Analysis Report for Task 1A of AP-114: Refinement of Rustler Halite Margins Within the Culebra Modeling Domain

(AP-114: Analysis Plan for Evaluation and Recalibration of Culebra Transmissivity Fields)

Task Number 1.4.1.1

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Table of Contents

convenience of most readers, a multi-layered Acrobat file (Rustler_mh_margins_10-5-07.pdf) is included in the electronic version of the report; the reader can select layers for each of the maps of a halite margin. Supporting information that can be helpful to the reader is included in a number of layers in the Acrobat file. This supplemental information is useful in interpreting the origin of the halite distribution as well as illustrating interpretations of geophysical log files used in understanding the distribution, but is not essential to the halite margin maps. These supplemental materials are only supplied in electronic version. Layers in this file are called out in the following text (e.g., “layer Strat”) to illustrate points. A printout is attached to the report of record of each of the data sets that are plotted for these four maps. An electronic file (Task1A_for_AP-114_Composite_Excel_Files_10-4-07.xls) prepared using Excel includes these data and background for many of the supplemental materials. A file listing at the end of the report shows the relationships between various figures, Excel worksheets, and layers in the multi-layered Acrobat file.

2.0 Rustler Formation Halite Margin Data and Methods

2.1 Methods for Establishing Halite Margins and Limits

There are two sources of additional data for revising or refining the inferred locations of halite margins within the Rustler Formation and understanding processes that are responsible for the location of these margins. The bulk of the information was developed through checking geophysical logs from oil and gas wells, both those that existed during earlier studies of halite distribution and those drilled since. Local information has also been improved in some areas by the evidence from hydrology wells drilled, cored, and logged since 2003.

In earlier versions of halite margin maps (e.g., Powers (2002)), data were generally plotted as halite present or absent. In this generation of margin mapping, an estimate was made by inspection of the geophysical or geologic log of the total thickness of halite in the particular halite facies of the mudstone/halite (M/H) unit of the Rustler. The estimated thickness of halite in Rustler halite beds has been used here to help discern general patterns and anomalous data points that may indicate typographical errors or other issues. Because the estimates are made visually and quickly during log examination, they should only be taken as indicating broad patterns. Some of those patterns will be discussed later.

Only part of the general hydrologic modeling area was re-examined in such detail. Most of the logs checked are from drillholes east of WIPP. Each halite margin is mapped separately, showing only drillhole locations where Rustler data have specifically been evaluated for halite. These data were compared to the earlier version of each margin. The halite margin previously plotted was then adjusted within this area to show changes based on additional data. Except for recent drillholes, data within the WIPP site were not revised. Data from a variable number of drillholes were used in this study to define each halite margin (see data source table: Task_1A_for_AP-114_Composite_Excel_Files_10-4-07.xls).

In general, the estimates of thickness are more reliable with increasing thickness. Very low values (<5 ft or 1 m) are mainly placekeepers indicating the possibility of halite present. Logs were interpreted individually rather than by direct comparison with adjacent neighbors. This helped provide an interpretation that is based more on log characteristics than on memory of the adjacent logs. Logs were interpreted over a period of more than one year, and some neighboring logs may have been interpreted at quite different times. The values were grouped for plotting, and different colors and symbols were used on the plots for different ranges of thickness estimates. Drillholes in which no halite is believed to be present are plotted with black dots and a value of zero. Following initial plotting, outliers near the margins were investigated to determine if a typographical error had been made as data were entered or if nearby logs had been interpreted differently at different times. These outliers were corrected where appropriate.

