areas may limit Culebra porosity and T; ground-water-chemistry data also show waters near halite saturation in these areas (e.g., Beauheim and Holt, 1990).

Here we develop the geological information and data for the Culebra necessary to create a geologically based quantitative model for predicting Culebra T. The principal geologic data necessary for this are elevations (structure-contour maps) of the top of the Culebra; thickness changes across an interval including the Rustler–Salado contact (as a means of determining the margin of dissolution of the upper Salado halite); and facies maps showing halite margins for various Rustler Formation members. Culebra overburden thickness can be obtained by subtracting interpolated Culebra elevations from topographic elevations (from digital elevation models) at grid points.

Weart and others (1998) introduce the location, function, broad setting, and some of the geological issues relevant to the WIPP for the interested reader. Part of our study area includes evaporite karst areas described by Lee (1925); we focus on more specific issues in this report.

DATA AND SOURCES

In the study area or domain, there are three principal sources of geological data for the Culebra, Rustler halite units, and upper Salado. These sources are WIPP-sponsored work, oil and gas drilling, and drill holes for potash deposits. Within the WIPP site, most of the information comes from WIPP-sponsored drill holes and shafts (e.g., Holt and Powers, 1990). Cores, cuttings, and geophysical logs are important sources of information, but major insights into the geology of the Culebra and Rustler have come from shaft observations. Non-WIPP data sources have been interpreted on the basis of experience gained through more direct investigation of the rocks for WIPP. The second source of data is the oil and gas wells drilled in the study domain. Intensive exploration and development of previously overlooked resources, beginning in the late 1980s, have increased the number of wells with useful shallow geophysical logs, and this study includes data from about 1,000 such drill holes. Geophysical logs from these more recent wells are commonly taken through the casing in the interval of interest to us, but the natural gamma log of the Rustler and upper Salado have distinctive signatures that are readily interpreted. The third source of geologic information for this study is the data recorded during drilling and coring to establish potash resources. Stratigraphic and lithologic data reported prior to the 1980s are sufficiently detailed to recognize consistently the important stratigraphic units. Recent potash drill-hole reports, however, commonly do not show the Culebra. To determine the margin of upper Salado dissolution, the interval from the top of Culebra to the base of the Vaca Triste Sandstone Member of the Salado Formation (Fig. 1) was most consistently reported across the various data sources. A narrower interval bounding the contact would have been preferable but was not practical. Rustler halite margins were interpreted on the basis of WIPP shafts, cores, and geophysical logs, and these margins were extended as possible, using open-hole geophysical logs from oil and gas wells and more detailed potash drill-hole descriptions.

Location data for the drill holes are most commonly the township, range, and section locations. For many drill holes, Dave Hughes (Washington TRU Solutions, LLC) provided an electronic data file of New Mexico State Plane (NAD27) locations. State Plane coordinates were converted to UTM metric using Corpscon for Windows (v. 5.11.08). As necessary, drill-hole locations were plotted on existing 7.5-minute quadrangle maps according to township, range, and section information. From these maps, UTM metric (NAD27) coordinates were obtained. Maps shown here in simplified form are based on 34- × 44-in. original maps.

ELEVATION OF TOP OF CULEBRA

The relevant geological factor related to Culebra T is depth (Fig. 3), and the specific relationship is described elsewhere. The elevation (structure) of the Culebra can be used to estimate the depth to Culebra between drill holes by combining digitized maps of Culebra structure and digital surface-elevation maps. The Culebra elevation map (Fig. 4) reveals features that indicate dissolution as well as deformation of evaporites, and it is important to place the discussion of Culebra T in the context of these features.

The southeastern part of the study domain illustrates the general eastward regional dip of formations in the Delaware Basin (Fig. 4). Units below the evaporite beds (i.e., Guadalupian and older) tend to dip about 20 m/km eastward and show few variations. The Culebra shows distinctive features attributable to several processes.

