Attachment F

Evaluation of Halite Dissolution in the Vicinity of Waste Control Specialists

Disposal Site, Andrews County, TX

(158 pages)

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WASTE CONTROL SPECIALISTS DISPOSAL SITE,

ANDREWS COUNTY, TX

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March 2007

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ABSTRACT

Waste Control Specialists (WCS) applied for a permit to dispose of low-level radioactive waste at their surface facility in western Andrews County, TX. The facility is located over Permian-age halite-bearing formations, and the possibility of dissolution and its effects on the long-term performance of the disposal site have to be considered. We develop three conceptual hydrologic models of dissolution processes (shallow, deep, and stratabound) based on experience and features found in the Delaware Basin west of the WCS site. We compare data from the WCS site and vicinity to the features of these models. Geophysical logs in the area of the WCS

facility yield stratigraphic and lithofacies data from the underlying halite bearing units, the Permian Rustler and Salado Formations. We find that halite units are continuous and that variations in thickness and lithofacies are depositional with no discernible post-depositional dissolution. These, and deeper, formations are modestly deformed, but the structural trends differ from local changes in evaporite thickness. Therefore, deformation is not related to thickness differences. Some thickness changes occur in the middle of the Salado, indicating depositional variations in thickness. Deeply buried halite bedded halite is difficult to dissolve. It behaves as a ductile material, and pore fluids within halite approach lithostatic pressure, so that fluid flow is outward from halite units into overlying and underlying rocks. Formation fluids at depth are commonly saline and slow moving, further limiting the dissolution process. We see no features in the study area at and around the WCS site indicating past dissolution, and the hydrologic systems at the site limit the potential for future dissolution.

The upper surface of pre-Cenozoic redbeds displays a ridge extending across the WCS site and northwest into New Mexico along Mescalero Ridge. Geophysical log data across this ridge reveal that the Rustler is modestly deformed, similar to the redbed paleosurface. The Rustler thins perpendicular to this ridge, and halite is consistently thick across the ridge trend. The redbed surface relief is not related to dissolution of Rustler halite.

Similar studies across a segment of Monument Draw, New Mexico, also indicate that the draw did not develop in response to dissolution of the Rustler.

Keywords: engineering geology, site investigations, hazardous waste, geological process, evaporites, dissolution

INTRODUCTION

WCS applied (WCS, 2004) to the State of Texas for licenses to operate facilities in Andrews County, TX, (Figure 1) that will dispose of radioactive waste. A review of the application by the State of Texas generated questions regarding the possible presence of features indicating dissolution of halite from rocks underlying the WCS site and in the surrounding area. We were requested by WCS to evaluate evidence regarding evaporite deposition and dissolution.

Much of the impetus for examining dissolution of evaporite rocks derives from projects to dispose of radioactive and hazardous material in these rocks, or in the near-surface environment over such rocks, as in the case of the WCS project. Some measure of the stability of the disposal system is required, including evaluating the likelihood of a release to the readily accessible biosphere over a specified regulatory period. Because halite is readily soluble in water over a considerable range of salinity, identifying dissolution features, associating the features with processes, and estimating rates are commonly high priorities for such projects. The WCS site overlies halite-bearing rocks, there is a regulatory period of performance, and there have been statements, inferences, and questions about the presence of features indicating dissolution and the significance for the WCS project. Detailed comments by the State are summarized and grouped here to provide a framework for the study and conclusions we have reached.

A broad concern within the State's comments is that salt dissolution, as a process, is related to understanding the long-term performance of the WCS site. There is also concern that the features that might result from subsidence after dissolution of Permian bedded salt will affect the performance of the site. The broad thrust of this report is to address these comments and requests for information and analysis to supplement the information in the application.

Comments posit that gypsum-filled fractures in overlying redbeds form "only above or in close association with areas of salt dissolution and subsidence," and that the origin of these fractures and fillings needs to be evaluated. In addition, the pre-Cenozoic paleotopography on redbeds forms a ridge that is ascribed to dissolution of Permian halite, and the State requested discussion of various features (e.g., fractures, lineaments) that may be associated with subsidence after this dissolution. Some specific sections of this study address these items.

In the region of west Texas and southeastern New Mexico, two projects sponsored by the US Department of Energy have resulted in detailed studies of halite-bearing rocks, including the features, processes, and rates of dissolution. North of the WCS site, in the panhandle of Texas, Permian-age rocks were studied intensively through the early 1980s as one of the potential locations for disposing of radioactive waste from US commercial reactors. These studies effectively ended with the policy decision to focus on Yucca Mountain, Nevada, for this activity. West of the WCS site, in southeastern New Mexico, upper Permian rocks have been studied since the early 1970s in support of the Waste Isolation Pilot Plant (WIPP) to ascertain, among other things, the extent of halite distribution, dissolution features, and the likelihood of affecting isolation of transuranic waste over a regulatory period of 10,000 years. Since 1984, we have been personally involved in the details of mapping large-diameter shafts through these rocks, describing the sedimentary features in cores, examining surface features that result from near-surface dissolution, and evaluating the effects of halite deposition and dissolution on the rocks and their hydrologic properties. These studies form much of the background for evaluating the area around the WCS site for evidence of dissolution of halite-bearing formations.

Dissolution of Evaporites

Evaporite rocks, especially halite, are particularly soluble, and the processes and consequences of dissolution of halite need to be evaluated for projects such as disposal of radioactive waste. Short-term effects of solution such as surface collapse are most common where the soluble rocks are near the surface and water is readily available. Slower dissolution rates are more commonly associated with deeper processes and more gradual disturbance, including subsidence. At the WCS site, halite and other soluble evaporites are at depths of 1500 ft (~460 m) or more and are overlain by a thick section of redbeds. This would indicate that dissolution processes, if or when they occur, are more likely to be slow, with gradual effects. Some features in the vicinity of the WCS site, such as the “red-bed ridge,” have been inferred to be the consequence of dissolution (e.g., Lehman, 1996).

Approach

Three basic hydrologic models are first described that provide a framework for analyzing the processes and effects of dissolution of evaporites, especially halite. Examples from the Delaware Basin west of the WCS site are used to illustrate these basic models.

We obtained data from geophysical logs on the presence, thickness, structure, and lateral variations of halite in stratigraphic units underlying the WCS site and surrounding area. These data are presented in map, cross-section, and tabular forms. The information is then evaluated to determine if any features identified can be linked to dissolution processes and the hydrologic setting of such processes. We did not use the previous geophysical log data reported in the application. Instead, we generated new interpretations from the available geophysical logs to bring a fresh perspective to the discussion of possible dissolution of evaporites at WCS.

Specific features such as the redbed ridge are addressed with specific data after presenting the broader evaluation of dissolution at the WCS site and surrounding area. Comments by the State suggested gypsum-filled fractures are related to halite dissolution; we found no evidence of dissolution at the WCS site, and our evaluation of such gypsum does not support a dissolution origin of these features at this location (Appendix A).

EVAPORITE STRATIGRAPHY AT THE WCS SITE

The lowermost evaporite-bearing unit at the WCS site is the Ochoan Salado Formation (Figure 2). It unconformably overlies the Guadalupian Tansill Formation. About 85 to 90 percent of the Salado is halite with the remainder consisting of anhydrite, polyhalite and minor amounts of other potassium-bearing minerals (Jones et al., 1973). Beds of anhydrite and polyhalite alternate with thicker beds of halite throughout the Salado section. The Salado is only a few tens of feet of brecciated insoluble material at outcrops in the western part of the Delaware Basin. It thickens to nearly 2,000 ft in the depositional center of the eastern part of the Delaware Basin and thins to around 1,080 ft at the WCS site.

Individual sulfate and clastic beds within the Salado are traceable for large distances. These areally persistent units allow the Salado to be subdivided on a fine scale (Figure 2). A system of numbering anhydrite and polyhalite beds as markerbeds was introduced by geologists of the US Geological Survey (Jones et al., 1960). This markerbed system is used extensively by mining companies in the Carlsbad potash district and by researchers at the Waste Isolation Pilot Plant for smaller scale stratigraphic control (e.g., Holt and Powers, 1990a). Other informal stratigraphic units within the Salado include the Union Anhydrite and the Vaca Triste sandstone. Several areally persistent units within the lower Salado have also been named and include from the base upward the Fletcher Anhydrite Member, the La Huerta Siltstone Member, the Infra-Cowden

halite, and the Cowden Anhydrite Member (Lang, 1942). The lowermost units, the Fletcher and the La Huerta, are present only over the Capitan reef and shelf on the margin of the Delaware Basin west of the WCS site; they are not present within the Delaware Basin.

Salado halite sequences that formed as saline lagoons desiccated to salt-pans and eventually saline mudflats (Holt and Powers, 1990a, 1990b; Holt et al., 2006). Depositional thickness within the Salado varies as a result of syndepositional subsidence in localized depositional centers along the Capitan shelf and in the Delaware Basin.

The Rustler Formation conformably overlies the Salado and is characterized by a variable lithology consisting of interbedded sulfates, carbonates, clastics, and halite. The Rustler varies in thickness from tens of feet, where exposed and subjected to solution and erosion, to nearly 560 ft in the northeastern part of the Delaware Basin. At the WCS site the Rustler is approximately 230 ft. thick. The Rustler has been removed by erosion west of the WCS in the middle of the Delaware Basin.

Within the Delaware Basin, the Rustler is subdivided into five members (Figure 2) including the Los Medaños Member, the Culebra Dolomite Member, the Tamarisk Member, the Magenta Dolomite Member, and the Forty-niner Member (Lang, 1939, Vine, 1963, and Powers and Holt, 1999). Holt and Powers (1988) further subdivided the Rustler into a series of informal stratigraphic units including anhydrites A-1 through A-5, and mudstone/halite units M1/H1 through M4/H4 (Figure 2). All of these units are areally extensive and are present at the WCS site.

Like the Salado, the Rustler consists of depositional sequences which record flooding followed by desiccation (Holt and Powers, 1988; Powers and Holt, 1990). Rustler rocks record flooding to lagoonal environments followed by episodes of isolation and evaporation in halite

pan to mud flat environments. This sequence of depositional environments produced several desiccating upward sequences in the Rustler, typically consisting of clastic or carbonate rocks at the base, followed by sulfate, and ultimately mudstone that grades laterally to halite. Although the general factors influencing Rustler deposition are similar to the Salado, Rustler depositional sequences show more compositional and lateral variability, reflecting changes in the dynamics of the Delaware Basin and surrounding shelf area after Salado time.

EVAPORITE DISSOLUTION CONCEPTUAL MODELS

For dissolution to occur, solutes derived from evaporite minerals must be transported away from the evaporite rocks. This solute transport can occur by diffusion into essentially stagnant groundwater, advection in flowing groundwater, or a combination of both. Diffusion-dominated dissolution requires a concentration gradient and is typically a slow process. In some instances, however, dissolution due to diffusion can create high-permeability pathways that can be exploited by advecting groundwater. Most evaporite karst features (e.g., caves, collapse features, etc.) result from relatively rapid dissolution by flowing groundwater. This type of dissolution (advection-dominated dissolution) requires 1) a source of evaporite unsaturated fluids, 2) a hydraulic connection with evaporite rocks, and 3) a hydraulic gradient that drives groundwater flow. During advection-dominated dissolution, evaporite unsaturated groundwaters moving along higher permeability pathways contact and dissolve evaporite minerals. Dissolved salts are then carried with the groundwaters in the direction of the hydraulic gradient and discharged from the evaporite section.

In the following, we develop three conceptual models for dissolution that reflect end-member hydrologic systems capable of advection- or diffusion-dominated dissolution and provide examples of each from the Rustler and Salado Formations. These models differ in the source of

evaporite unsaturated groundwaters, the nature of the hydraulic connection, and the character of the hydraulic gradient driving groundwater flow and dissolution.

Dissolution in Shallow Hydrologic Systems

For the purposes of this study, we define shallow hydrologic systems as those that are capable of responding to recharge events or changes in the phreatic groundwater surface (Figure 3). In these systems, the primary source of evaporite unsaturated groundwater is recharge through the unsaturated zone to the phreatic surface. In arid regions, such as southeastern New Mexico and west Texas, precipitation events may lead to local perched aquifers capable of inducing fracture flow and dissolution within the vadose zone. In the absence of pumping or other groundwater sinks, the phreatic surface typically mimics the topography, and groundwater flows from topographically high to low areas. Evaporites along the groundwater flow path are dissolved at a rate proportional to the groundwater flux, and the resulting solutes are discharged from the local watershed or drainage basin in either groundwater or surface water. Salinity increases down gradient, and in slower-moving zones and depressions, brine aquifers can form.

Dissolution is most efficient where groundwater flow converges due to local topography and increases the local groundwater flux. This effect occurs along the up-dip edge of evaporite sequences where vertical flow due to recharge converges with horizontal flow. Several feedbacks accelerate dissolution. Headward subrosion causes subsidence and fracturing, forcing infiltration and groundwater flow to converge. Small dissolution embayments into the edge of undissolved evaporites causes collapse of overlying units, thereby increasing permeability and providing preferential groundwater flow paths. Where evaporites are isolated from unsaturated groundwaters by low permeability strata, slow dissolution may occur due to diffusion and slow advection of groundwaters. Evaporites buried below the elevation of the local (watershed or

drainage basin) groundwater discharge area are difficult to dissolve with flowing groundwater and dissolution is diffusion limited.

Diagnostic indicators for shallow dissolution include surficial karst (e.g., sinkholes, caves, karst valleys, etc.) and subsurface features including dissolution residues consisting of insoluble materials, cavernous porosity, breccias reflecting collapse and upward stoping.

A well-known example of active evaporite dissolution in a shallow hydrologic system exists is Nash Draw in southeastern New Mexico (Figure 4) (Lee, 1926; see review in Powers et al., 2006). Lee (1926) noted surface sinks, caves, and chaotic stratigraphic relationships in outcrops of the Rustler and recent sediments deposited within subsided or subsiding areas. Robinson and Lang (1938) described more of the relationships, and they discovered a brine-saturated zone along the axis of the draw within argillaceous beds on top of the Salado and beneath the Rustler. Along with later investigators, Robinson and Lang identified the argillaceous beds as a residue after dissolution of halite from the upper Salado. Vine (1963) had subsurface data available from potash and oil and gas exploration; he noted, however, the difficulty in piecing together complete stratigraphic relationships in the Rustler from shallow and exposed beds within Nash Draw because of the localized disruption from subsidence after dissolution of halite from the underlying Salado Formation. The stratigraphic relationships were clear by the time Bachman remapped Nash Draw (1981), and he provided more detailed information relating late Cenozoic to recent collapse and sedimentation within and around the draw. Powers and Holt (1993, 1999, 2000), Powers and Owsley (2003), and Powers et al. (2006) filled in more detail of the stratigraphic relationships and related dissolution features to surface and near-surface hydrologic processes. Thus Nash Draw can serve as an example of the characteristics of evaporite dissolution related to shallow hydrologic processes. A number of details have already been

described in Powers et al. (2006), and the essentials are abstracted here to illustrate our conceptual model for dissolution in shallow hydrologic systems.

Figure 3 can also be considered a generalized cross-section from the center of Nash Draw across the eastern margin. It illustrates the features found within Nash Draw and is consistent with the general hydrologic processes at work in Nash Draw. At Nash Draw, all stratigraphic units earlier than late Cenozoic dip to the east (right) at about 1º. Erosion from upgradient (northward) development of the ancestral Pecos River intersected halite-bearing rocks of the Salado, and tributaries incised the initial Nash Draw valley, also reaching the Salado by erosion or by infiltrating waters. The overlying Rustler here consists of siliciclastics, dolomites, and sulfates; Rustler halite units occur farther east (Holt and Powers, 1988; Powers and Holt, 2000). These non-halitic rocks responded variably to dissolution and permitted infiltration and lateral flow of brines and saline waters to the Pecos River. Within the center of Nash Draw, the surface topography has developed internal drainage. High salinity waters (called the "brine aquifer" at Nash Draw) characterize this zone. A thick section of dissolution residue (mainly clay) isolates Salado halite from the overlying brine aquifer and dissolution is diffusion limited along a very low concentration gradient.

The relationships along the eastern margin of Nash Draw show the hydrologic system, dominated by gravity and infiltration, dissolves halite along the updip halite beds. We acknowledge that the hydraulic system in the beds overlying the halite is complex, with vadose zone processes predominating. Nevertheless, the system has had recharge, and low-salinity waters move downward to the top of the halite-bearing units or a saturated zone overlying the halite-bearing beds. Flow is focused toward the low-angle slope of the halite, and here dissolution is advection dominated.

At the surface, a retreating escarpment (Livingston Ridge) has developed that shows local subsidence in the last 0.5 Ma because a pedogenic calcrete ("Mescalero caliche") of that age drapes the surface (Figure 5). The Livingston Ridge escarpment directly overlies dramatic changes in the surface on the "top of Salado halite" (Figure 6). Subsidence creates fractures parallel to the escarpment that can enhance vertical infiltration (Figure 7).

Dissolution in Deep Hydrologic Systems

It is difficult to establish a hydraulic gradient from deep aquifers toward deeply buried bedded halite rocks. Pore pressures in deeply buried halite (>1,000 ft.) are likely at or very close to lithostatic pressure (Beauheim and Roberts, 2002; Roberts et al., 1999), and drillstem tests in Salado halite in the Delaware Basin show pressure buildups indicative of brine levels above the ground surface (Mercer, 1987). This is not surprising. Halite is capable of creep deformation and plastic behavior, and pore fluids bear much of the lithostatic pressure. As a consequence, hydraulic gradients and fluid flow directions are outward from the halite toward overlying and underlying rocks.

In the context of this paper, deep hydrologic systems (depths of 1,000+ ft.) include those aquifers which underlie evaporite sequences. The areal extent of these hydrologic systems is greater than that of the overlying evaporites, and natural hydraulic gradients change slowly, over near geologic time scales, in response to changes in recharge rates and areas. The dissolution potential of groundwater in deeper aquifers is reduced relative to shallow systems due to long periods of time for rock – water interaction and increased salinities. If low permeability beds separate the aquifer system from the evaporite section, dissolution is diffusion-limited and occurs due to concentration gradients. Fractures or other high permeability features in the low permeability beds do not necessarily lead to circulation of groundwater and evaporite

dissolution, as advection-dominated dissolution requires a hydraulic gradient that drives unsaturated fluid from the aquifer into the evaporite section. Fracturing can, however, lead to a process known as “brine density flow” (e.g., Anderson and Kirkland, 1980; Wood et al., 1982). In density flow, static fluids in contact with halite dissolve halite, increasing the fluid density. When the fluid density is sufficiently high to create a pressure gradient downward into the underlying aquifer, the dense brine moves downward along the fractures and is replaced by halite-unsaturated fluid. This process has been shown to have limited effectiveness for halite dissolution over geologic time scales (Wood et al., 1982). Large-scale dissolution features (e.g., breccia pipes and sinks) are created by advection-dominated transport processes and require significant circulation of halite unsaturated groundwater.

We believe that special circumstances are required to establish groundwater circulation at the base of a halite sequence (Figure 8). High permeability pathways must exist and be of sufficient size to allow fluids to flow past the halite and discharge back into the aquifer. For efficient dissolution, fluid pressures at the dissolution site must remain less than up-gradient fluid pressures within the aquifer and greater than down-gradient aquifer pressures. High permeability pathways capable of supporting advection-dominated dissolution can originate from a pathological combination of fractures in the rocks separating the aquifer and halite or from collapse of cavernous porosity within the aquifer or in beds between the aquifer and the overlying halites. Because the permeability of the intact halite is so low, pressure and fluid flow from the aquifer can overcome the hydraulic system within the halite and circulate in the fractures, dissolving halite and causing further collapse.