Early work on halite margins before intense drilling in the area relied mostly on older, open-hole geophysical logs that commonly included an acoustic or density log that was very useful for interpreting the presence of halite in the Rustler. Holt and Powers (1988) examined facies variability using many of these logs. More recently, the Rustler is seldom logged in an open hole; through-the-casing natural gamma and neutron data are most common. The natural gamma still is the standard for interpreting the stratigraphic contacts for these wells. Halite is less conclusively interpreted with neutron, as the main characteristics of low gamma and high neutron are also generally representative of anhydrite. These responses do, however, also show some differences between anhydrite, gypsum, and halite, and these have been used to fill in data on presence of halite and estimate thicknesses. Examples of Rustler log signatures (Appendix A) across the depositional basin center southeast of WIPP (IDnums #5220/5218) to the area of elevated Culebra (IDnum #5167) illustrate some of the differences between logs from a single drillhole (#5167) to differences between nearby drillholes. Neutron logs (IDnums #5220, 5196, and 5167 left) show high neutron returns for both anhydrite and relatively pure halite, making distinctions more difficult and making reference to open-hole logs in the area more important. Density logs are less common than sonic or acoustic logs in open hole, but the differences between halite and anhydrite are generally very distinctive in these logs.

2.2 Halite Margin Data and Estimated Thickness of Halite

2.2.1 Rustler M-1/H-1 Margin. As noted in some previous reports and articles (e.g., Powers et al., 2006), the M-1/H-1 unit here represents all the lower Rustler, below A-1 (layer Strat), whereas Holt and Powers (1988) actually subdivided this portion into more units, with a specific M-1/H-1 that is in the upper part of this segment.

The thickness data shown for H-1 (Figure 1; layer H1 Margin) are less clear than the data for other Rustler members because there are both beds dominated by halite as well as halite-cemented clastic zones. To the east of WIPP, some intervals below A-1 are relatively pure halite and easy to interpret (Appendix A). Across WIPP, from east to west such intervals of relatively pure halite become thinner and more argillaceous. Along the H-1 margin west of WIPP (Figure 1A, simplified from Figure 1), geophysical logs may not be easily interpretable for the presence of halite. Some adjustments have been made northwest of the WIPP site accounting for the core evidence of halite cementing part of this lower Rustler section (Powers and Richardson, 2003), but log data are of variable value for this interval.