Northeast of the WIPP site, the Culebra has been deformed by movement in the underlying evaporites of the Castile Formation and Salado Formation. The Culebra forms a northwest–southeast-trending anticline ("Divide anticline"), with structural relief ap-

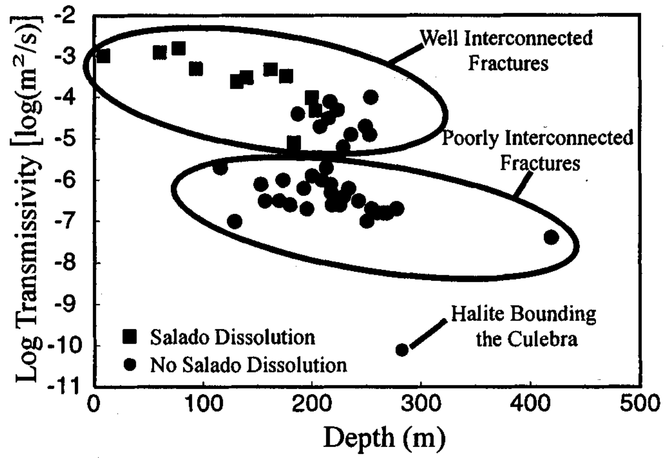

Figure 3. Log Culebra transmissivity (T) shows a strong relationship to depth. The lower field of T values is from test holes without well-interconnected fractures. The upper field is from drill holes with well-interconnected fractures and includes places where the upper Salado has been dissolved. The 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.

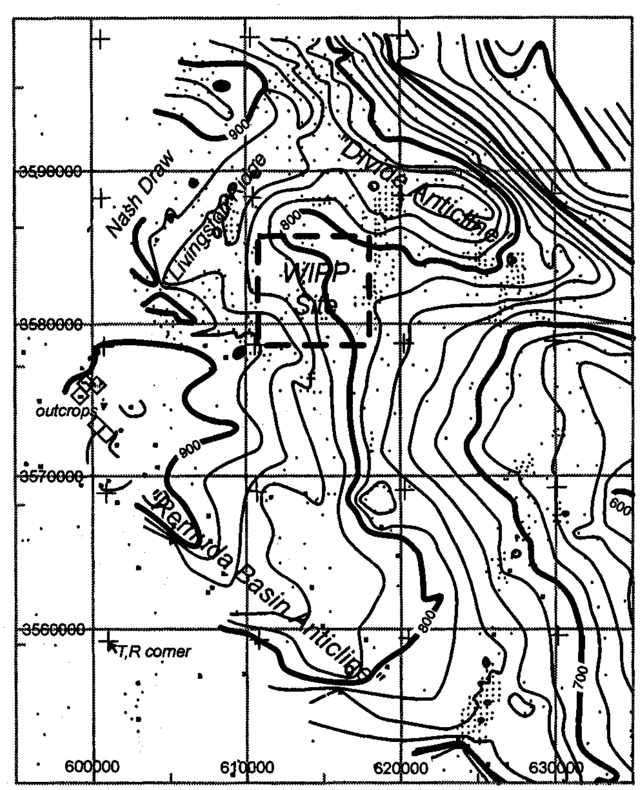

Figure 4. Elevation (structure-contour) map of the top of the Culebra Dolomite Member (in meters above mean sea level). The contour interval is 20 m. The grid lines represent the UTM (NAD27) coordinate system, in meters, for Zone 13. Small crosses show the corners for townships in the township, range system for New Mexico (see Fig. 5 to determine township numbers). Dots represent drill holes from which records were examined to obtain data. Some geophysical or geological logs were not interpretable for this datum. The data were originally plotted on large-format maps for data checking and contouring before producing this less detailed map.

proaching 100 m. Although the underlying evaporites are more significantly deformed, the structural relief diminishes upward.

In the southwestern part of the map, another northwest–southeast-trending anticline ("Remuda Basin anticline") is formed. The northern flank is a combination of eastward dip and some dissolution of Salado in the southeastern part of Nash Draw. The southern flank was created by substantial dissolution and possibly erosion associated with development of the Loving–Balmorhea trough (Maley and Huffington, 1953).

The structure map of the Culebra becomes more complicated in the vicinity of Nash Draw, marking the downdropped section where Salado dissolution has occurred (see below). Fewer reliable data points, and subsidence, indicate areas where contours are not likely to be very accurate, and therefore the structure contours haven't been extended into some of these areas.

Across the domain of interest, the Culebra structure contours are considered predictable and reliable; these are the conditions necessary for predicting the depth of the Culebra on a closely spaced (e.g., 50-m) grid by subtracting Culebra elevations from surface elevations (using digital elevation maps) at the grid points.