The process might be described as “opportunistic” because it will be focused by features such as collapse and fracturing. For deep systems, there is little potential for general dissolution along

the basal surface of a halite bed without fracturing the beds underlying halite, including possible collapse. The hydrostatic pressure within the halite is greater than within the underlying aquifer. Diffusion across intervening beds and slow flow within the aquifer limits the potential to dissolve halite along the flow path.

Dissolution from deep aquifers results in features such as large surface sinks (San Simon sink and swale in southeastern New Mexico) and collapse chimneys (aka “breccia pipes”). Solution collapse chimneys are known from southeastern New Mexico as well as other locations such as Saskatchewan (e.g., Christiansen, 1971). Similar processes likely produce modern collapses around poorly plugged or cemented drillholes that have connected underlying aquifers through halite (Baumgardner et al, 1980; Johnson, 1993; Powers, 2003); the drillhole likely circumvents the need for fracturing and collapse to allow access to the halite beds.

The Delaware Basin provides specific examples of such collapse. Along the northern edge, several collapse chimneys have formed (Figure 9), in response to collapse and upward stoping from the underlying Permian Capitan reef (Anderson, 1978; Bachman, 1980; Snyder and Gard, 1982; see review by Powers, 1996). San Simon sink and swale are also located along the margin of the Delaware Basin, overlying the Capitan reef (Bachman, 1980). Recent collapses (Wink sinks, Jal sink) attributed to drillholes (Baumgardner et al, 1980; Johnson, 1993; Powers, 2003) were associated with drillholes that penetrated the Capitan reef, a major source of water in the area. Bachman (1980) proposed that collapse in the natural collapse chimneys along the northern margin of the Delaware Basin occurred after the Pecos River eroded into the Capitan reef near Carlsbad. Spring flow decreased fluid pressure within the Capitan and the Capitan carbonates and overlying rocks collapsed. Circulation clearly has been limited; coring these collapse features recovered halite, and there has been no interpretable collapse since about 0.5 Ma

(Snyder and Gard, 1982). San Simon sink and swale continue to collapse, however, with historic drops and annular subsidence fractures (Figure 10).

Although Hill (1993, 2003) has suggested that other depressions or “sinks” within the northern Delaware Basin are collapse chimneys, there are no surface fractures or drillhole evidence indicating that they formed in such a fashion.

Stratabound Dissolution

Stratabound dissolution occurs when an aquifer is present within the evaporite sequence, and the basic characteristics of hydrologic systems that may develop stratabound dissolution can have characteristics in common with both shallow and deep hydrologic systems. The halite unit is bedded and is also overlain and underlain by less soluble, generally low permeability units. Here we assume an aquifer underlying the halite bed that can remove solutes by advection (Figure 11). Without significant fracturing and collapse of the aquifer or the overlying low-permeability unit or vertical recharge in the system (flow lines would be focused along the depositional edge of the halite), diffusion dominates the delivery system from the halite bed to the aquifer. Dissolution occurs along the direction of flow in the aquifer, and the width of the dissolution zone will be a function of the flow velocity and diffusion coefficient. It will be a relatively narrow zone for slower fluid velocity because diffusion can deliver more solutes before being removed from a location. The characteristics of this system should include laterally thinning beds, solution residue/breccia, and collapse in the overlying units.

The Rustler Formation in the vicinity of the WIPP site in southeastern New Mexico was believed at one time to demonstrate these relationships and this process. Extended and detailed study of the Rustler over the past 20 years, however, indicates that laterally thinning halite beds and equivalent mudstones are by and large the results of depositional processes, including some

syndepositional dissolution (e.g., Holt and Powers, 1984, 1986, 1988; 1990; Powers and Holt, 1990, 2000). There are local areas along depositional margins of halite, however, where breccias and lateral relationships indicate limited dissolution of such halite (Beauheim and Holt, 1990; Mercer et al., 1998; Holt, 1997). Cores from drillholes at the H-19 complex near WIPP show such brecciation and expected effects of post-depositional dissolution of halite, illustrating stratabound dissolution (Figure 12).

GEOLOGIC OBSERVATIONS AT THE WCS SITE

We conducted a geophysical log-based study to evaluate the presence of subsurface halite dissolution at the WCS site. The subsurface geologic conditions at the site were determined by interpreting 67 geophysical logs in the vicinity of the site (Figure 13) and a smaller suite of logs west of the study area. The evaporite stratigraphy present at the WCS site is equivalent to much of that present in the WIPP site area. We began by correlating geophysical logs with shaft and core data from the WIPP area and extending these correlations east to the WCS site. We identified all major units within the Rustler and focused on a suite of markerbeds and other stratigraphic units within the Salado.

We recognize differences between the data we present and the more limited data presented in the application, but these differences are not generally great. One example involves drillhole API#25-12112 where previous workers placed the base of Salado at the bottom of the borehole casing where natural gamma increases. We recognize the effects of the casing and place the base of the Salado at a large natural gamma increase associated with the top of the Tansill. We also found that the log quality through the Salado was too poor to interpret for three other logs (API#25-09969, API#25-12114, API#3-05906).

Because some sedimentary information is not available from geophysical logs (e.g., brecciation, etc), we focused on identifying broad-scale features associated with collapse and upward stoping, including abrupt thinning of the evaporite section with accompanying thickening of overlying rocks, complicated contours of elevation on stratigraphic units or of unit thicknesses, or complete stratigraphic disruption. To aid our interpretation of dissolution, we constructed structure contour maps on the tops of the Tansill, Salado, and Rustler Formations (Figures 14-16); isopach maps of the top of Tansill to Cowden interval, the Salado, and the Rustler (Figures 17-19; and east to west (Figure 20) and north to south (Figure 21) stratigraphic sections and cross-sections (Figures 22) across the WCS site area.

Structure contour maps show several important structures in the WCS area (Figures 14-16). A structural high exists in the western most part of the site area and is likely the eastern limb of a north-northwest trending anticline. Relief across this feature ranges from ~ 400 ft on the top of the Tansill (Figure 14) to ~ 450 on the top of the Salado and Rustler (Figures 15 and 16), and this increase reflects thickening of the Salado and, to a lesser extent, the Rustler. A southeastward plunging syncline and anticline pair occur along the western margin and center of the WCS site. The anticline becomes more pronounced upward and is well defined on the top of the Rustler and appears to coincide with the "Redbed Ridge" at the WCS site. The northern and central portion of the study area shows a southeasterly dip less than 1°. A structural high is present in the northeastern part of the study area, and a broad syncline occurs in the southeastern corner of the study area. The structure contour data and maps reveal no complications (e.g., closed depressions, complicated contours, or stratigraphic disruption) that are attributable to dissolution and collapse.

A series of isopach maps (Figures 17-19), a west to east stratigraphic section (Figure 20), and a south to north stratigraphic section (Figure 21) were constructed to evaluate rapid thinning or thickening due to dissolution and collapse and to illustrate important stratigraphic relationships. Salado and Rustler stratigraphic units are easily identifiable in most geophysical logs and readily traceable from the Delaware Basin to the WCS site area. A stratigraphic sections hung on the base of the Cowden Anhydrite illustrates the remarkable continuity of these units in the WCS area (Figure 20). Elevation changes along these stratigraphic sections at small vertical exaggerations illustrate the limited structural deformation (Figure 22). Geophysical log cross-sections (Figures 23 and 24) from the application (originally designated A-A' and B-B' and here called C-C' and D-D', respectively) have been re-interpreted and included here for comparison. They reveal that there are generally only minor differences between our interpretation of stratigraphic contacts within the evaporites and the original stratigraphic picks.

The lowermost evaporite-bearing zone at the WCS site is in the lower Salado and consists of the Infra-Cowden halite and stratigraphic equivalents to the La Huerta Siltstone and Fletcher Anhydrite. An isopach of this zone reveals a thickness change of only 61 ft. within the study area (Figure 17). The average thickness is 279 ft. with a standard deviation of only 14.8 ft. The interval thickens to the west, suggesting that early Salado depositional patterns were influenced by the Delaware Basin. The lower Salado shows no stratigraphic disruption or thinning that could be attributed to dissolution from underlying aquifers.

With the exception of two boreholes (API #3-31589 and API #3-03756) located along the easternmost edge of the study area, the Salado shows remarkably regular thickness variations (Figure 18). The Salado is generally thickest in the southwestern portion of the study area and thins to the northeast. Most thickness variations in the Salado occur within an interval bounded

by the Vaca Triste Sandstone and the Cowden Anhydrite (Figures 20 and 21), and the upper and lower Salado are remarkably uniform across the site area.

The Rustler contains the uppermost halite unit present at the site (H-3 from Holt and Powers, 1988). H-3 shows little thickness variation across the site area, and appears to thicken in the easternmost part of the study area (Figures 20 and 21). The Rustler is thickest in the area south of the site and generally thins to the north and northeast (Figures 16 and 21). Marked thinning in the upper Salado with accompanying thickening of the Rustler is observed in boreholes 3-31589 and 3-03756 (over 11 mi. from the WCS site) along the eastern margin of the study area.

EVALUATION OF DISSOLUTION MODELS AT THE WCS SITE

In this section, we evaluate our observations at WCS site with respect to each of our conceptual models for dissolution: 1) dissolution from above in a shallow hydrologic system, 2) dissolution from below in a deep hydrologic system, and 3) stratabound dissolution from within the evaporite sequence.

Dissolution in Shallow Hydrologic Systems

There are several shallow aquifers present above the evaporites in the WCS site area. The two aquifers closest to the evaporite section are present in sandstones of the lower Dockum Group. The lowermost aquifer is about 250 ft. thick and occurs in the Santa Rosa Formation. The uppermost aquifer is 100 ft. thick and occurs in the Trujillo Formation roughly 850 feet above the top of the Rustler. The evaporites of the Rustler are isolated from the Santa Rosa aquifer by ~180 to 200 ft. of the Dewey Lake Redbeds, which consist of low permeability, anhydrite- and gypsum-cemented mudstones, siltstones, and very fine sandstones in the Delaware Basin.

Both lower Dockum aquifers have low salinities, less than 5,000 mg/L total dissolved solids (Cook-Joyce and Intera, 2006), indicating that they are not in contact with Rustler halites. Active recharge to these aquifers is believed to be very limited in the site area, due to low permeability in the overlying rocks, with the last appreciable recharge occurring 15,000 to 35,000 years ago prior to the integration of the Pecos River drainage (Dutton, 1995; Dutton and Simpkins, 1986).

Structure contour maps on the tops of the Salado and Rustler (Figures 15 and 16) show no closed depressions or stratigraphic disruptions that could be attributed to large-scale dissolution and collapse of the uppermost evaporites. With the possible exception of two boreholes in the eastern most part of the study area, isopach maps also show regular thickness changes attributable to depositional processes. The uppermost halite unit (the H-3 interval of the Rustler) shows a relatively constant thickness over the site area and thickens slightly to the east (Figure 20).

Abrupt thinning in the upper Salado with accompanying thickening of the Rustler has been observed in boreholes 3-31589 and 3-03756 along the eastern margin of the study area (Figures 18 and 19). The Salado is 60 to 90 ft. thinner than in nearby boreholes. Thinning appears to occur in the uppermost Salado section above Markerbed 103, where the gamma log suggests that the halite section has been reduced and is more argillaceous. At this location, the Rustler is between 50 and 60 ft. thicker than in surrounding boreholes. The Los Medaños Member of the Rustler is unusually thin at this location, and the thickness increase appears to be in the Tamarisk Member of the Rustler. While we can pick the top of the H-3 interval based on the gamma log signature, we cannot determine weather or not halite is present in the H-3 interval at this location

because no density, caliper, or acoustic logs are available. Logs of nearby boreholes clearly show evidence of a thick section of halite in the H-3 interval (API #3-06707 and API #3-07838).

Without extending the study to the east, we are unable to interpret the origin of this feature. It may reflect depositional thinning in the upper Salado and depositional thickening of the Rustler, syndepositional dissolution of upper Salado and lower Rustler halites followed by accumulation of a thick sequence of halite in the H-3 interval, or post-depositional dissolution of halite within the Rustler and Salado with associated collapse and upward stoping lengthening the Rustler section. If this feature is related to dissolution, it likely formed prior to the development of the Pecos River when the lower Dockum aquifer received more recharge. Nevertheless, the feature along this edge of the area studied is distant from the site and doesn't appear to be an active zone posing a threat to the WCS site.

Dissolution in Deep Hydrologic Systems

Within Andrews County Texas, the closest aquifer underlying the Salado is in the Yates Formation. Water quality samples taken from the Yates at depths below 3,000 ft. reveal that Yates waters are brines, with total dissolved solids ranging from 80,000 to 225,000 mg/L (TWDB, 1972), that have the capacity to dissolve halite. Salado halite is separated from these aquifers by several hundred feet of intervening Yates and Tansill sediments and the Fletcher Anhydrite. While these formations are likely fractured, it is unlikely that these formations have interconnected high permeability pathways capable of supporting advection-dominated dissolution from the Yates aquifer.

We also find no evidence of dissolution of halite from aquifers below at the WCS site. The lower Salado does not show abrupt thinning, and overlying units are stratigraphically intact (Figures 15, 17, 20, and 21). The interval between the base of the Cowden Anhydrite and the top

of the Tansill shows little variation over the 200 mi^2 study area. A thicker section to the west is consistent with depositional trends and indicates that lower Salado deposition was influenced by the Delaware Basin. Because the lower Salado is deeply buried at the WCS site, it is likely that pore pressures in Salado halite are at, or close to, lithostatic pressure and that the hydraulic gradient is downward from the Salado into the Yates. If dissolution of halite is occurring, it is diffusion-limited and too slow to generate observable features.

Stratabound Dissolution

Stratabound dissolution requires the presence of an aquifer within the evaporite sequence, and we find no evidence of an aquifer capable of supporting stratabound dissolution at the WCS site. The Salado does not contain aquifers within the Delaware Basin (Beauheim and Holt, 1990), and we find no evidence of Salado water-bearing zones at the WCS. The Magenta and Culebra Dolomite Members of the Rustler are aquifers in the vicinity of the WIPP site and in the western portion of the Delaware Basin (Beauheim and Holt, 1990). However, their character changes in the eastern part of the basin and on the eastern shelf.

The Magenta and Culebra thin from ~ 25 ft in the Delaware Basin to less than 5 ft at the WCS site. Based on density and acoustic log signatures, the Magenta at the WCS site consists of dolomitic anhydrite, and its porosity and permeability are likely equivalent to anhydrite. Geophysical logs indicate that the Culebra becomes increasingly thinner and more argillaceous eastward along the platform. At the WCS site, no dolomite is recognizable in the Culebra interval. Both of these units are bounded by or underlain by Rustler halite beds, conditions which frequently lead to the presence of halite cements and very low permeability in these rocks elsewhere (e.g., Holt, 1997; Holt et al., 2005; and Powers et al., 2006). We do not see the local features of stratabound dissolution in the geophysical logs across the WCS site area, and we do

not consider either the Magenta or Culebra to be viable aquifers capable of supporting stratabound dissolution at the WCS site.

DISSOLUTION AND THE REDBED RIDGE

The application submitted by WCS (2004) recognized that the paleo-surface of the pre-Cenozoic redbeds at the site and vicinity displayed elevation changes (“structure”) that some had suggested or inferred was due to dissolution of underlying Permian halite (e.g., Nicholson and Clebsch, 1961, p. 43; Lehman, 1996). The State of Texas requested that WCS further evaluate this inference. A part of this structure has a northwest-southeast trend and passes generally under the WCS site. The earlier sections of this report show that some similar structure pervades units underlying the evaporites as well as stratigraphic contacts within and overlying the evaporites (e.g., Figures 14-16). With the additional evidence that halite of these units at and around the WCS site has not been thinned in ways consistent with dissolution or the structure of the paleosurface, there is no reason to interpret the “structure” as a consequence of dissolution.

To further examine this proposition at another location, we chose to examine the upper evaporite section (Rustler Formation) along the Mescalero Ridge (Figure 25), an escarpment northwest of the WCS site area, where drillhole control is dense and the redbed ridge has been defined in the past (e.g., Nicholson and Clebsch, 1961; Lehman, 1996).

A few drillhole geophysical logs (Figure 26) at this ancillary study site illustrate the relationships between Rustler stratigraphic units that are similar to that at WCS. There is limited salt in the uppermost member (Forty-niner) of the Rustler and thicker halite within the middle member (Tamarisk). Halite is also present in the lower part of the Rustler. The geophysical log signatures of the top of Rustler and top of Salado are straightforward to interpret throughout this small study area crossing the “redbed ridge.”

To illustrate the structure and thickness relationships, we mapped the elevation of the top of the Salado (Figure 27; Appendix C), the top of the Rustler (Figure 28), and the thickness of the Rustler (Figure 29). The topography of the escarpment and area are included for reference, as is the general trend of the "redbed ridge" as shown by Lehman (1996).

The evidence is straightforward that both the top of Salado and top of Rustler show some structure broadly similar to that of the redbed ridge, with a flank to the southwest parallel to the Mescalero Ridge escarpment and a slight flank to the northeast. These structure contours show rising elevations to the northwest, similar to the redbed ridge. The top of both formations show some closure to the northeast, in contrast to the contours shown by Lehman (1996).

The thickness of the Rustler, however, contrasts singularly with the elevation contours. The Rustler is generally thinning to the north-northeast across the area with structure, showing no changes that parallel the structure contours that would be clear if dissolution of upper Permian evaporites were the cause of the trend and general southeast plunge of the redbed ridge. This is completely consistent with the evidence from the WCS site and surroundings that indicate no relationship between evaporite bed thicknesses and the elevation of the redbed ridge.

More abrupt elevation changes in the southwest corner of the map area are likely related to general fault trends in this area (e.g., Holt and Powers, 1988; Corbet and Knupp, 1998), but the our data have not been extended to clarify this.

Fallin (1989) relates the topography on the redbed paleosurface to erosion and deposition prior to sedimentation of the Ogallala Formation. There may be some control from deep-seated and older deformation. Nevertheless, we note that none of the references cited as a source of the notion that dissolution of halite created the redbed ridge provided any direct evidence of this process in the form of thinned beds or textures from cores.

As a further note, a variety of surficial linear features, or features along lineaments, have been suggested as indicators of dissolution at depth. These are parallel, linear features tens of miles in length. There is no example known to us of control of such linear features by dissolution alone, as the margins of areas of dissolution are much more irregular on that scale.

DISSOLUTION AND MONUMENT DRAW, NEW MEXICO

Nicholson and Clebsch (1961, p. 44-45) reviewed the limited shallow data from drillholes across Monument Draw, New Mexico, in the immediate vicinity of the carbon black plant (section 3, T21S, R37E) (Figure 30). The redbed surface under the draw is shown to be depressed in their data, with fill of Quaternary sediments they interpreted to be derived from erosion of the Ogallala. Although Nicholson and Clebsch inferred that the surface on the redbeds resembled an erosional feature, they also considered that such a depression could have a dissolution origin. They also noted that dissolution features are not normally as linear as the trends of Monument Draw, NM. We examined drillhole geophysical logs of the uppermost halite-bearing formation, the Rustler, in the vicinity of the carbon black plant to resolve this modest ambiguity.