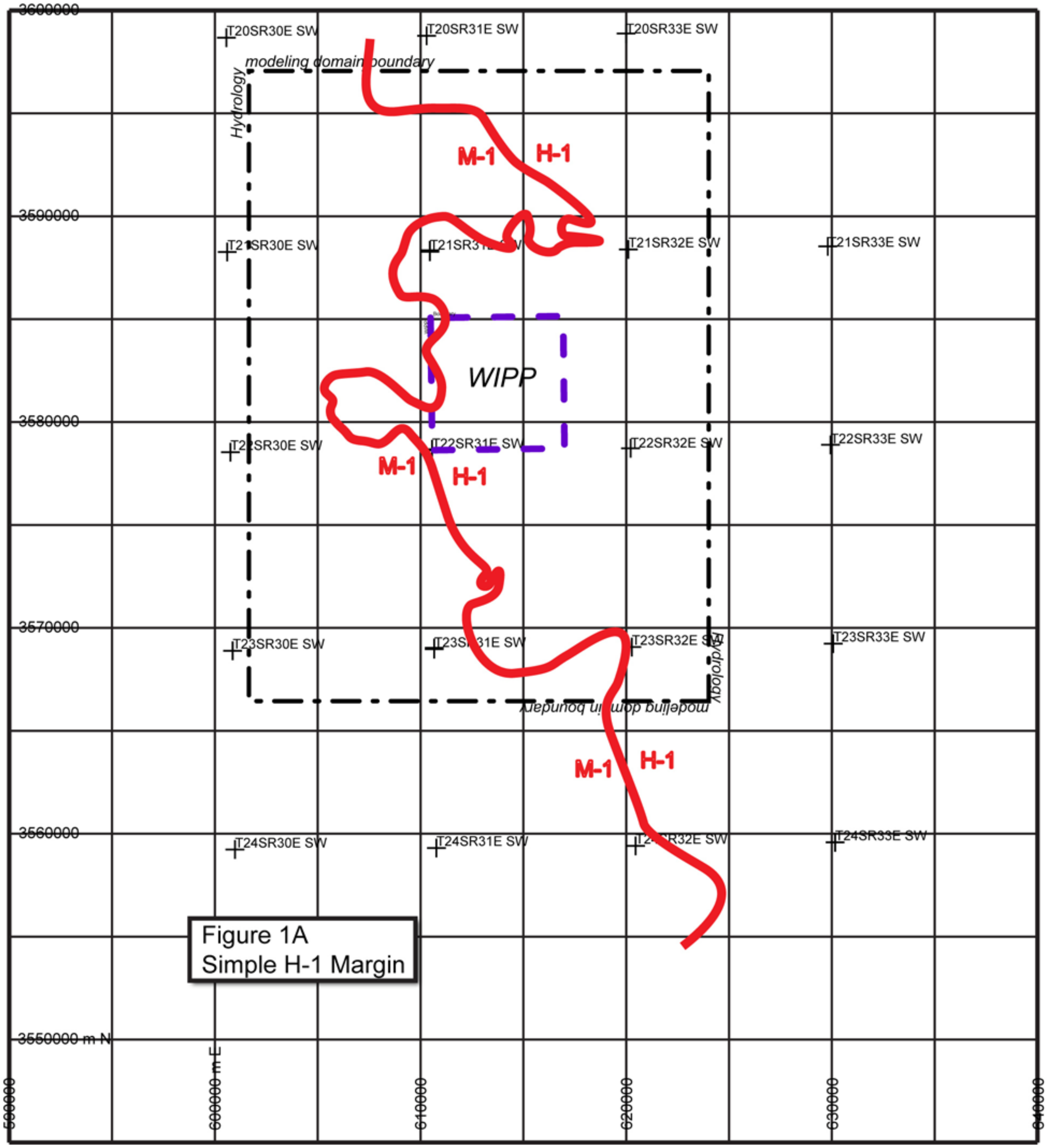


Figure 1A
Simple H-1 Margin

Figure 1A is a simplified version of Figure 1 without drillhole locations and H-1 thicknesses.

Data from across WIPP and to the east generally show an apparent eastward thickening of halite below A-1 (layer H1 Margin). This only partially indicates a specific halite bed; much of the area shows log characteristics more consistent with halitic or possible halite-cemented zones. Geophysical log cross-sections (Cross_section_ABC10-5-07.pdf; Cross_section_DEF10-5-07.pdf) illustrate differences in the lower Los Medaños, with halite zones only indicated by salmon-colored highlights below A-1. These cross-sections will be referred to only by letter in subsequent sections.

Along the western side of the WIPP site, the margin of H-1 has been adjusted mainly in response to the core and drilling data from two recent WIPP wells (SNL-2 and SNL-10; IDnum 20169 and 20181, respectively; green stars on layer Drillhole locations and green IDnum on layer Drillhole IDnums)). Halite in SNL-10 fills in data where data were sparse, and halite cements at SNL-2 were not generally interpreted in logs of oil wells nearby. In large part, the margin west of WIPP has not been significantly modified and has been reproduced from Powers (2002).

North of WIPP, core and drilling data from SNL-5 (halite present; IDnum 20171) and SNL-3 (no H-1; IDnum 20170) (both green stars on layer Drillhole locations and green IDnum on layer Drillhole IDnums) resulted in modifications of the margin and re-interpretation of logs from nearby oil wells. The margin in this area has become more complicated (compare layers Composite halite margins and 2003 halite margins composite).

H-1 is more difficult to interpret than other intervals because of the nature of the halite, especially zones where siltstone and fine sandstone are cemented with halite. There is more uncertainty in placing this zone, and the current margin most likely is biased by not representing fully the areas west of WIPP where halite cements are present.

2.2.2 Rustler M-2/H-2 Margin. Because H-2 underlies the Culebra (see layer Strat), more well logs were examined within the mudstone facies, and there are some significant differences (Figures 2, 2A) from the previous interpretation of the halite margin (layer H2 Margin) (compare layers Composite halite margins and 2003 halite margins composite).