DISSOLUTION OF UPPER SALADO HALITE

Across the east-central part of the study area, the interval between the top of the Culebra and the base of the Vaca Triste is about 200–220 m thick. As indicated by a broad arrow (Fig. 5), the interval tends to thin toward the northwest; in the vicinity of the WIPP site, it is about 190 m thick. From previous analysis of logs, part of this increase in thickness to the southeast is attributable to the presence of halite beds in the Los Medaños Member of the Rustler (see below). Core studies show that halite in the Los Medaños thins and disappears to the northwest owing to synsedimentary dissolution (Holt and Powers, 1988), and this process also occurred in other Rustler members (Powers and Holt, 2000).

To the north, west, and south of the WIPP site, the Culebra–Vaca Triste interval thins over a narrow band, as is shown in several areas where drill-hole control is very good. Along Livingston Ridge, the thickness of the interval drops from ~190 m to <150 m over a lateral distance ranging from about 200 to 400 m (Figs. 6, 7). The position of the dissolution margin corresponds directly to the Livingston Ridge escarpment (Fig. 8).

South of the WIPP, the interval thickness changes less dramatically. Geophysical logs reveal that halite beds of the upper Salado are thinner to the south. Cores are not available for the examination of textures, and we infer that thinning of this interval is due to dissolution rather than to depositional processes. The position of the dissolution margin (Fig. 5), placing WIPP drill hole H-9 in the zone of dissolution, is consistent with hydraulic-test results for this drill hole.

Dissolution reentrants (Fig. 5) have been interpreted west and north of the WIPP site where thickness changes occur, but these thickness changes generally are not as sharply defined as along Livingston Ridge. The reentrant to the west of the WIPP is controlled by a single datum. Data from other potash drill holes in the area did not include sufficient detail to calculate the interval thickness. The reentrant was extended from the trend of the dissolution margin along Livingston Ridge, because some connection to an outlet or inlet is required. The reentrant is extended to Livingston Ridge in an area where the Miocene–Pleistocene Gatuña Formation is thicker (Powers and Holt, 1993), possibly reflecting valley development over a dissolving trend (or a dissolving trend developing under a valley). The reentrant is also evident where a series of potash drill holes encountered water at depths where the Culebra is reasonably expected, though the drill-hole reports did not include data for Rustler stratigraphic units. Each of these reentrants will be tested by drilling and coring during FY03.

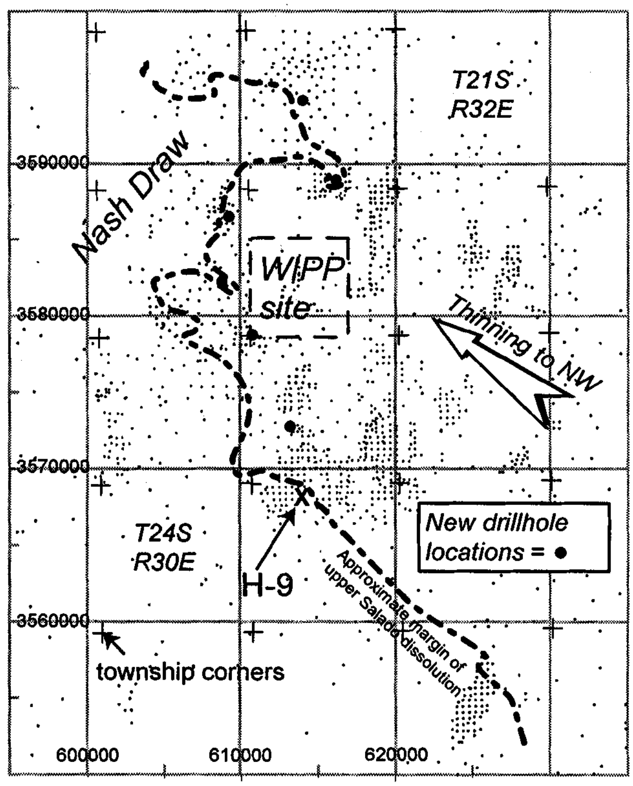

Figure 5. Map showing the dissolution margin of the upper Salado Formation. The margin is based on thickness changes for the interval between the top of the Culebra Dolomite Member and the base of the Vaca Triste Sandstone Member (see Fig. 1). Figure 6 shows a segment of the line along Livingston Ridge and the thickness data. The interval is thinner in general to the northwest, owing in part to depositional changes in the Los Medaños Member of the Rustler Formation (Fig. 1). A few township identifiers are included for reference. The data were originally plotted on large-format maps for data checking and contouring before production of this less detailed map.