Geophysical logs from 49 wells within and across Monument Draw in this area were interpreted to obtain data on the elevation of the top of the Salado (Figure 31; Appendix D), top of the Rustler (Figure 32), and the thickness of the Rustler (Figure 33). The majority of the logs are from drillholes in section 3 and immediate adjacent sections; data from a few logs to the northeast and southwest were added to provide some extra control on contour trends. Dissolving halite from the Rustler or Salado should be revealed as structural features and as localized changes in thickness; thus these maps were developed to try to reveal such features along this section of Monument Draw, NM.

The top of the Salado (Figure 31) dips generally to the east and northeast across the area of Monument Draw. With the limited data available presented here, there is some indication that the Salado "structure" does two things in the vicinity of the draw: 1) the slope of the surface increases east of the draw and 2) there is some indication that the contours bend similar to the bend in the trend of Monument Draw. There is nothing particular to indicate that this structure is controlled by dissolution (see next paragraph) of the halite. Lower elevations on the top of the Salado to the northwest along the draw are opposite the gradient of the draw itself, indicating there is limited relationship between the structure contours and the draw position and gradient.

The elevation of the top of the Rustler (Figure 32) parallels the top of the Salado in most respects, including the increased gradient to the east and northeast and a possible bend in the contours similar to the bend in the draw. There are some lower elevations to the northwest, similar to the elevations on the Salado.

The gradient of Monument Draw is to the southeast and south in this area. The gradient parallels structure contour lines of these formations that are more than 1000 ft below the ground surface. The draw does not trend along the downslope gradient of the tops of the formations, as might be expected if there is a fairly direct relationship between draw and structure. Both contoured surfaces also display lower areas upstream on this stretch of Monument Draw, which is also not consistent with the notion that the draw is related to structure developed in response to dissolution.

As found in other areas in this study, the Rustler includes stratigraphic intervals with halite and is the uppermost halite-bearing formation. A possible, but not unique, indicator of dissolution control of Monument Draw would be thinning of the Rustler parallel to the draw, with geophysical logs displaying thinner halite at that point. Uncontoured data (Figure 33) of

Rustler thickness shows a general trend of thinning from west to east, consistent with broader data not included here. There is no consistent difference in thickness relatable to Monument Draw, NM.

A short cross-section of geophysical logs across Monument Draw (Figure 34) also shows no change in thickness that is relatable to Monument Draw. One of the differences in these logs regionally is that some of the carbonate and anhydrite units in the lower middle part of the Rustler disappear laterally because of differences in the depositional environment, similar to findings for the vicinity of the WCS site. Highly soluble halite beds persist below and above this zone, showing that these are depositional changes rather than loss of units by dissolution.

Regional controls on the location, form, and gradient of Monument Draw, NM, in this study area are not revealed here, but the remnant suggestion that dissolution of halite has a role can be laid to rest.

SUMMARY

The objective of this report is to address specific concerns raised by the State of Texas related to the extent of dissolution and relationship to surficial features at the WCS site and the potential impact of dissolution of Permian salt.

We first developed three conceptual models for dissolution based on end-member hydrologic systems that enable advection-dominated dissolution and provide examples of each within the same rocks present at the WCS site (the Rustler and Salado Formations). Each model is constructed with special emphasis on the source of evaporite unsaturated fluids, the hydraulic connection with evaporite rocks, and the hydraulic gradient that drives groundwater flow. These models include: 1) dissolution from above in a shallow hydrologic system, 2) dissolution from

below in a deep hydrologic system, and 3) stratabound dissolution from within the evaporite sequence.

We then conducted a geophysical log study to evaluate the presence of subsurface halite dissolution at the WCS site. We began by correlating shaft and core logs with geophysical logs in the Delaware Basin and extending these correlations eastward to the WCS site. We found remarkable correlation between Rustler and Salado units present at the WCS site and those 20–50 miles to the west. We focused on identifying broad-scale features associated with collapse and upward stoping, including abrupt thinning of the evaporite section with accompanying thickening of overlying rocks, complicated contours of elevation on stratigraphic units or of unit thicknesses, or complete stratigraphic disruption.

We find no evidence of dissolution or conditions suitable for any of the three conceptual models for dissolution across most of the WCS site area. Structure contour maps revealed no features attributable to dissolution and showed a southeast plunging anticline that appears coincident with the redbed ridge at the WCS site. Isopach maps revealed depositionally controlled thickness variations across most of the WCS area. One possible exception was identified. In the easternmost portion of the study area, geophysical logs from a single borehole show a thick Rustler section underlain by a thinner Salado section. Because we have no geophysical log data east of this occurrence, we are unable to provide a definitive interpretation of this feature. We offer three possibilities to explain this feature. It may 1) reflect depositional thinning in the upper Salado and depositional thickening of the Rustler, 2) syndepositional dissolution of upper Salado and lower Rustler halite followed by accumulation of a thick sequence of halite in the H-3 interval, or 3) post-depositional dissolution of halite within the Rustler and Salado with associated collapse and upward stoping lengthening the Rustler section.

If dissolution is responsible for this feature, it likely formed prior to the integration of the Pecos River when the lower Dockum aquifer received much more recharge. There is no evidence of an active process at this location that would affect the WCS site.

The Rustler Formation across a segment of the Mescalero Ridge in New Mexico shows some structure paralleling the surface on redbeds of the “redbed ridge.” The Rustler thins to the northeast, not consistent with the structure, and halite beds are not thinned to create the overlying structure. The redbed ridge is not related to dissolution of the uppermost halite-bearing bed. A similar study of a short section of Monument Draw in New Mexico also shows no thinned halite or dissolution control of the location or gradient of the draw.

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FIGURES

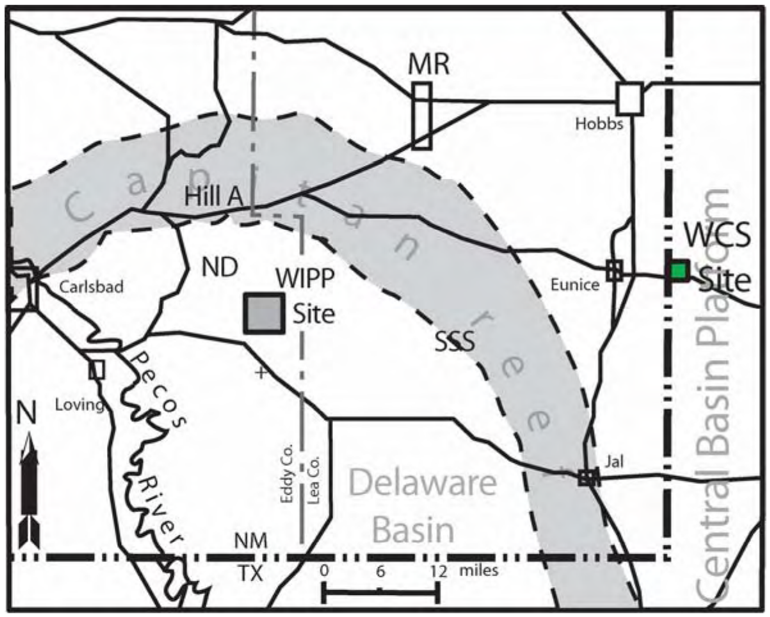

Figure 1 – Location of WCS site. Large structural elements include the Central Basin Platform, underlying the WCS site, and the Delaware Basin, where some examples regarding dissolution have been developed. ND notes the general location of Nash Draw. SSS shows the general location of San Simon sink and swale. Hill A is at the location of one of the collapse chimneys described later. The small rectangle marked MR is the central area examined across the Mescalero Ridge to understand the origin of the underlying "redbed ridge."

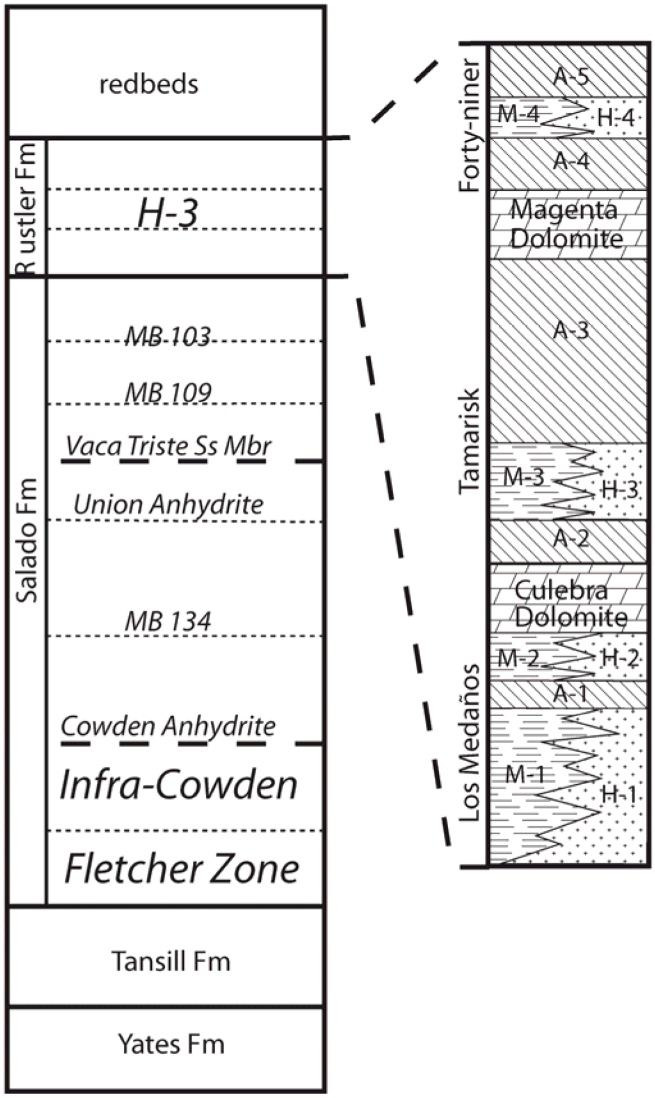

Figure 2 – Stratigraphy of the evaporite-bearing formations above the Tansill Formation at WCS. Thin sulfate beds within the Salado are continuous over very large areas and have been numbered (Jones et al., 1960) as marker beds (MB) for convenient reference. Three MB have been used as major reference points through the WCS site area. Other formal and informal units found within or adjacent to the Delaware Basin are correlated within the site area to show lateral changes. The Rustler Formation has been divided into five formal members and a number of informal, but useful, units by Holt and Powers (1988), as shown on the right side.

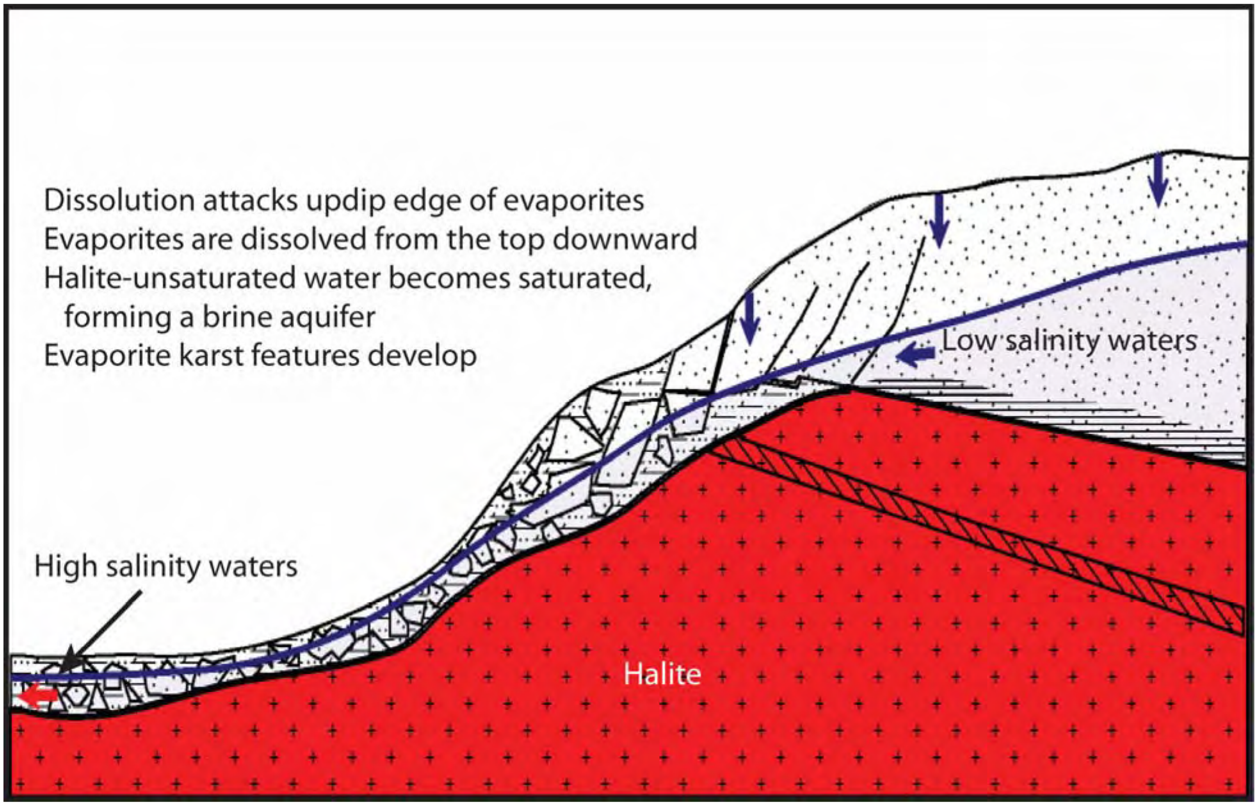

Figure 3 –Conceptual model 1 – dissolution in shallow hydrologic systems. This model shows infiltration of meteoric water, movement downgradient, and dissolution of halite from the top downward. Evaporite karst features can form at the surface and in shallow areas in response to dissolution of halite and other soluble rocks by the surface to shallow hydrologic system. This conceptual model is generalized from features and processes at Nash Draw (Figures 4 – 7) and draws on information from Powers et al. (2006a) as well as other sources.

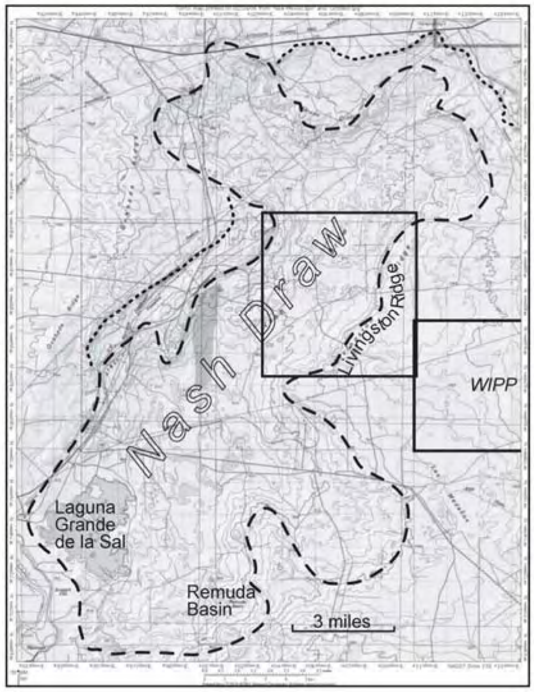

Figure 4 – Nash Draw. The draw is a closed topographic depression that developed from erosion and solution (Lee, 1926). Livingston Ridge, the eastern margin of Nash Draw, reveals the basic processes of attacking halite in the shallow subsurface from meteoric infiltration. Figures 5, 6, and 7 come from the area of the rectangle along Livingston Ridge.

Figure 5 – Mescalero caliche drapes the Livingston Ridge escarpment in response to local subsidence since the caliche formed beginning ~ 0.5 Ma.

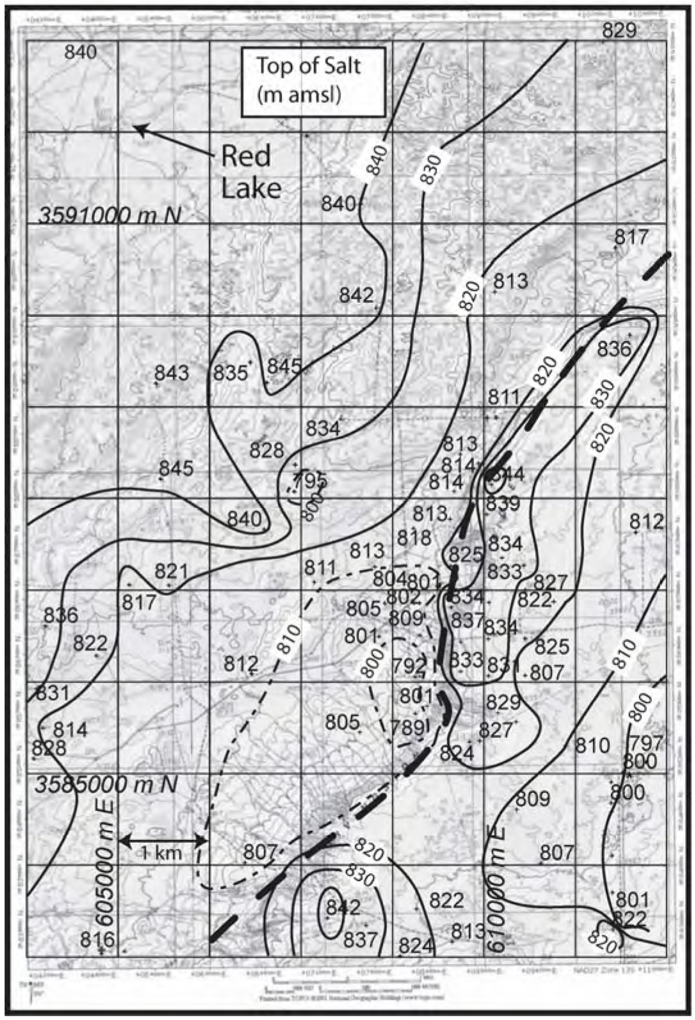

Figure 6 – Elevation on top of Salado halite underlying Livingston Ridge (see location Figure 4). Contour elevations are in meters above mean sea level (modified from figure 4 of Powers et al., 2006a).

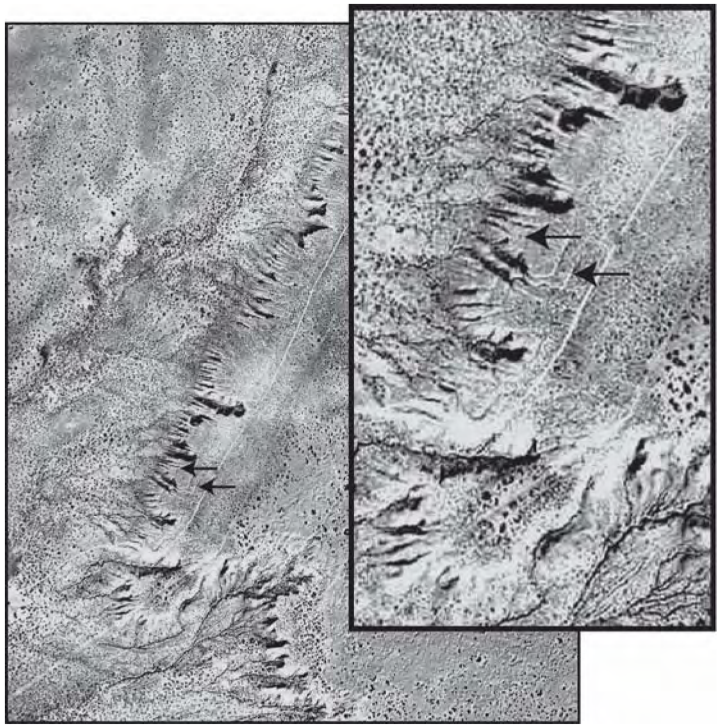

Figure 7 – An aerial photo (dated 10/24/1957) showing fractures (arrows) paralleling the Livingston Ridge escarpment along Nash Draw in response to subsidence over a dissolution margin. This photo covers the ridge in the right center portion of Figure 6 and predates the drilling used as a basis for Figure 6.