Southeast of WIPP (Figure 2A), some new wells along the east side of T23S, R31E result in modifications to the margin and some more complexity. Here the difference between wells within the same square mile can be from no halite to as much as 30 ft of estimated thickness. [Note that the estimates of thickness here are shown as feet for better distinction of zones; Figured 2; layer H2 Margin.]

Cores and new drillholes northeast of WIPP (Figure 2) provide evidence that was used to modify the margin. Near WIPP, the margin was moved to the northwest slightly. Within north-central T22S, R32E, new data provide evidence that M-2 swings farther east than previously interpreted.

In the eastern part of T22S, R32E, the H-2 margin swings north, and there is an area along the boundary between R32E and R33E in which halite is present in significant thickness continuously from south to north. In the northwestern part of T22S, R33E, estimates of halite show a significant area with greater than 40 ft (~12 m) thickness, outlined with a black line (Figure 2). The southeastern part of T22S, R33E does not show any halite. The wedge-like mudstone (M-2) area along the east-central boundary of the study area generally lines up along a W-NW trend with the M-2 trend northeast of WIPP.

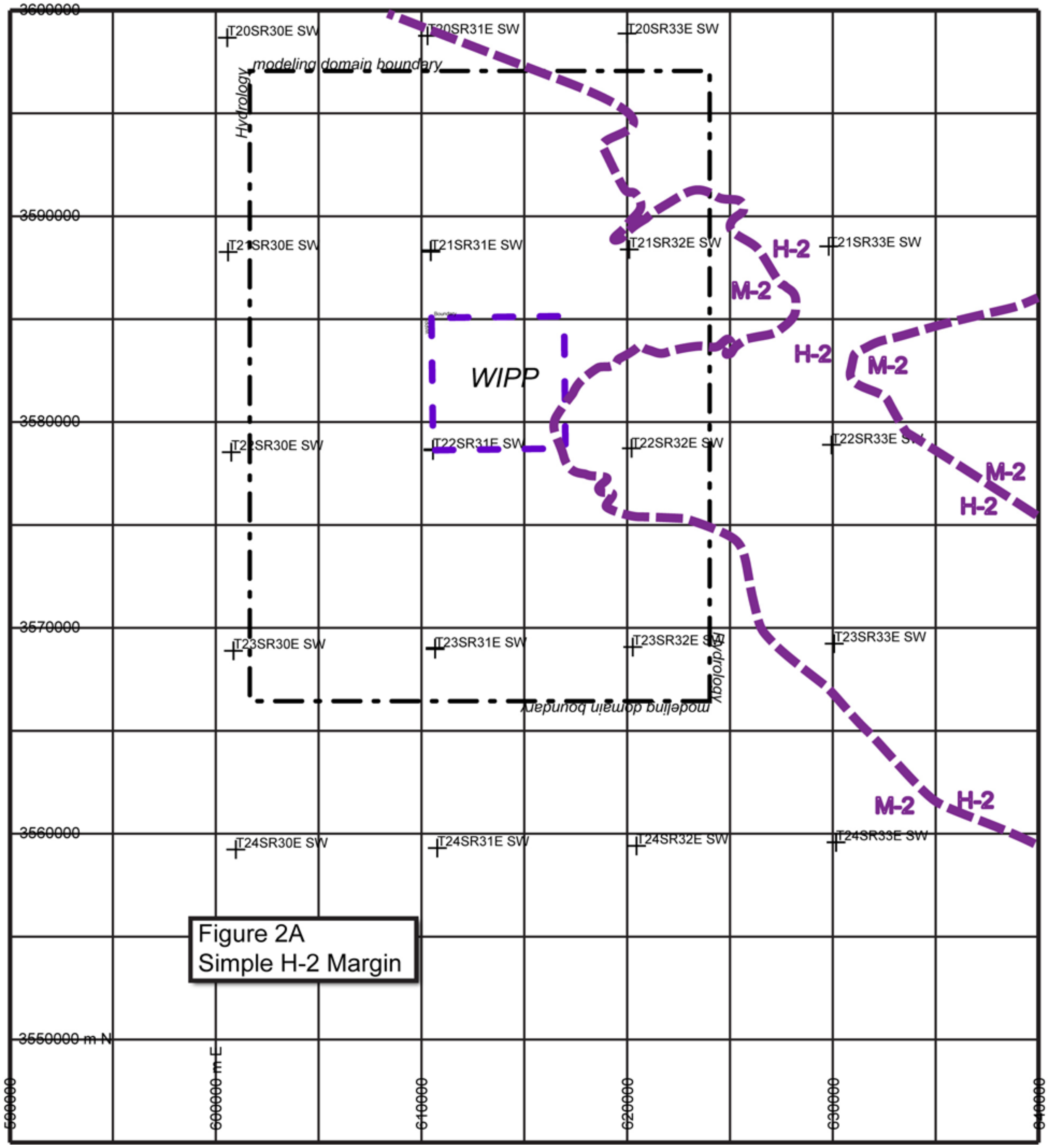


Figure 2A
Simple H-2 Margin

Figure 2A is a simplified version of Figure 2 without drillhole locations and H-2 thicknesses.

Much of this margin also shows a relatively narrow transition zone from no halite to halite that ranges commonly to 20–30 ft thick (Figure 2; layer H2 Margin).

2.2.3 Rustler M-3/H-3 Margin. Because the presence or absence of halite in H-3 is related to areal variations of Culebra transmissivity (Holt and Yarbrough, 2002), areas along the margin south and north of WIPP were examined in detail. Although the margin has changed somewhat (layer H3 Margin) from that presented by Powers (2002) (layer 2003 halite margins composite), there are other surprising elements in this map.