RUSTLER HALITE MARGINS

The database for determining Rustler halite margins (Fig. 9) is more restricted than for Salado dissolution or Culebra structure. Cores, shafts, and geophysical logs from uncased drill holes provide most of the data used to establish the margins. Some potash drill holes near the northern edge of the study area yielded sufficient detail to improve and extend the Rustler halite margins in those areas where other data sources are limited. Geophysical logs from recent oil and gas drill holes were more commonly taken through casing, and these logs have not been interpreted with respect to halite in the Rustler.

Rustler mudstone/halite facies tracts were interpreted by Holt and Powers (1988) and Powers and Holt (2000) as mainly the result of depositional processes, including syndepositional dissolution of halite. The margins of these halite tracts are the logical location for any post-depositional dissolution (Holt and Powers, 1988; Beauheim and Holt, 1990) that might affect the hydraulic properties of the Culebra. T values affected by such processes represent a small part of the field (Fig. 3). In addition, Culebra regions underlain or bounded by halite may have lower T.

The margin for halite (M-1/H-1) in the lower Los Medaños Member extends well west of most of the areas with halite in the remainder of the Rustler (Fig. 9). The M-1/H-1 margin very broadly parallels the margin of dissolution of the upper Salado (Fig. 5). Cores and shafts do not indicate alteration of the Culebra by late post-depositional dissolution of halite in M-1/H-1. M-2/H-2 directly underlies the Culebra, and it should be most relevant to changes in Culebra T from dissolution of Rustler halite. There is significant evidence of syndepositional and very early depositional adjustments in the basal Culebra from settling and probable dissolution of some halite from M-2/H-2 at that time (e.g., Holt and Powers, 1984, 1986, 1988, 1990; Holt, 1997). There is limited evidence of post-depositional dissolution of halite in M-3/H-3 in the vicinity of the site (Holt and Powers, 1988; Beauheim and Holt, 1990; Mercer and others, 1998). Some higher T values occur in these areas, but the exact relationship to dissolution in the Tamarisk Member is unclear. The M-4/H-4 margin generally follows the M-3/H-3 and M-2/H-2 margins except in the northeastern part of the site. It is not known to have any relationship to Culebra T.

The halite margins in the Rustler generally indicate that a saline pan environment existed to the east and that saline-mud-flat to mud-flat environments

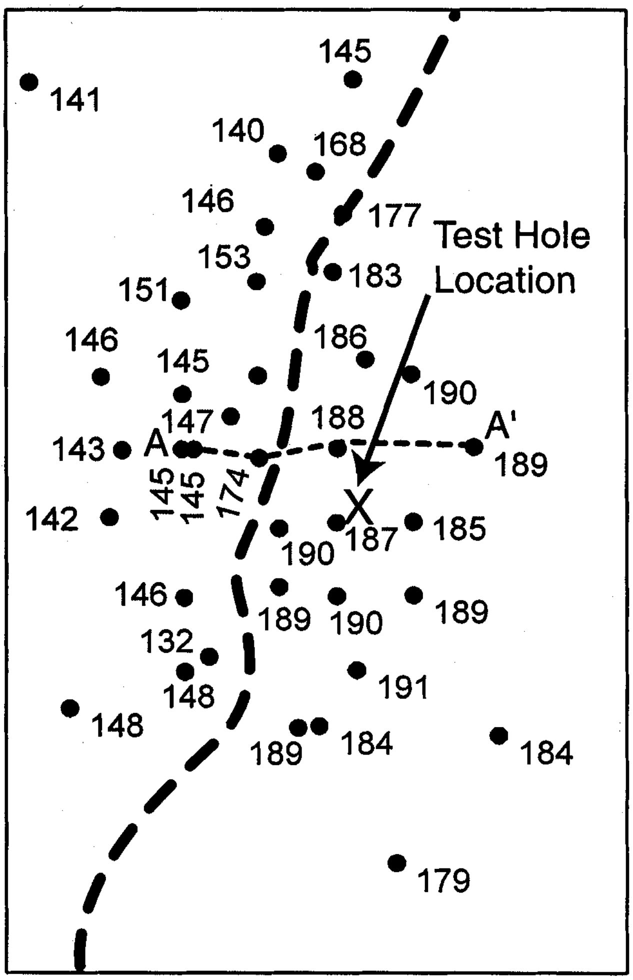

Figure 6. Thickness of upper Salado/lower Rustler strata, in meters. Along parts of Livingston Ridge, oil exploration and development drill holes are closely spaced, providing control for the margin of upper Salado dissolution based on thickness changes. The margin directly underlies the escarpment at Livingston Ridge, and the margin controls the location and development of the escarpment. The cross section (A–A′) is shown in Figure 7. Livingston Ridge is shown in an oblique aerial photograph in Figure 8. A test hole (x) will be drilled during 2003 east of this margin and near the line of the cross section.