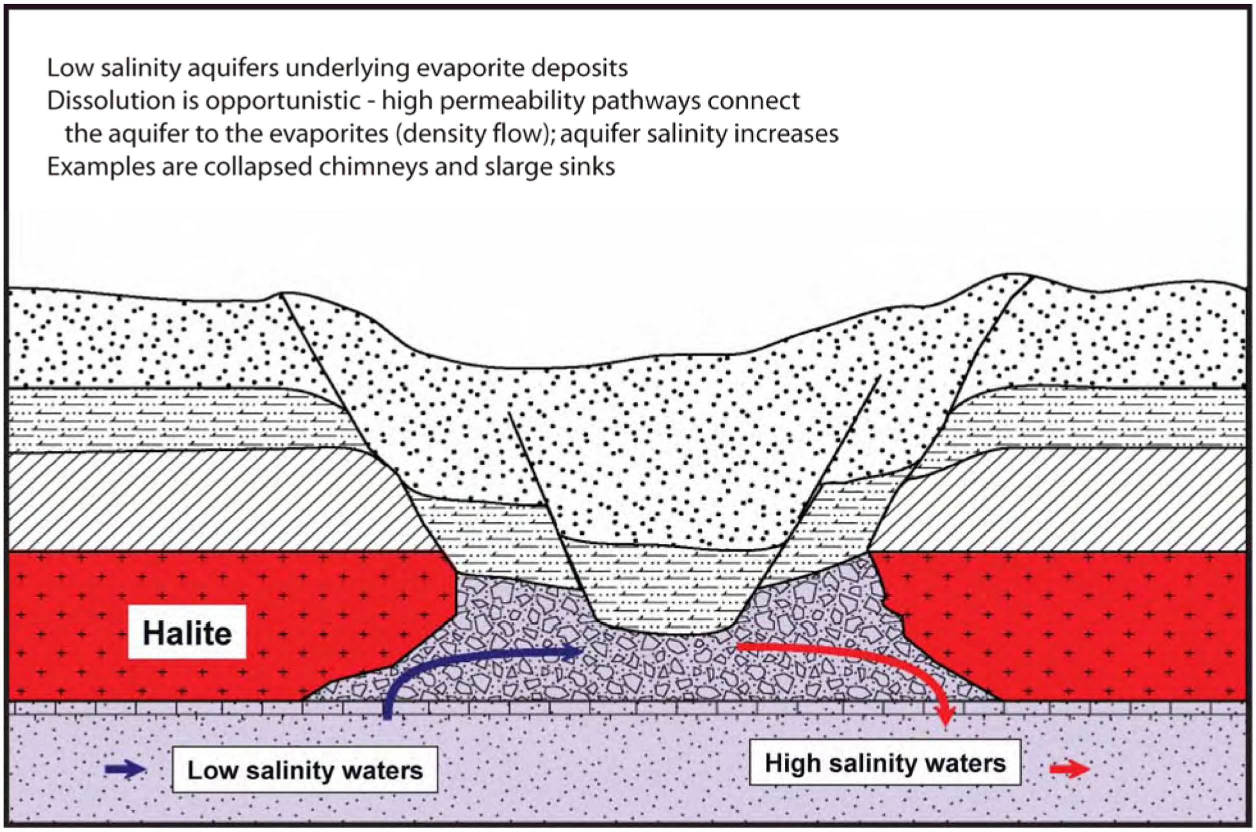

Figure 8 – Conceptual model 2 – deep dissolution. These features can range from those with width or circumference less than depth (e.g. collapse chimneys or "breccia pipes" – Figure 9) to those with greater width than depth (e.g., San Simon sink and swale – Figure 10).

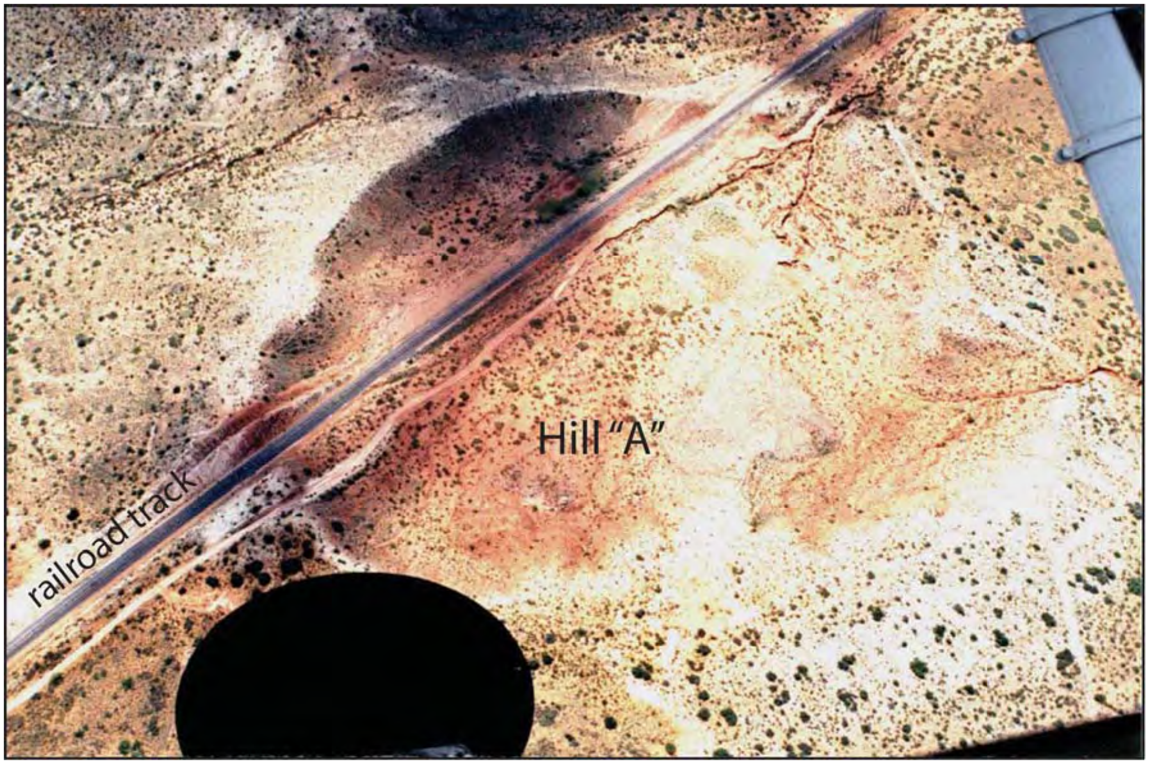

Figure 9 – Aerial photograph of collapse chimney ("breccia pipe") called Hill A along the northern Delaware Basin margin above the Capitan reef (see Figure 1). The diameter of these features is generally ~ 1000 ft, and the depth of the collapse > 2000 ft (Snyder and Gard, 1982; Bachman, 1980). Low angle photograph by Dennis Powers, 2004.

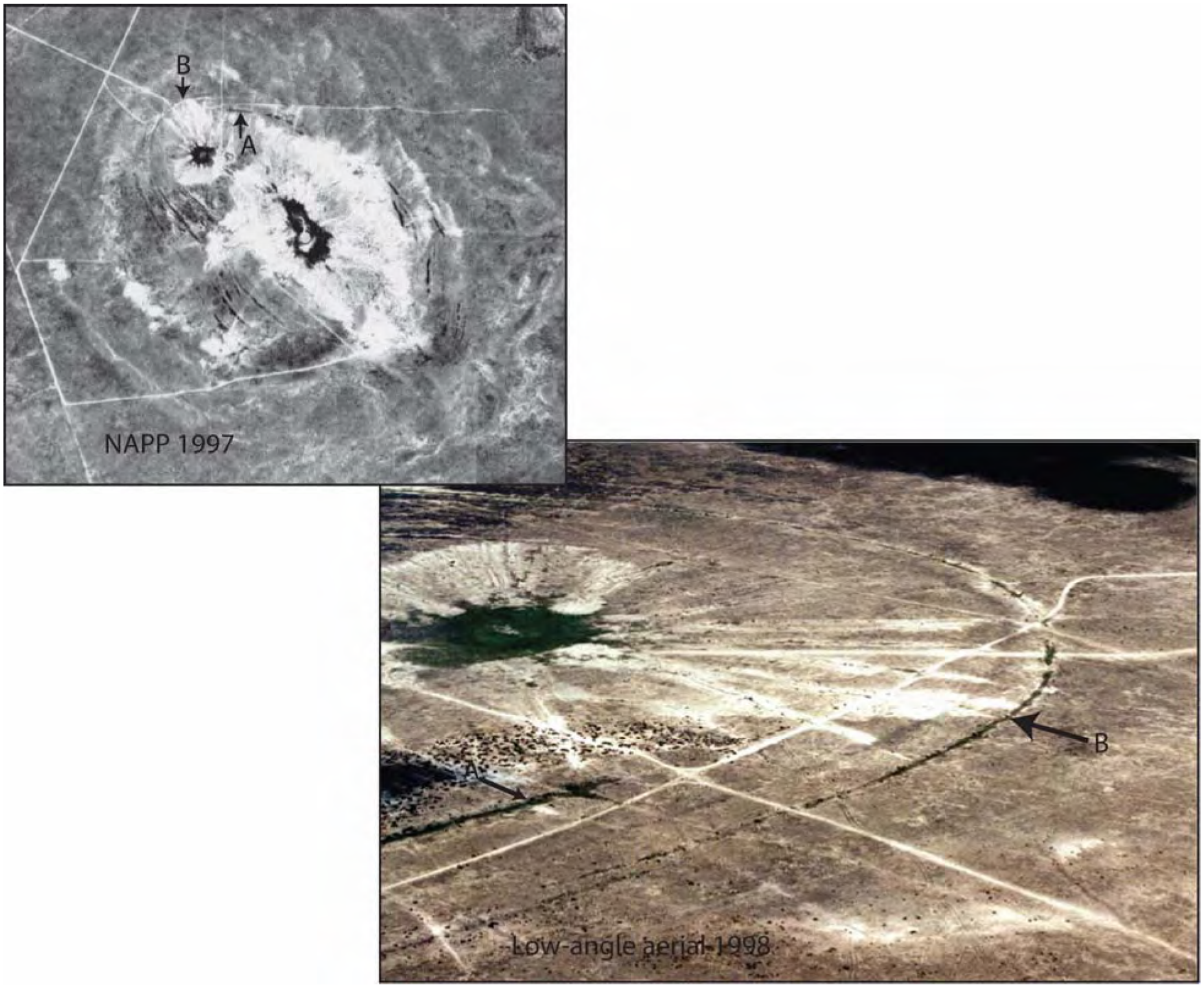

Figure 10 – San Simon sink within San Simon swale along the northeastern margin of the Delaware Basin above the Capitan reef. NAPP aerial photograph from 1996 and low-angle photograph by Dennis Powers, 2000. Collapse has continued in historic time, and the annular rings are still very visible, although populated by vegetation responding to local infiltration. Points A and B are shown to relate the two photographs.

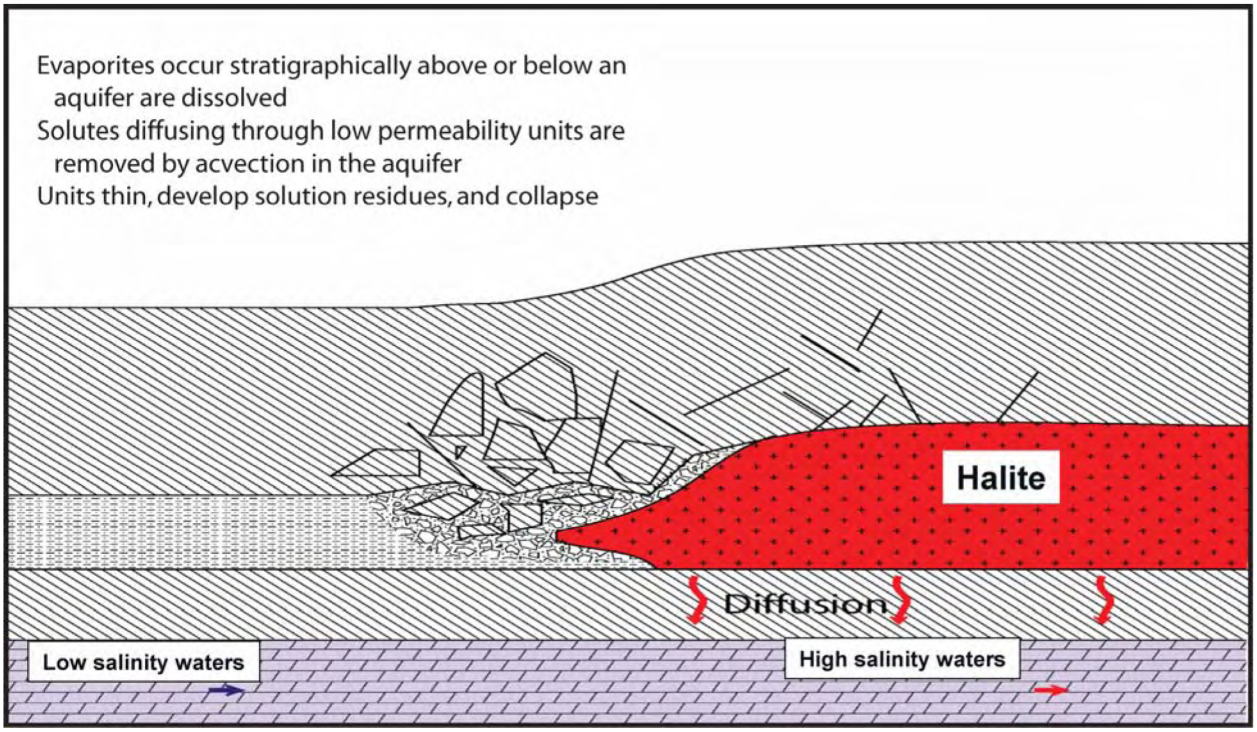

Figure 11 – Conceptual model 3 – stratabound dissolution. Vertical infiltration is limited in this model. A relatively low permeability unit overlies the water-bearing unit and limits solute movement to mainly diffusion.

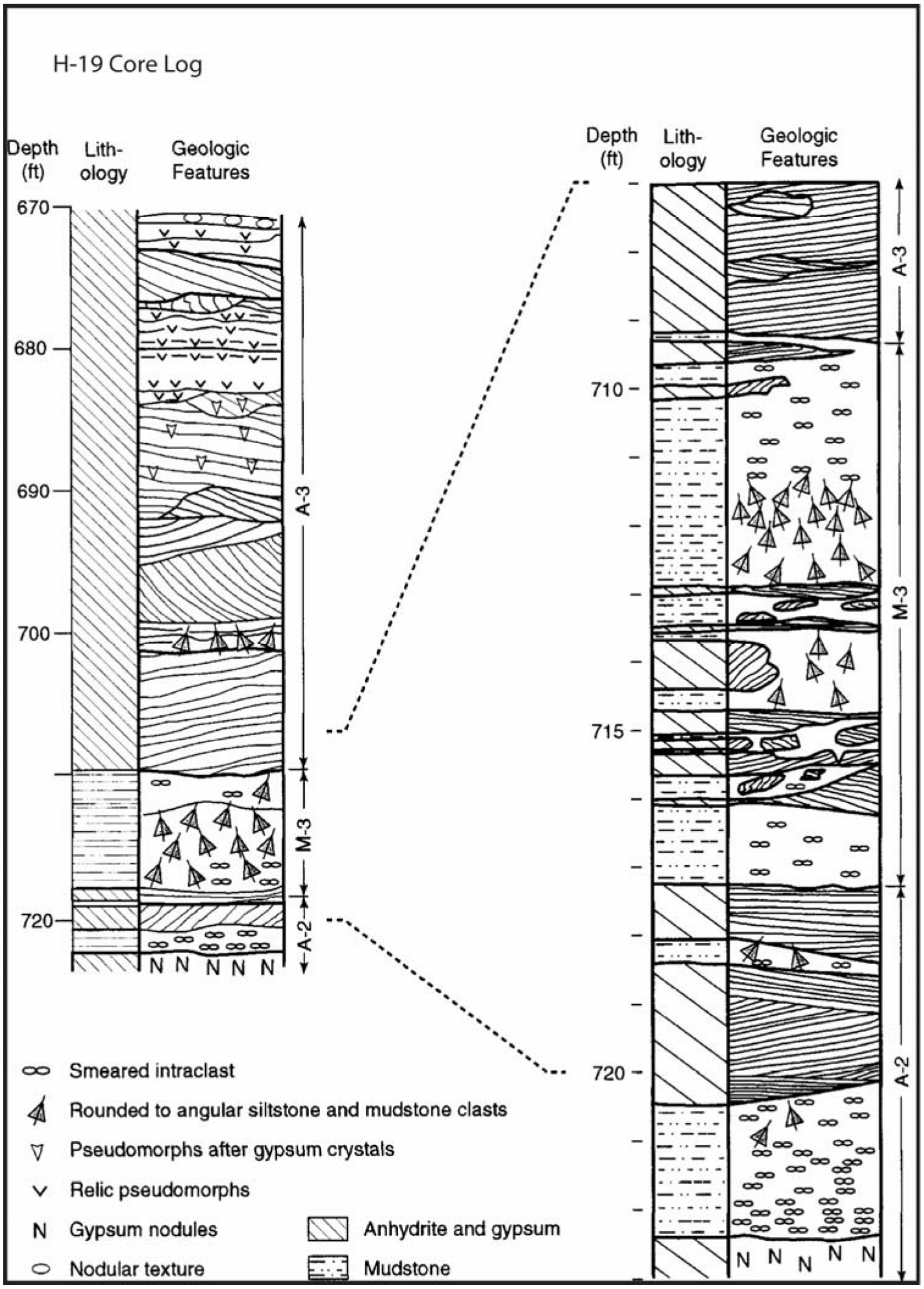

Figure 12 – Core is brecciated along the Tamarisk Member (Rustler Formation) halite margin (Mercer et al., 1997) at a drillhole near WIPP. This provides an example of stratabound dissolution and is analogous to conceptual model 3.