Southeast of the WIPP site (Figures 3, 3A), near the eastern side of T23S, R31E, some additional drillholes were evaluated and show drillholes with no apparent halite close to drillholes with ~10 m of halite. The margin is more complex than previously shown (Powers, 2002, 2003).

Along the eastern boundary of WIPP, the margin has not changed, as there are no new, different data points within the site. Northeast along the margin, additional data result in refining the location and some local complexity.

North-northeast of WIPP (Figure 3A), along the western half of T21S, R32E, additional data and re-evaluated logs indicate significant halite west of the previous margin (compare layers Composite halite margins and 2003 halite margins composite). Further west to northwest (southwestern half of T21S, R31E), the margin has not been significantly altered because the potash drillhole source data have not changed and there is no drilling for oil or gas. The thickness of the M-3/H-3 unit in this area is similar to the thickness in other areas where H-3 is known to be absent, and on this basis H-3 is presumed to be absent.

The biggest difference from the previous margin is displayed east and northeast of WIPP (Figures 3, 3A). Like H-2, there is a wedge-like area of mudstone along the east-central study area boundary. Like H-2, there is also an east to southeast extension of M-3 in the northern part of T22S, R32E. These two areas with no halite generally align west-northwest like M-2 in the same area. Like H-2, there is a zone of H-3 along the boundary between T22S, R32E and T22S, R33 that connects with thicker halite to the south and north.

The small area of M-3 along the east-central study area boundary (Figure 3A) is in the general area of the upland extent of San Simon Swale (SSS, layer Capitan outline) that trends southeast along the boundary of the Capitan reef (layer Capitan outline). The deepest part of the swale, about 10 km east of the study area (layer Capitan outline), is a depression, called the San Simon Sink, with annular fissures indicating modern subsidence.