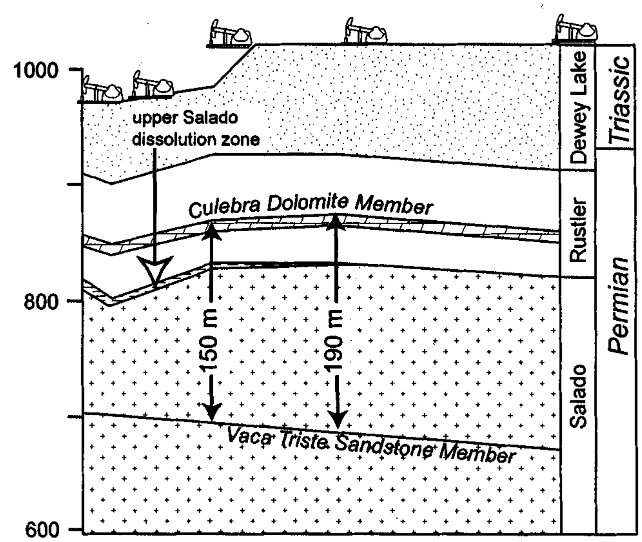

Figure 7. Cross section across Livingston Ridge, based on geophysical logs, shows the structural changes of the Culebra and the thickness changes of the interval between the Culebra and Vaca Triste. Drill holes are indicated by pump symbols; see Figure 6 for the cross-section position.