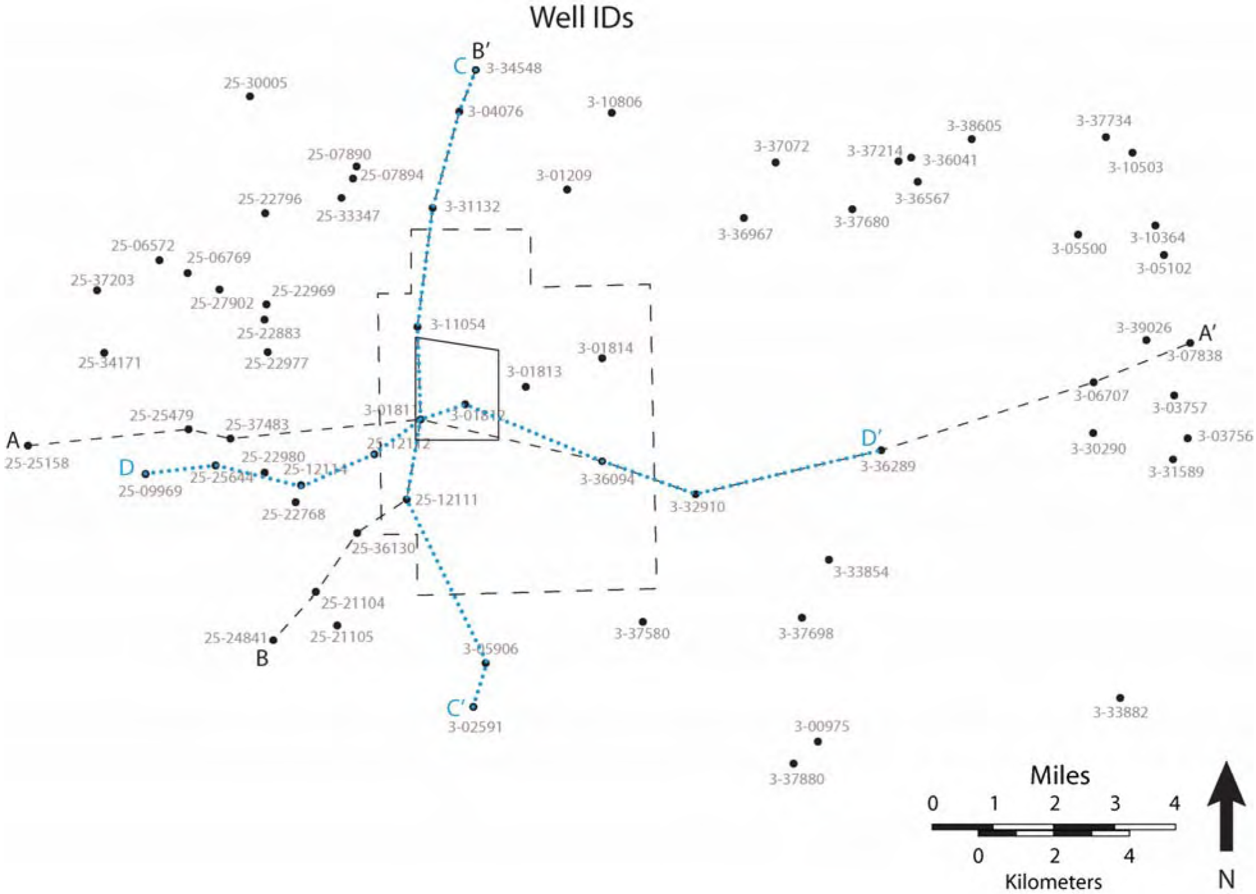

Figure 13 – WCS study area base map with drillhole locations and shortened API numbers as drillhole identifiers (the “25” prefix denotes logs from Lea County, NM, and “03” indicates logs from Andrews County, TX). The lines A-A’ and B-B’ show drillholes selected to illustrate stratigraphic relationships across the site area in Figures 20 and 21, respectively, as well as in line drawings of elevation relationships along these lines in Figure 22. Lines C-C’ and D-D’, both shown as blue dots, repeat lines A-A’ and B-B’ included in the original application. Rustler and Salado Formation boundaries have been re-interpreted in Figures 23 and 24, overlaying the original figures.

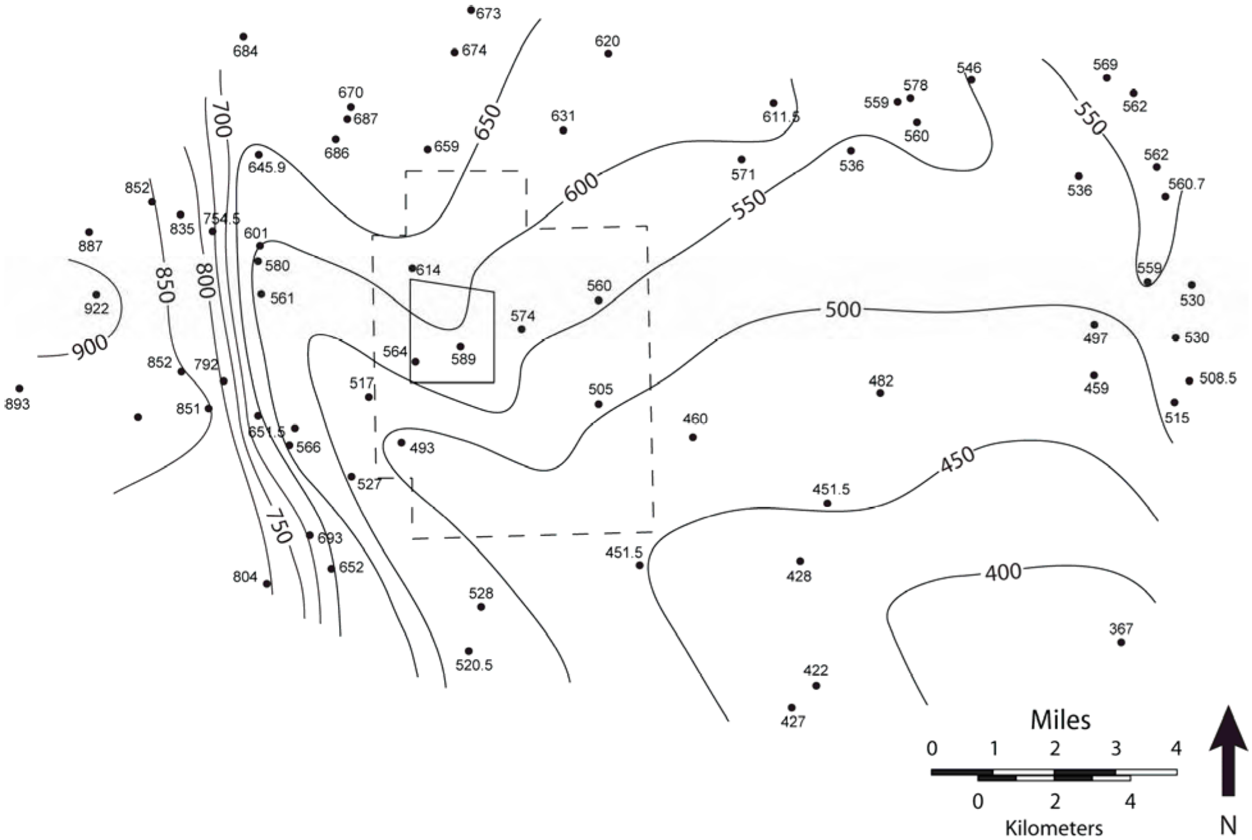

Figure 14 – Elevation (ft above mean sea level – amsl) of the top of the Tansill Formation.

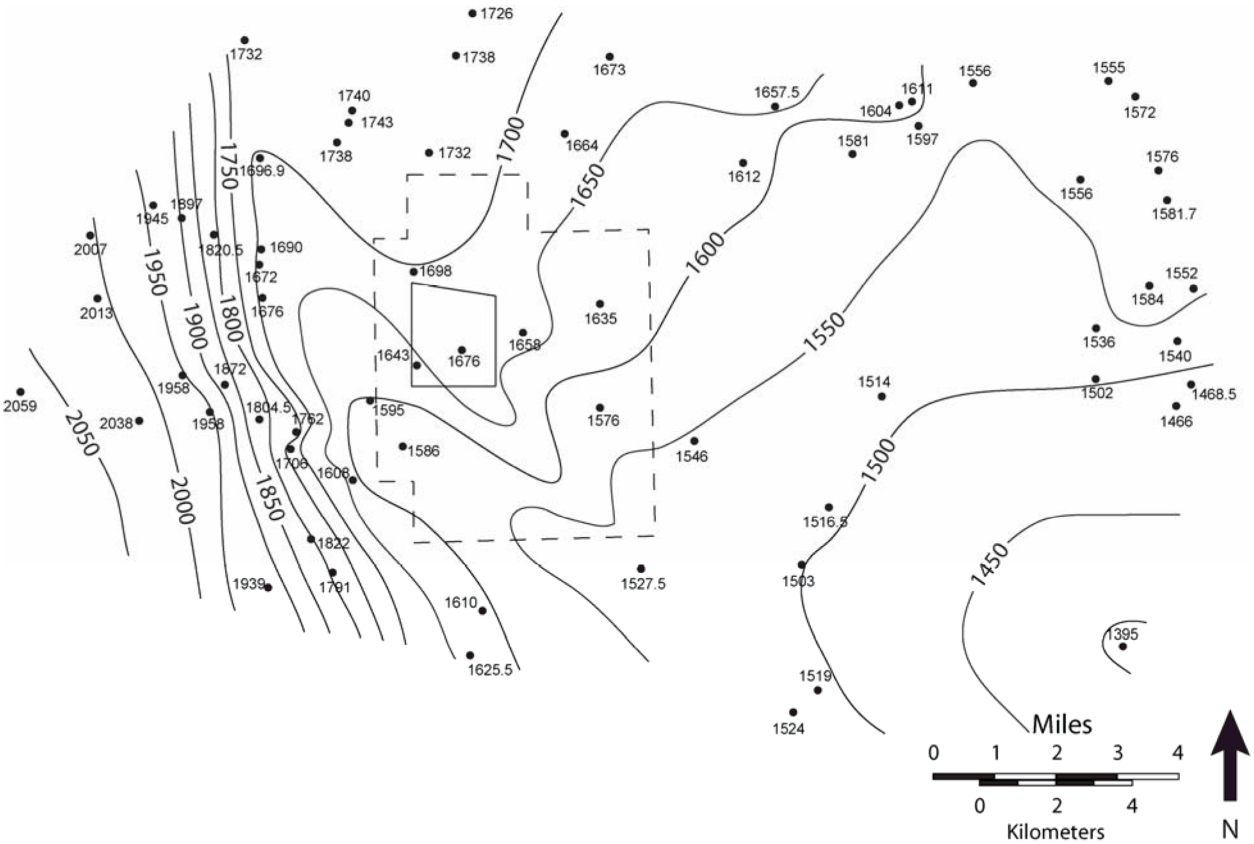

Figure 15 – Elevation (ft amsl) of the top of the Salado Formation.

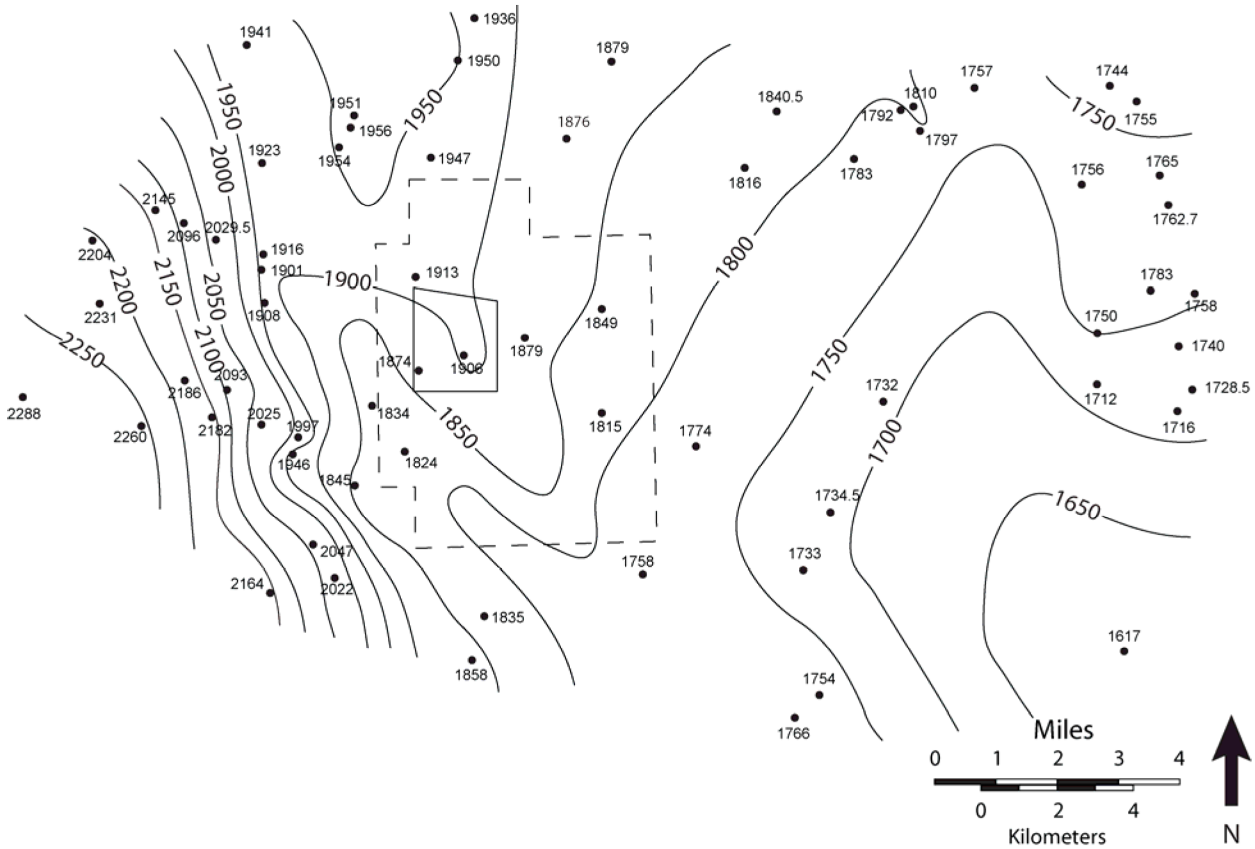

Figure 16 – Elevation (ft amsl) of the top of the Rustler Formation.

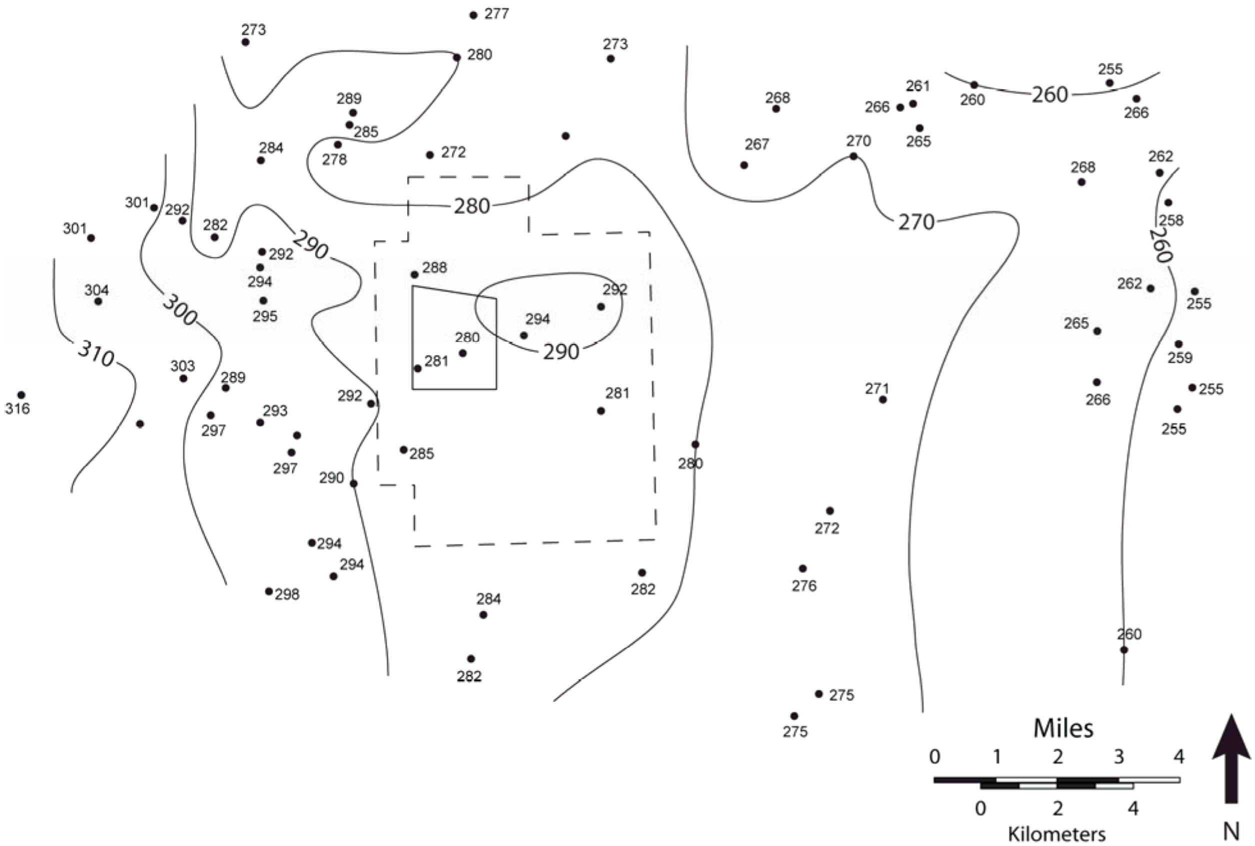

Figure 17 – Thickness (ft) of the interval from the top of the Tansill to the base of the Cowden Anhydrite (of the Salado Formation).

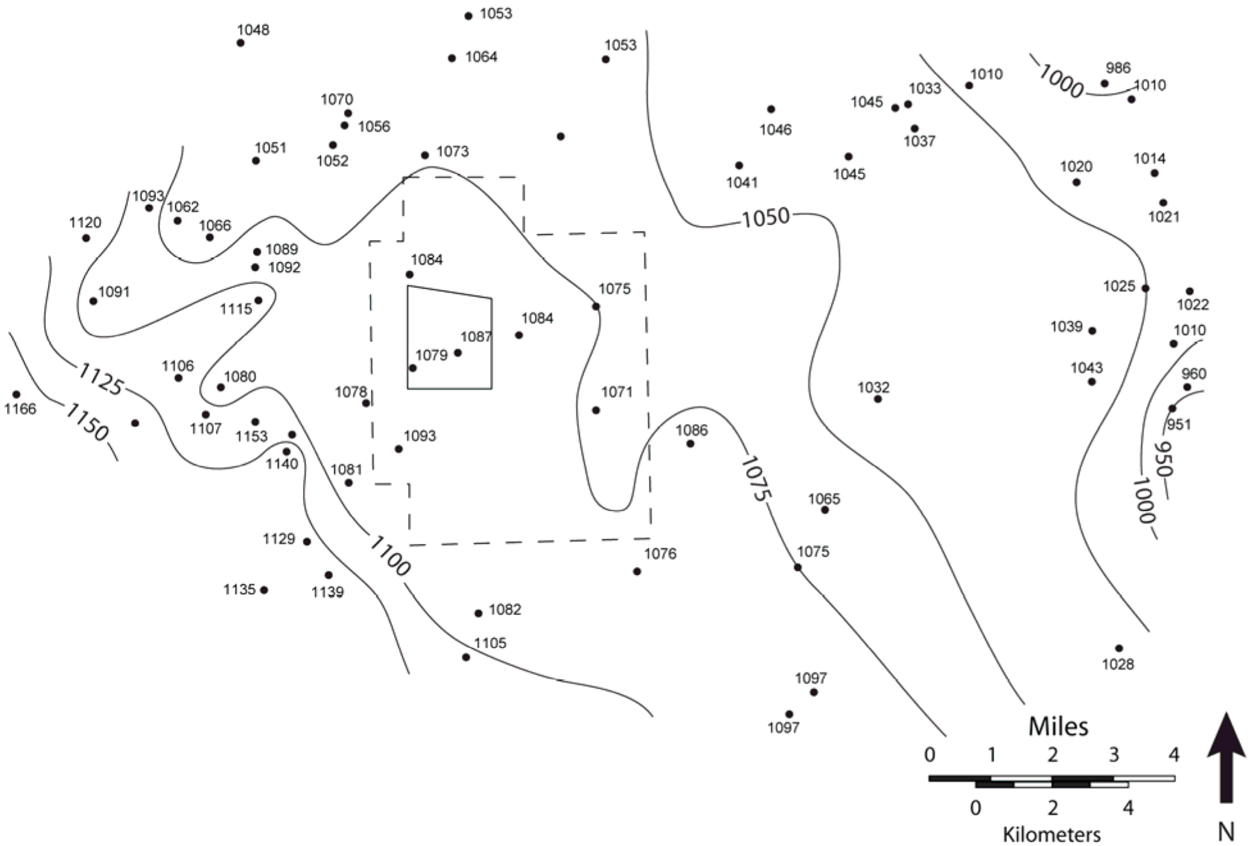

Figure 18 – Thickness (ft) of the Salado Formation, including the interval in Figure 17.