Geophysical log cross-sections (Cross_section_ABC10-5-07.pdf; Cross_section_DEF10-5-07.pdf) show important details of the halite beds included in H-3 (see also Appendix A). In the cross-sections, one or two halite zones (salmon color) occur variably between the dolomite beds. The thin white zone between the two halites is mudstone or halitic mudstone. The red dashed line marks the presence of a polyhalite bed marked by very high natural gamma, high sonic velocity, and low neutron. Stratigraphic relationships reveal the polyhalite near the base of the upper halite where the upper halite is thick. With the exception of cross-section B-B', each cross-section displays one or more log(s) in which the polyhalite extends laterally under the overlying anhydrite, without any overlying halite. Some of these logs show halite under the polyhalite, while others display polyhalite under the overlying anhydrite (A-3) and an underlying mudstone or halitic mudstone. A few geophysical logs around the margin of H-3 do show that polyhalite extends beyond any halite in the M-3/H-3 interval (Powers and Holt, 2000), but these are not included in any cross-section. This relationship is important to unraveling the processes leading to the distribution of halite in the Rustler and will be discussed later.

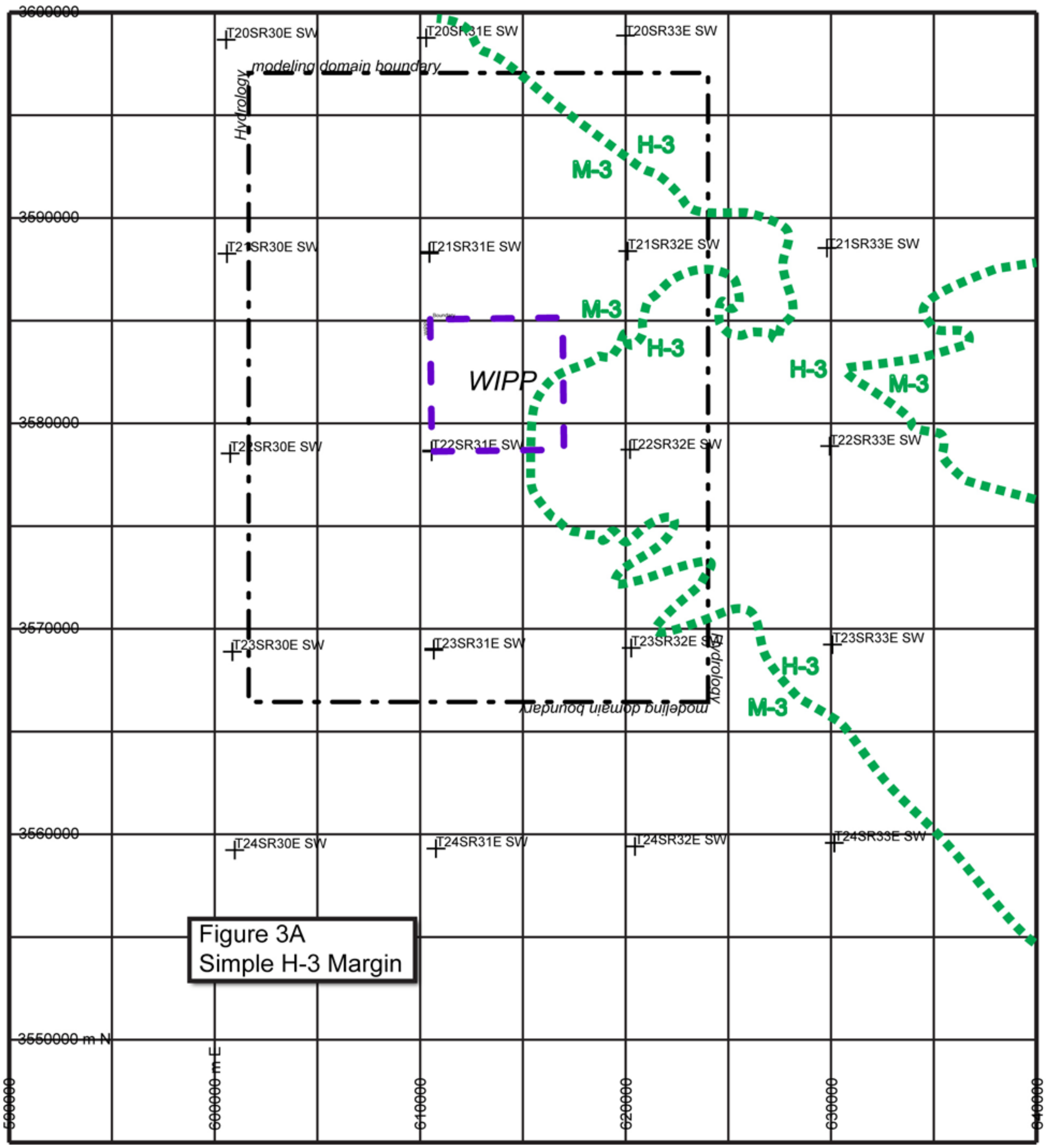


Figure 3A is a simplified version of Figure 3 without drillhole locations and H-3 thicknesses.

Along segments of the H-3 margin, there are variable differences in the thickness of the halite adjacent to the drawn margin. In some areas, the halite appears to become gradually thinner, while in other areas the thickness change is more significant across short distances. Within the halite depositional basin, however, there are similar differences in thickness across short lateral distances. Such changes might be considered indirect evidence of halite dissolution, but the magnitude of thickness changes within the basin is attributable to local changes in the depositional basin. There is no particular reason to assume that similar differences next to the margin are better indicators of dissolution than of depositional changes. Without more direct evidence (e.g., cores) of dissolution, the interpretation remains that this is principally a margin representing the depositional limits of halite, following Powers and Holt (2000).