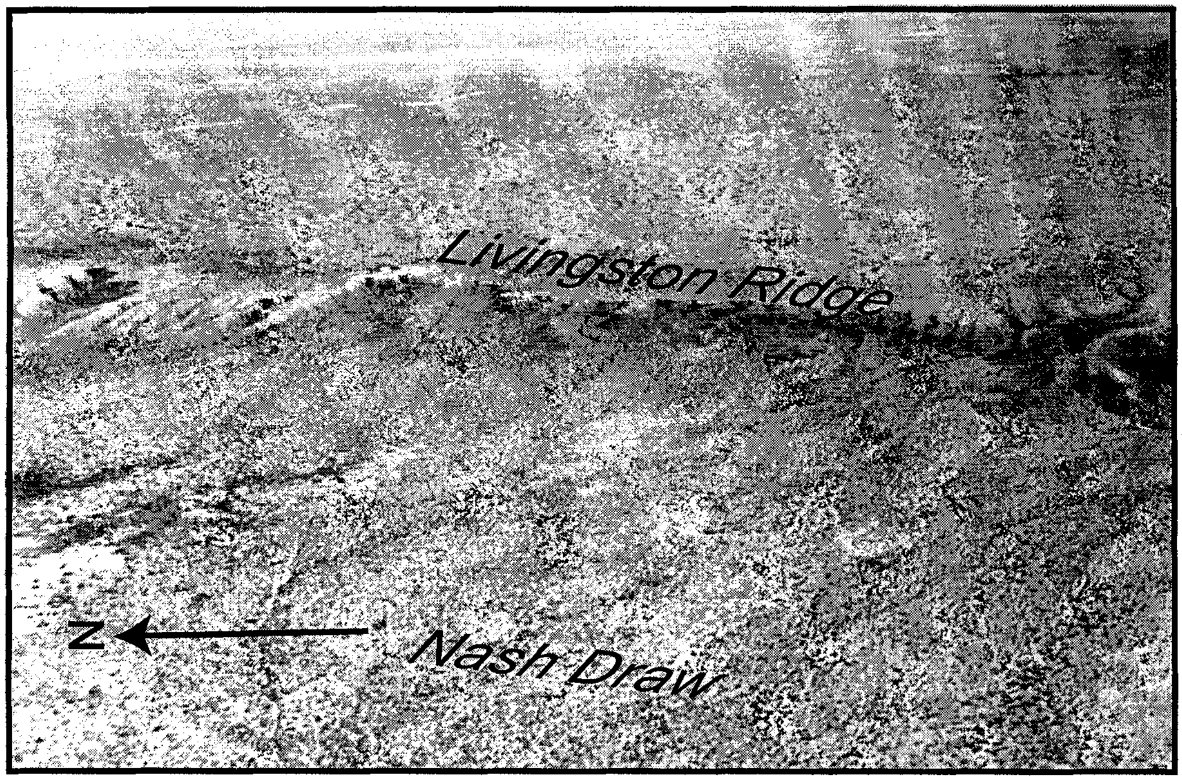

Figure 8. Low-angle aerial photograph of Livingston Ridge, just south of the area shown in Figure 6, displays downwarping across the dissolution margin and the escarpment eroded directly above the margin. The eastern part of Nash Draw is in the lower part of the photograph. The Mescalero caliche drapes the monocline, and internal textures suggest that subsidence occurred since the development of the caliche, starting about 570,000 years before present.

bordered the pan on the west. The general shapes of the depositional basins locally during these desiccating periods must have been similar.

DISCUSSION

Culebra Elevation

Within the study area, the Culebra generally dips to the east, and the surface topography generally rises to the east. The dip and topography combine to create a general increase in depth to the east, with a trend similar to structure contours. The general trend is for T values to decrease to the east because of depth, the presence of Rustler halite, and the lack of Salado dissolution. Drill holes with T values are sparse northeast of the WIPP site across the "Divide anticline" (Fig. 4). They do not constitute an adequate sample to determine if the structure created by deformation of deeper evaporites is a factor for estimating Culebra T.

Upper Salado Dissolution

This study is the first effort in which the margin of upper Salado dissolution has been identified and bounded in any detail. This is a function mainly of a database that expanded greatly in the last 15 years because of oil and gas exploration and development in the area. Most of the potash exploration occurred earlier, but the drill holes are generally not as closely spaced as in developed oil or gas fields. Finding a relationship between Culebra T and Salado dissolution provided the impetus for delineating the margin of dissolution.

Two features of the upper Salado dissolution margin stand out. The first is that the margin underlies the escarpment (Livingston Ridge) on the east side of Nash Draw (Figs. 6–8). The second is that the margin appears to be relatively narrow; earlier interpretations suggested a much broader, thin wedge of dissolution penetrating significantly beyond Livingston Ridge (e.g., Mercer, 1983).

The escarpment at Livingston Ridge is believed to have been controlled by the dissolution of halite at the top of the Salado. The drill-hole evidence is now dense enough to support this conclusion. As overlying units subside above a relatively narrow dissolution margin, strain accumulates in fractures directly above the margin. These fractures would be expected to be parallel to the dissolution margin, which will be parallel to the escarpment. In parts of Nash Draw, such fractures are observable. The uneroded surface will form a monocline. Parts of Livingston Ridge (Fig. 8) also show such a monoclinal structure, in which the Mescalero caliche (which formed beginning about 570,000 ± 110,000 years before present; Rosholt and McKinney, 1980) has been deformed as well. This indicates local movement (dissolution) since the Mescalero caliche was formed. The fracture system parallel to the escarpment likely contributes to infiltration and further dissolution.

Where drill-hole data are closely spaced because of oil and gas drilling, the thickness between the top of the Culebra and the base of the Vaca Triste is narrowly constrained (e.g., Fig. 6). Adjacent boreholes along Livingston Ridge are commonly spaced 200–400 m apart. They show that the thickness is reduced across about this distance. The interval in drill holes adjacent to, and east of, the margin is slightly thinner than in drill holes farther to the east. This narrow zone may be part of the dissolution margin, or it may be a continuation of the northwestward-thinning trend. It is probably the indicator of incipient dissolution.

Although the dissolution margin generally appears narrow, changes in thickness and direct borehole evidence suggest that dissolution may have advanced along two reentrants (Fig. 5), ahead of the migration of the general front and escarpment. A drill hole has been planned in each of these reentrants as a further test of the hypothesis linking Culebra T and upper Salado dissolution.

Rustler Halite Facies

The present margins of halite in the Rustler in the study area are generally consistent among investigators, but our interpretation as dominantly depositional margins (based on intensive shaft, core, and geophysical-log studies) differs considerably from earlier interpretations of the margins as resulting from dissolution (based on changes in thickness) (see discussion in Powers and Holt, 2000).