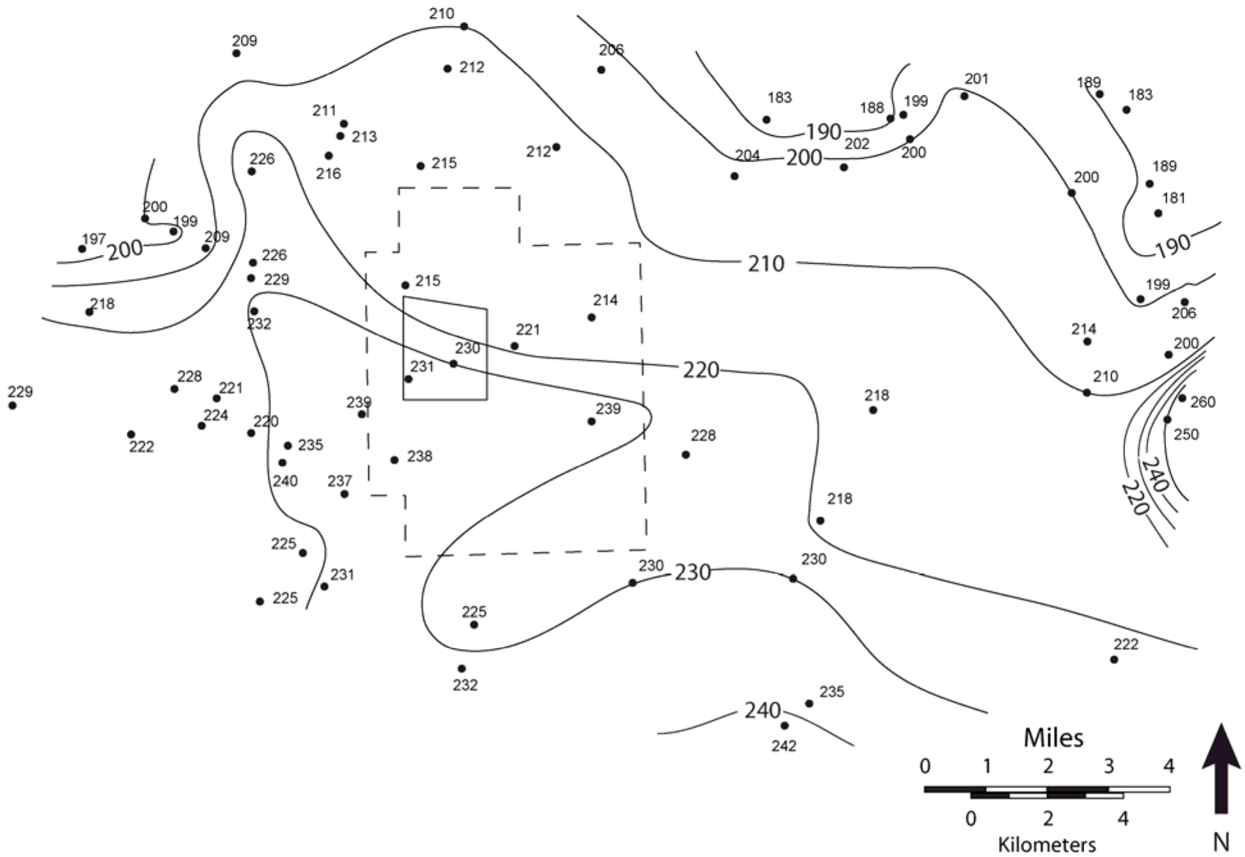

Figure 19 – Thickness (ft) of the Rustler Formation.

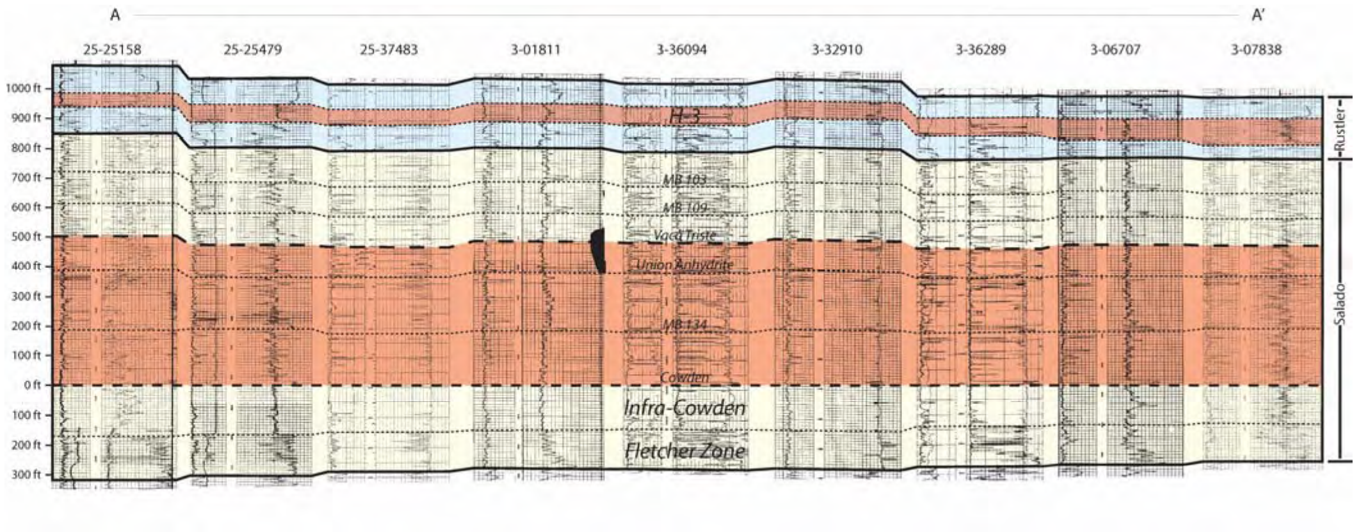

Figure 20 – West to east stratigraphic relationships across the study area and WCS facility from geophysical logs (not spaced to horizontal scale). See Figure 13 for locations. Different intervals are color coded for easier tracking. The black spot near the center is from the original scanned log.

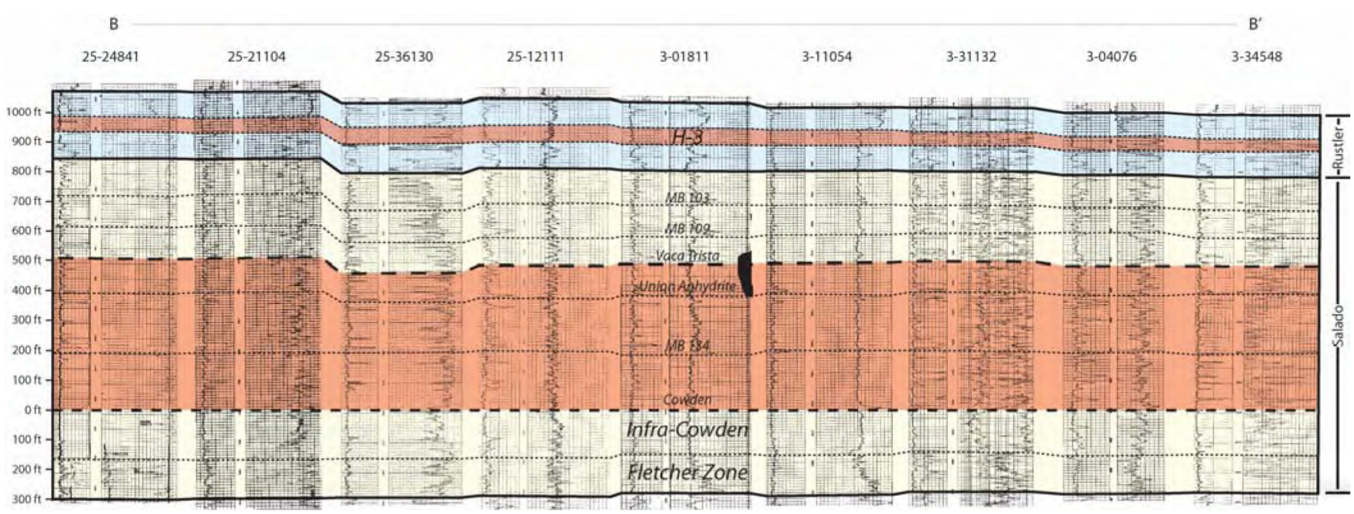

Figure 21 – South to north stratigraphic relationships across the study area and WCS facility from geophysical logs (not spaced to horizontal scale). See Figure 13 for locations. Different intervals are color coded for easier tracking. The black spot near the center is from the original scanned log.

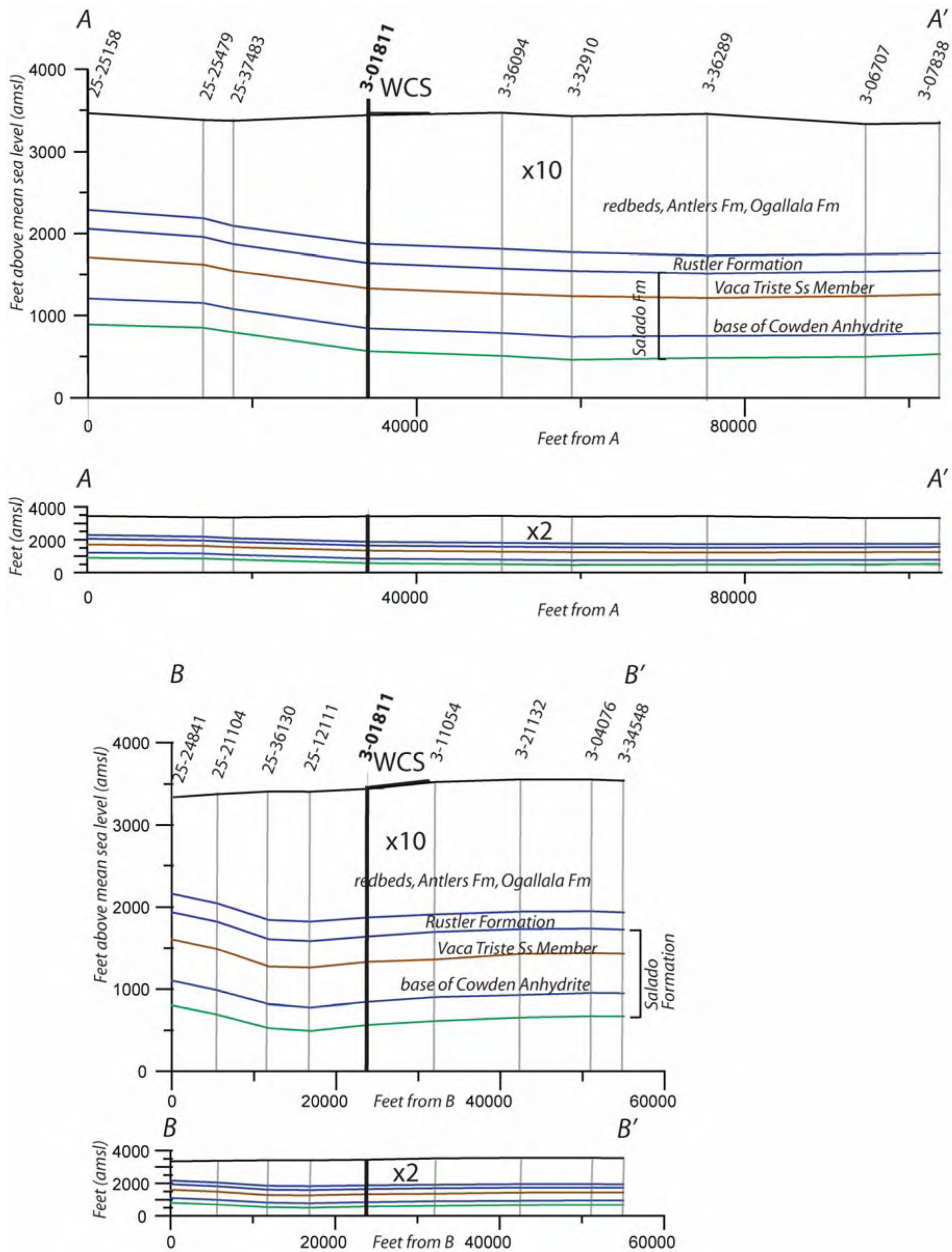

Figure 22 – Line drawings of elevation changes along cross-section A-A' (Figure 20) and B-B' (Figure 21) showing vertical exaggerations of 2 (lower graphics) and 10 (upper graphics). Horizontal scale is in feet measured from one end of the cross-section.

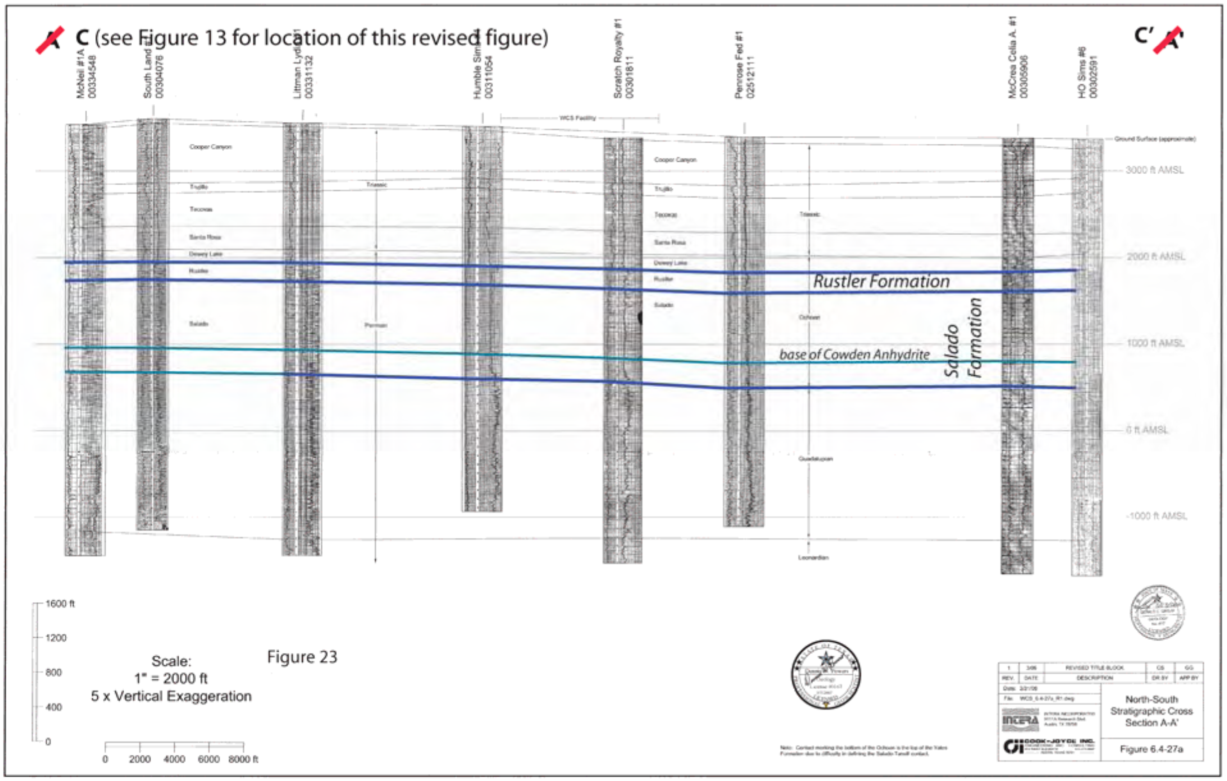

Figure 23 – Re-interpreted stratigraphic contacts (blue) for the Rustler and Salado Formations and base of Cowden Anhydrite (green) on cross-section (A-A') originally included in the application. A larger paper print of this figure is included in a pocket for this report.

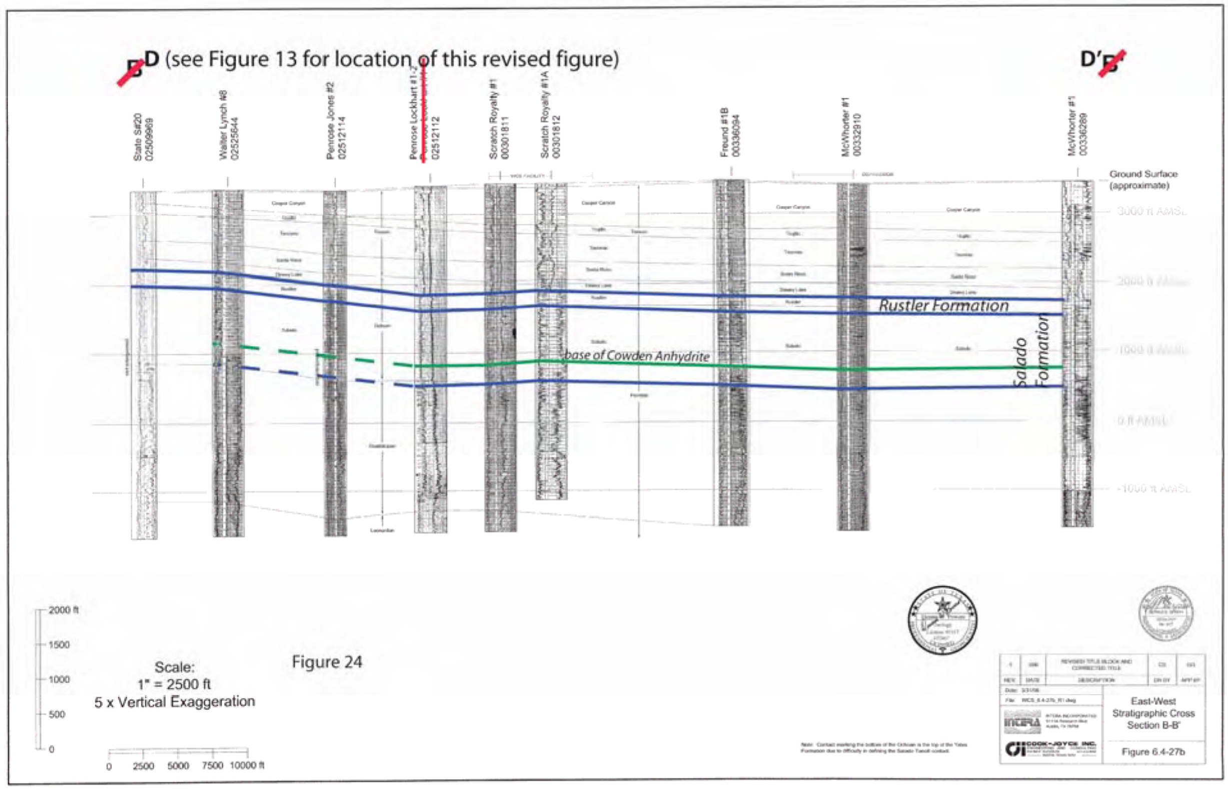

Figure 24 – Re-interpreted stratigraphic contacts (blue) for the Rustler and Salado Formations and base of Cowden Anhydrite (green) on cross-section (B-B') originally included in the application. A larger paper print of this figure is included in a pocket for this report.

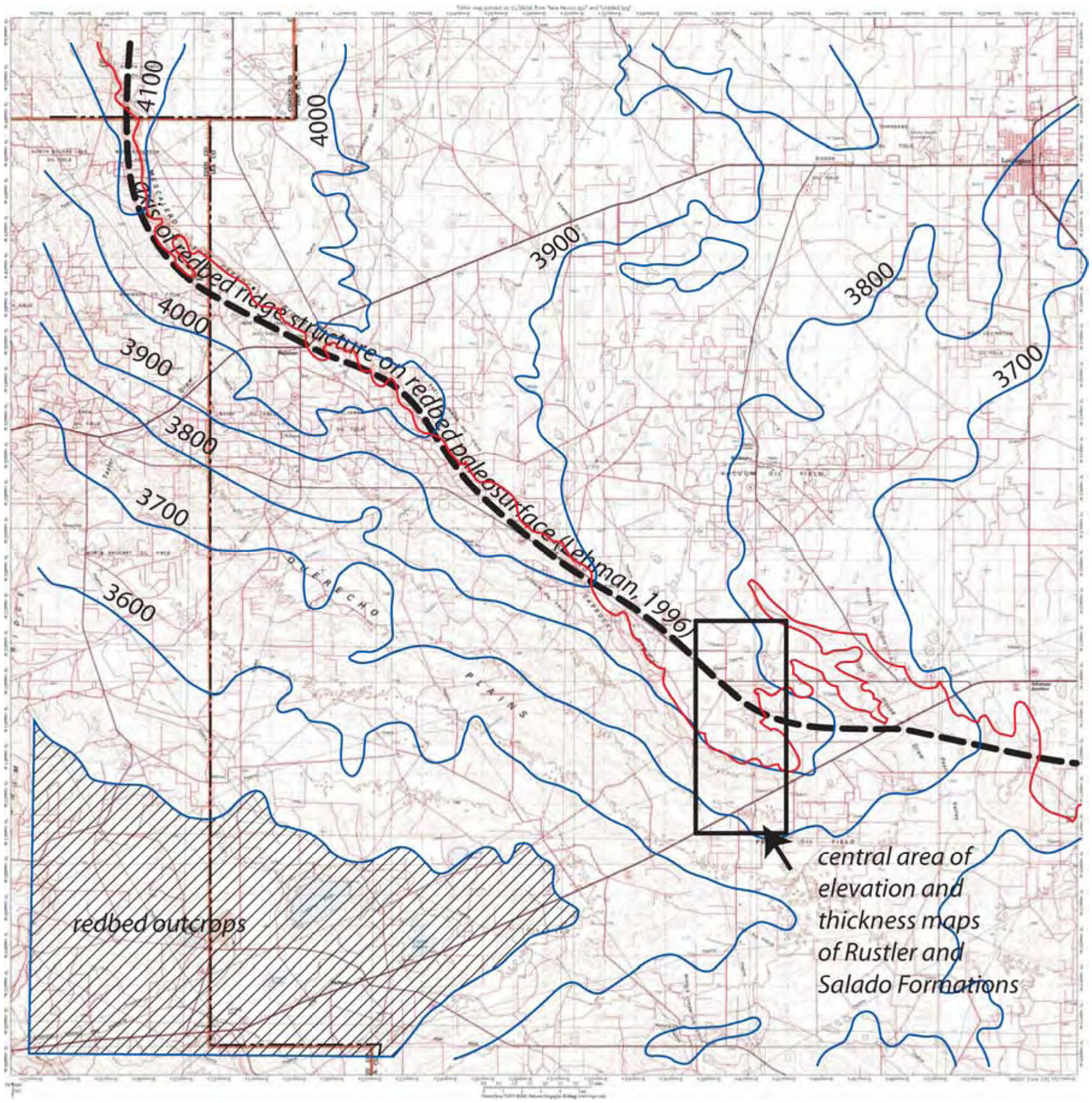

Figure 25 – The "redbed ridge" area in southeastern New Mexico shows contours (100 ft interval) of the elevation of the top of pre-Cretaceous redbeds and the axis (dashed line) of the "folding" based on Lehman (1996). The redbed ridge has been interpreted as a feature developed in response to dissolution of halite. The rectangle near the center identifies the central area of elevation and isopach maps (Figures 23-25) used to compare Rustler stratigraphic and isopach data with the elevation on the redbed paleosurface.

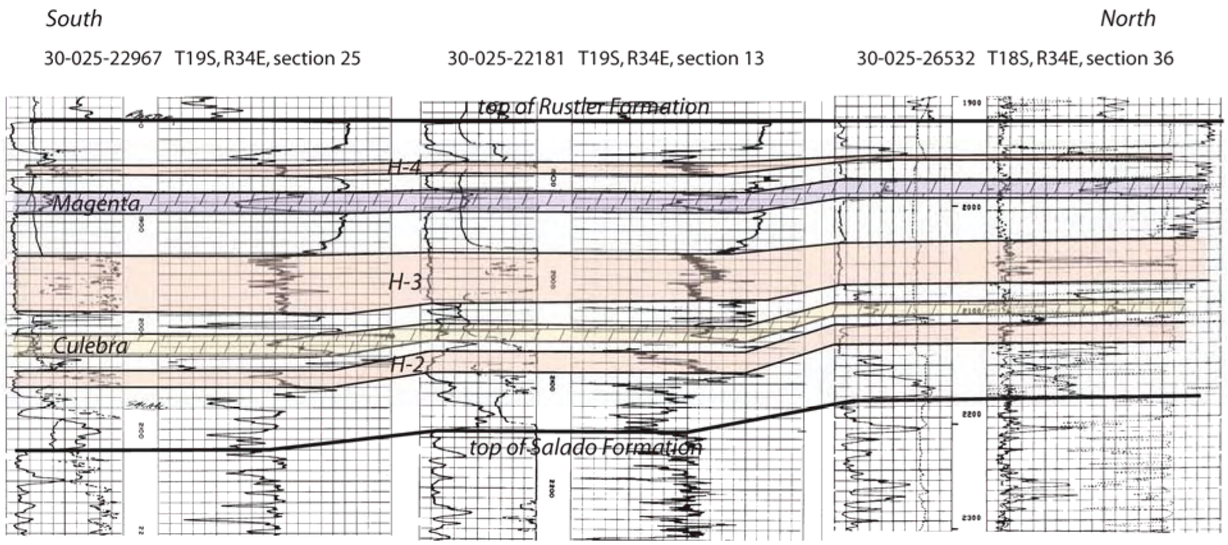

Figure 26 – Three geophysical logs illustrate persistent stratigraphic relationships of the Rustler Formation perpendicular to the trend of the redbed ridge. The formation thins consistently to the northeast (Figure 29).

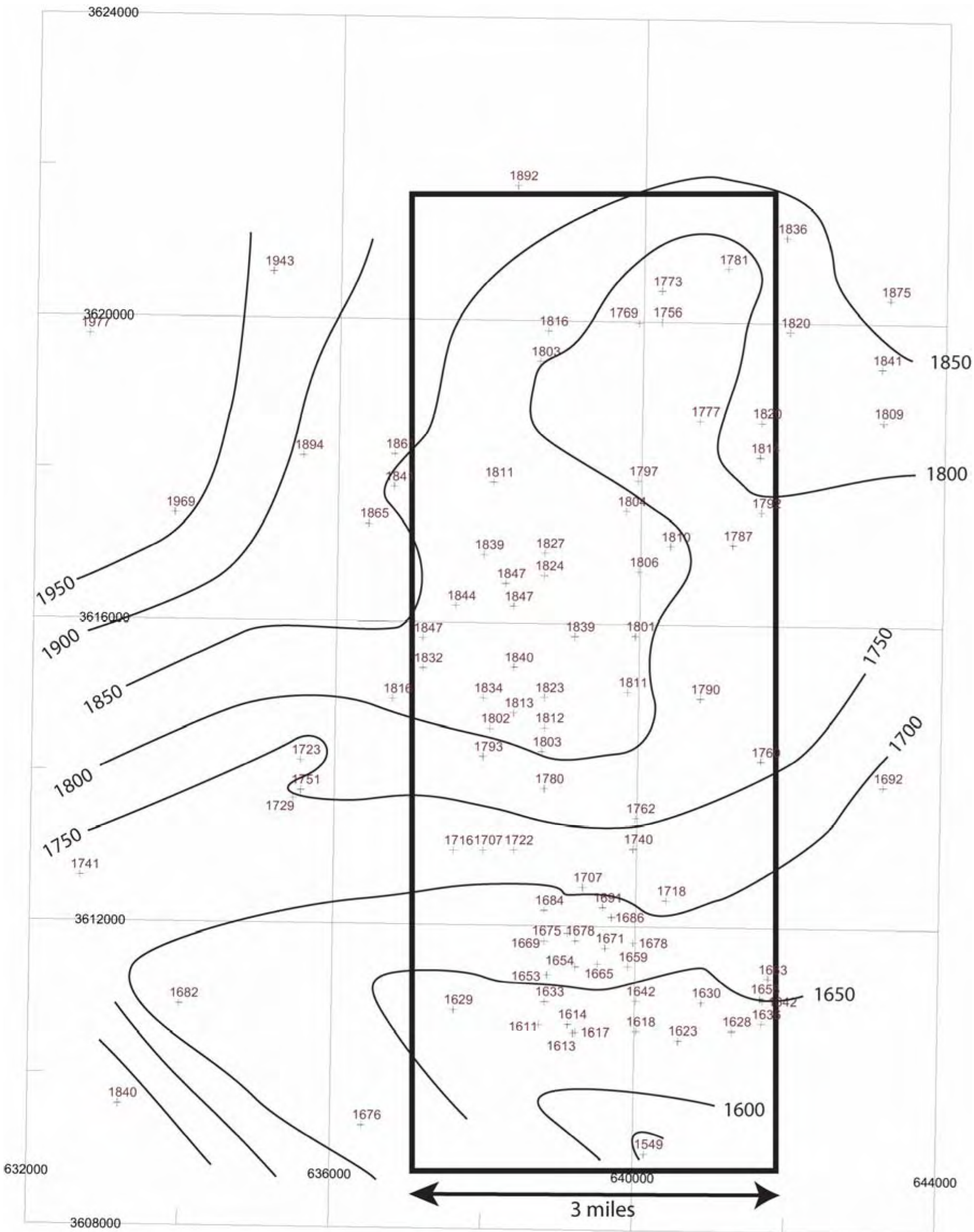

Figure 27 – Elevation (ft amsl) for the top of the Salado across the trend of the redbed ridge. Gridlines are UTM coordinates (m; Zone 13). Rectangle is shown in Figure 25.

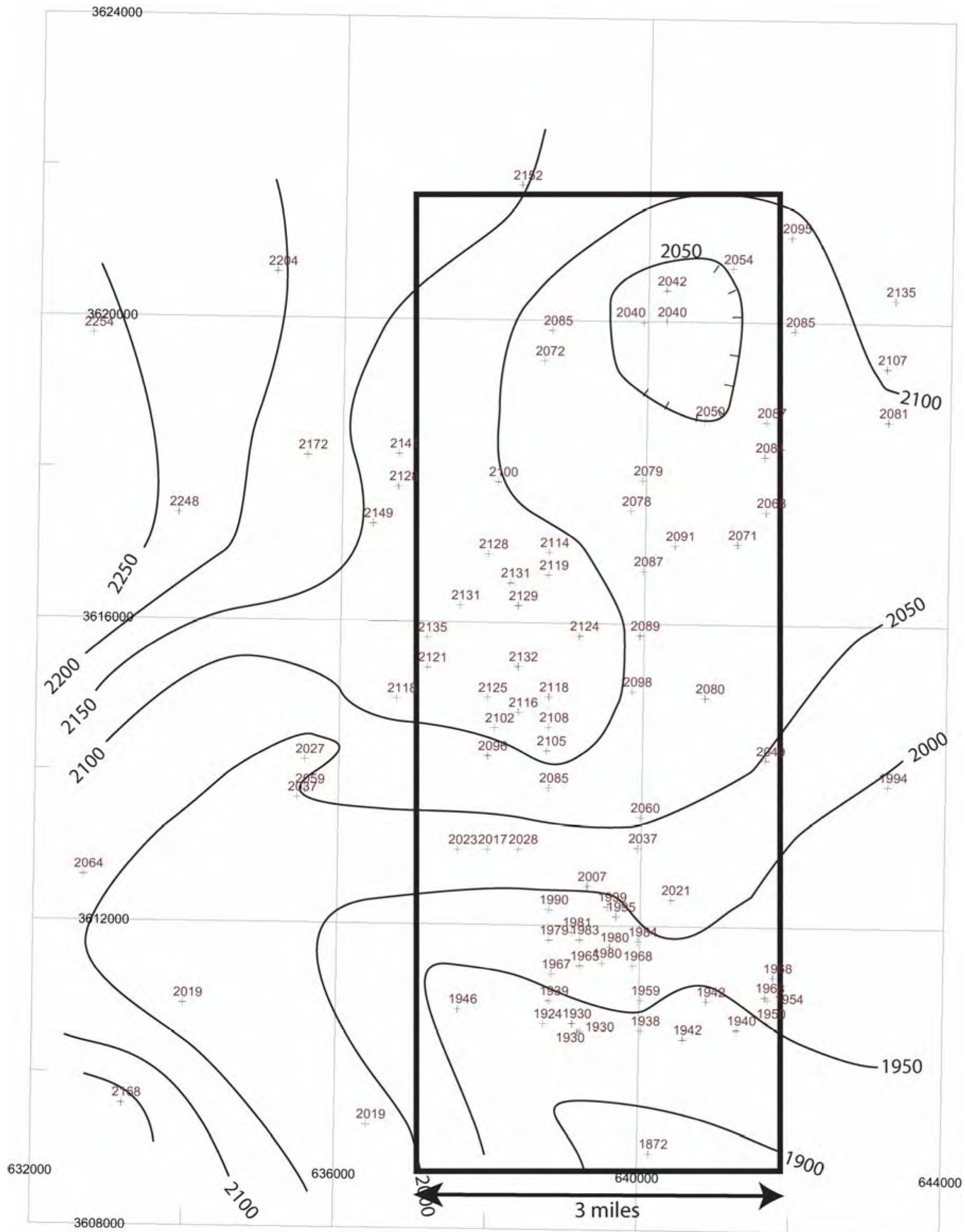

Figure 28 – Elevation (ft amsl) for the top of the Rustler across the trend of the redbed ridge. Gridlines are UTM coordinates (m; Zone 13). Rectangle is shown in Figure 25.

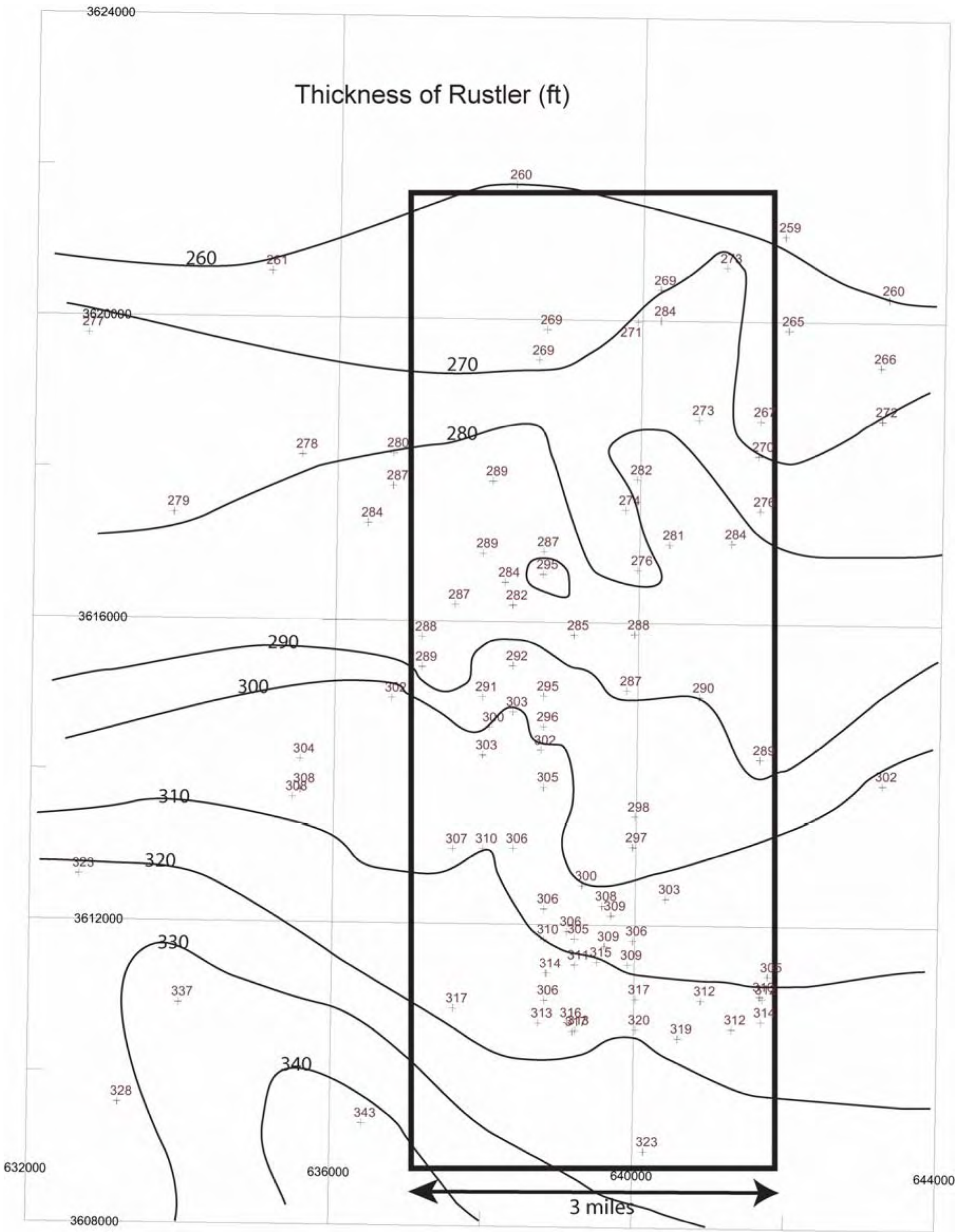

Figure 29 – Thickness (ft) of the Rustler across the trend of the redbed ridge. Gridlines are UTM coordinates (m; Zone 13). Rectangle is shown in Figure 25.