The halite margin in the Tamarisk Member, for example, changes thickness across the depositional basin over many kilometers (e.g., Holt and Powers, 1988; Powers and Holt, 2000) rather than over the short width of the Salado dissolution margin demonstrated here. The margins expressed here are interpreted from the best information about where halite currently exists, but facies margins are commonly not so precise as to be defined by the width of a line on a map. The margins do represent well, however, the position where post-depositional dissolution might have occurred.

Textural features show that the saline mud flats were subaerially exposed and that halite was removed syndepositionally from the facies. Halite may also have survived locally in the saline-mud-flat facies and been removed later. An example is the minor disruption of the M-3 (Tamarisk) facies in the northwestern part of the WIPP site (Fig. 9). As a consequence, these facies tracts are considered to have local areas where Culebra T may have been affected by removal of Rustler halite.

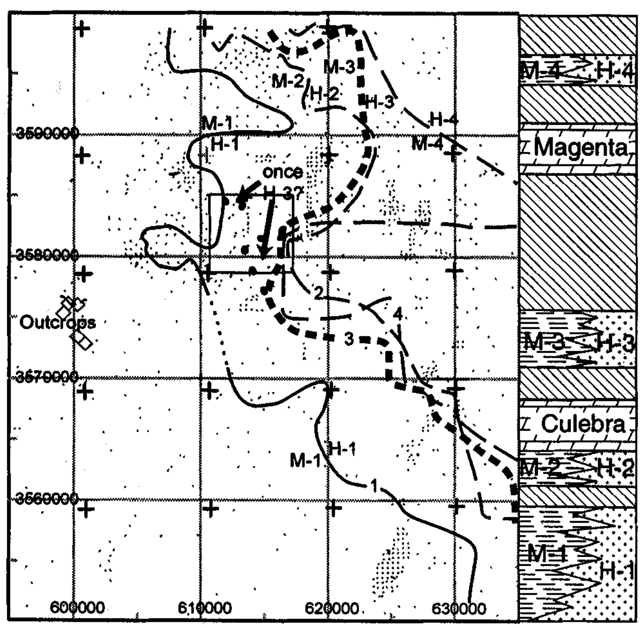

Figure 9. Rustler halite margins for four halite-bearing intervals (denoted M-x/H-x, as shown on the right side) are based on shaft and core descriptions and extrapolated to open-hole geophysical logs through the Rustler. The margins mark depositional facies changes (Holt and Powers, 1988; Powers and Holt, 2000), with some minor exceptions. The margin line for M-3/H-3 is thicker to distinguish it more easily, and the dotted lines near it are noted as areas of possible post-depositional dissolution of this halite margin or halite remnants after syndepositional dissolution.

CONCLUSIONS

Culebra T values show a strong relationship to factors such as depth, dissolution of upper Salado halite, and distribution of Rustler halite facies. As a consequence, we acquired and interpreted data on Culebra structure, the thickness of an interval from the Culebra to the Vaca Triste, and distribution of halite in the Rustler. The data are the basis of further modeling studies (in progress). Drill holes have been located, partly on the basis of these data, to obtain additional data about Culebra hydraulic properties and geological factors contributing to these properties.

The structure of the Culebra differs from the regional structure of formations below the evaporites because of dissolution of the upper Salado and because of deformed evaporites of the Castile and Salado Formations. Over the study area, however, the structure appears well defined, and the maps will provide a basis for developing detailed estimates of depth to the Culebra as one of the factors for estimating Culebra T between test holes.

The map of the thickness of an interval, including the top of the Salado, provides details not previously reported, partly because drilling was not close-spaced in these areas until recently. We conclude that the upper Salado dissolution margin is commonly narrow (i.e., a few hundred meters wide) across much of the study area. The escarpment at Livingston Ridge overlies and is controlled by this narrow margin. Dissolution reentrants have been interpreted along Nash

Draw, based on much smaller changes in thickness. This interpretation will be directly tested by drilling, coring, and testing drill holes during 2003.

The map of Rustler halite margins is the most current representation of the distribution of halite in the Rustler. Although halite was syndepositionally dissolved from saline-mud-flat facies, there is evidence of local post-depositional dissolution of remnants in unpredictable locations. These are accounted for in modeling studies under way.

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