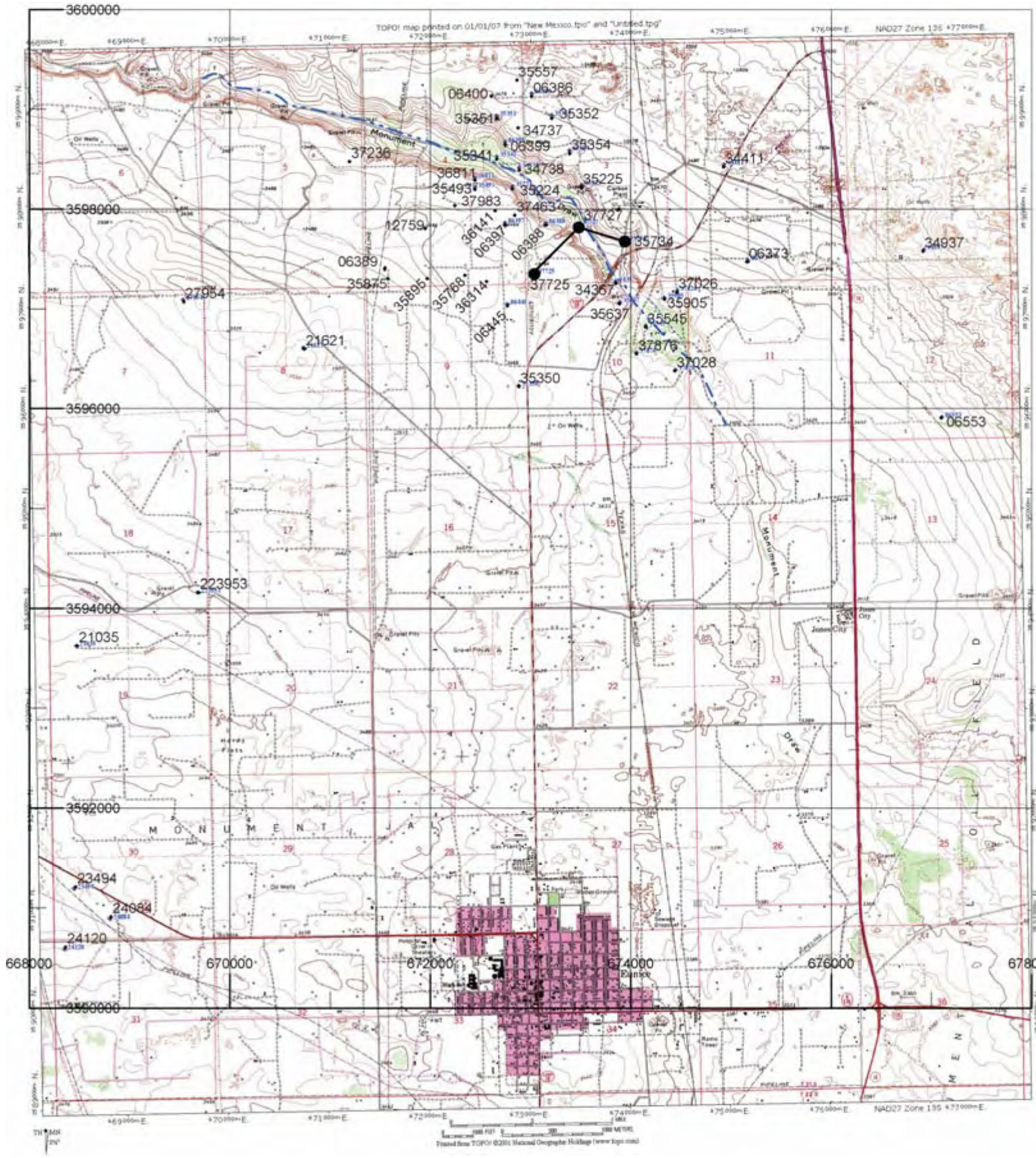

Figure 30 – Topographic base (T21S, R37E) with abbreviated API numbers (add 30-025- to the number) for drillholes for which geophysical logs were interpreted at and around section 3 and the carbon black plant. The dashed blue line indicates the topographic location of the Monument Draw drainage and is repeated in subsequent contour maps. Black overlay lines and values are UTM (NAD27; Zone 13) coordinates in meters with a 2000-m spacing. Three black dots connected by a line is the location of a log section into the draw (Figure 34).

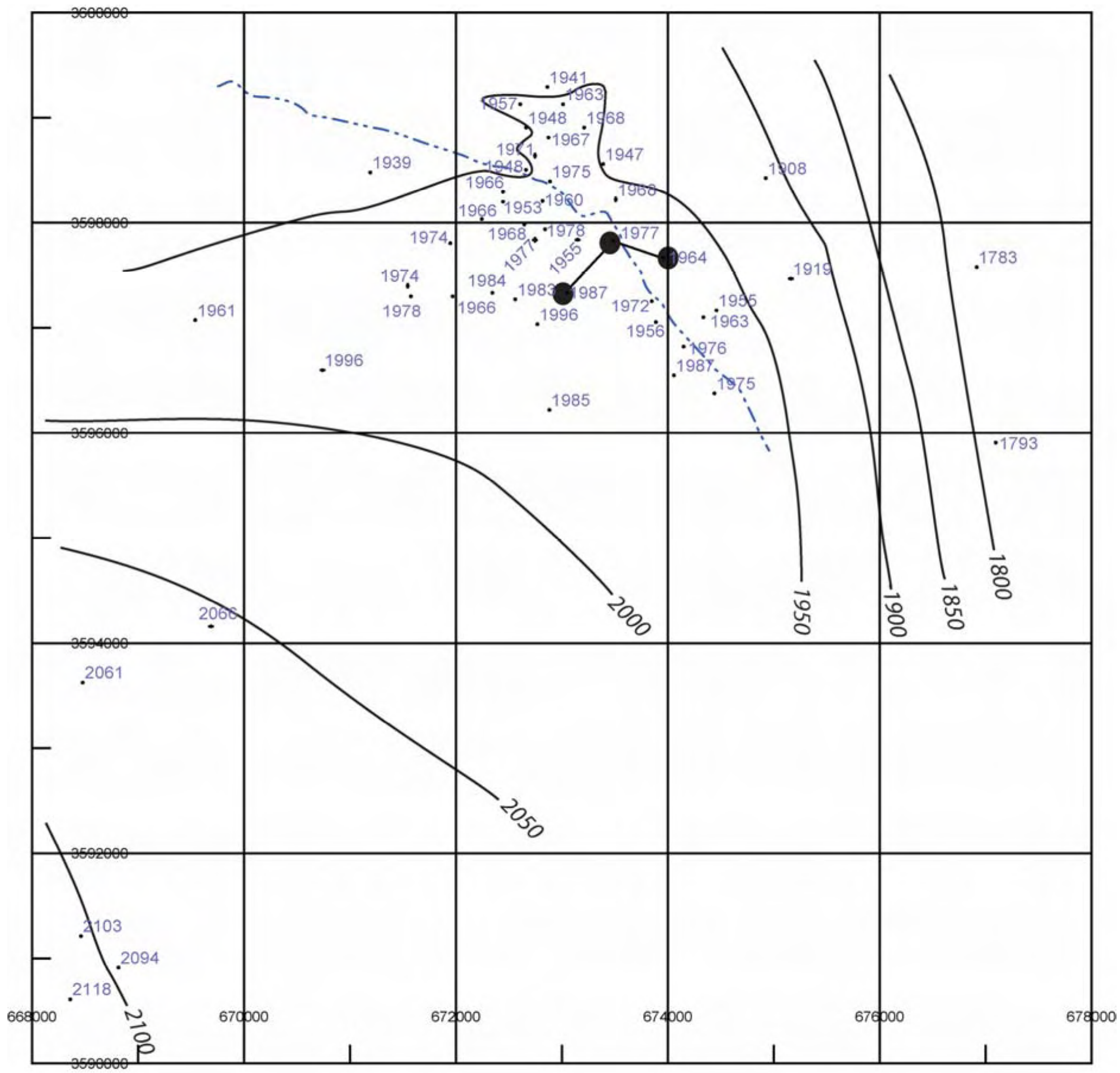

Figure 31 – Elevation (ft amsl) of the top of the Salado Formation in the vicinity of this segment of Monument Draw, NM. Only a few wells were selected at greater distances from section 3 to provide more control on contours. Grid lines show UTM coordinates (m; Zone 13).

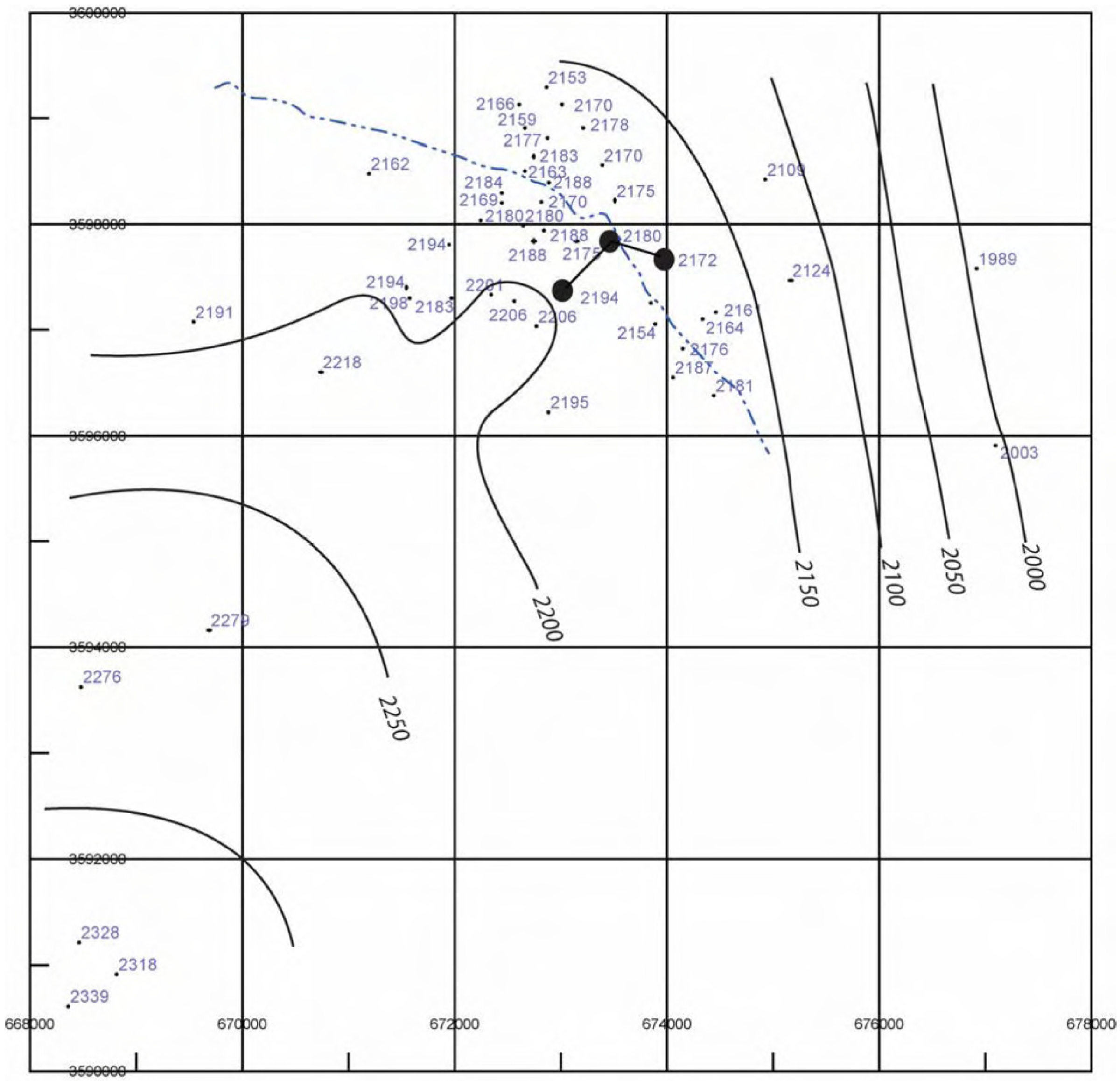

Figure 32 – Elevation (ft amsl) of the top of the Rustler Formation in the vicinity of this segment of Monument Draw, NM. Only a few wells were selected at greater distances from section 3 to provide more control on contours. Grid lines show UTM coordinates (m; Zone 13).

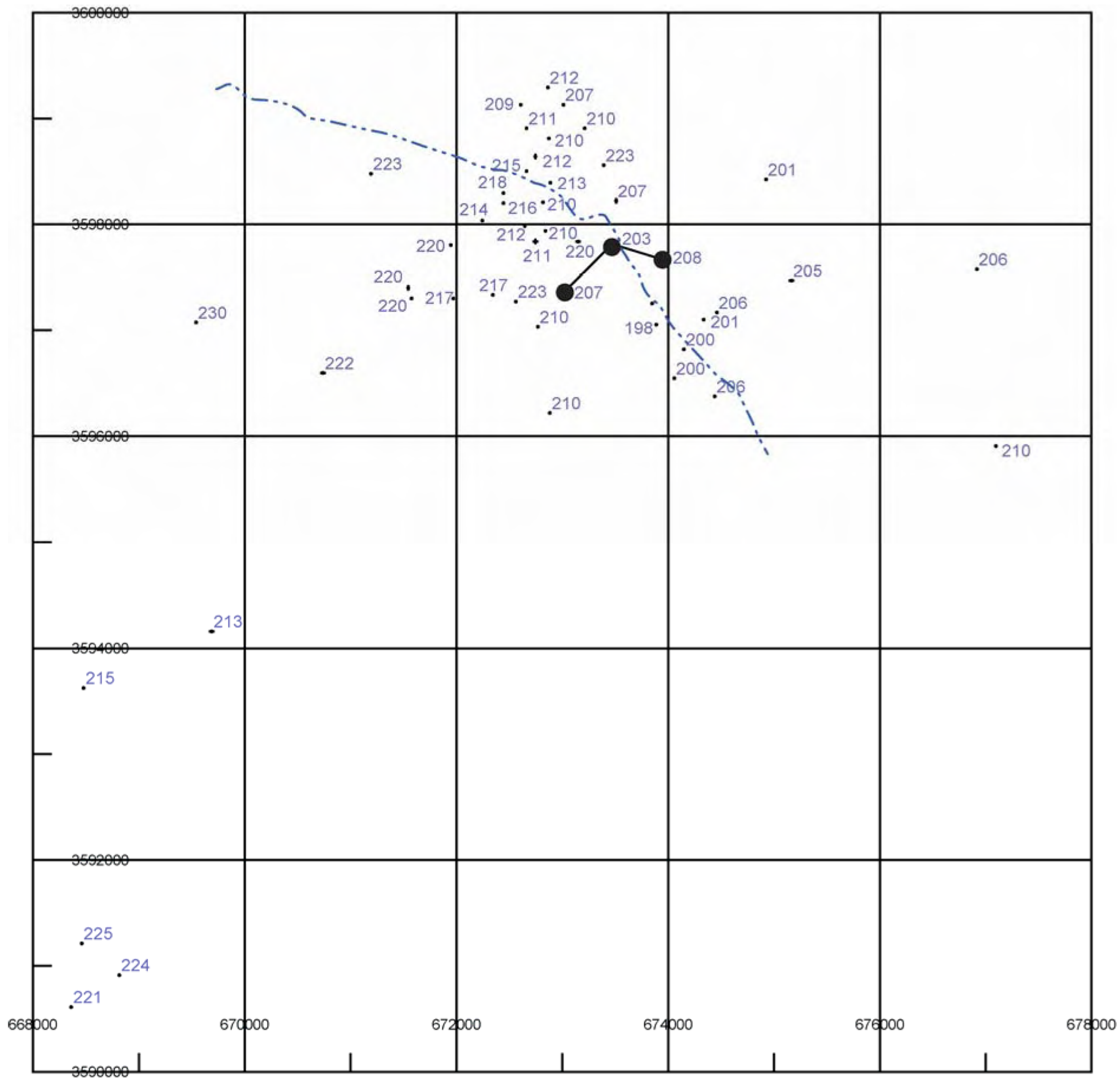

Figure 33 – Thickness (ft) of the Rustler in the vicinity of this segment of Monument Draw, NM. No contours were drawn because of the limited variation. Grid lines show UTM coordinates (m; Zone 13).

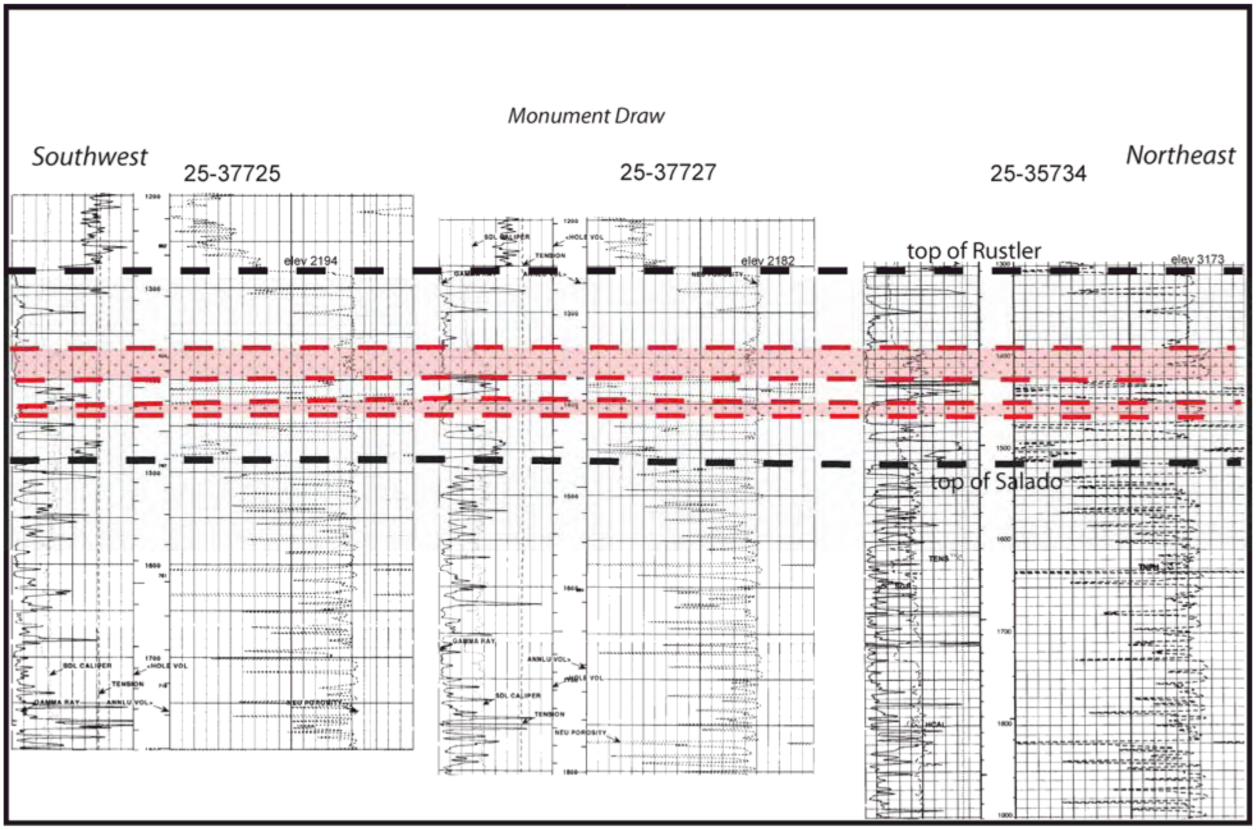

Figure 34 – Geophysical logs (see Figure 30 for location) illustrating little change in thickness for the Rustler and upper Salado from outside Monument Draw to the center and eastern side of the draw. Light red shows halitic zones, the uppermost in this area, are persistent and little changed. The Draw did not develop at its present location in response to solution of this halite and subsequent subsidence.

APPENDIX A

GYPSUM IN REDBEDS AT THE WCS SITE