Where significant halite has been dissolved in the recent geological past, as along Livingston Ridge, the dissolution margin is sharp and an escarpment developed directly overlying the Salado dissolution margin (e.g., Powers et al, 2006). The thickness difference between the H-3 maximum and the M-3 facies is about the same as that across the Salado dissolution margin at Livingston Ridge. The thickness change for H-3, however, is not sharply defined, and there is no surface escarpment. Gradual thinning is consistent with the interpreted depositional margin; it is not known if a surface escarpment would mirror a sharp dissolution margin, if it could develop, at the greater depths to H-3 in this area.

2.2.4 Rustler M-4/H-4 Margin. The presence or absence of halite in H-4 is not at this time known to be related to variations of Culebra transmissivity (Holt and Yarbrough, 2002). Findings of halite cements in Magenta Dolomite cores (Powers et al., 2006) east and northeast of WIPP are consistent with halite in the overlying M-4/H-4, but data on the hydraulic properties of the Magenta or higher stratigraphic units are not available to correlate with the existence of this halite. It is mapped (layer H4 Margin), however, to help guide understanding of halite in the Rustler as a whole. The margin of H-4 (Figures 4, 4A; compare layers Composite halite margins and 2003 halite margins composite) has changed somewhat, with more details and complex local relationships between M-4 and H-4, but much of the broad pattern previously shown (Powers, 2002, 2003) is still present.

Southeast of the WIPP site (Figures 4, 4A), in the northeastern quadrant of T23S, R31E, additional drillholes were evaluated that indicate H-4 is generally ~3 m thick. In addition, south of the H-4 margin in T23S, R31E, as now drawn, more detailed interpretation suggests that there are possible small outliers of H-4 (value of 1 is used as a general indicator rather than as a thickness estimate). Some additional drillhole data in T23S, R33E and T24S, R33E resulted in a revised H-4 margin in this area.

Along the eastern boundary of WIPP, the M-4/H-4 margin remains unchanged, but the thickness estimates provide a somewhat clearer definition of lateral changes. East-northeast of WIPP, log data show a NW-SE trending zone lacking halite, with halite thickening to the north and south of this trend. Cross-sections A, B, and F (layer Cross-sections) also show this trend where M-4 is present. This mudstone trend parallels similar trends in other mudstone-halite intervals.

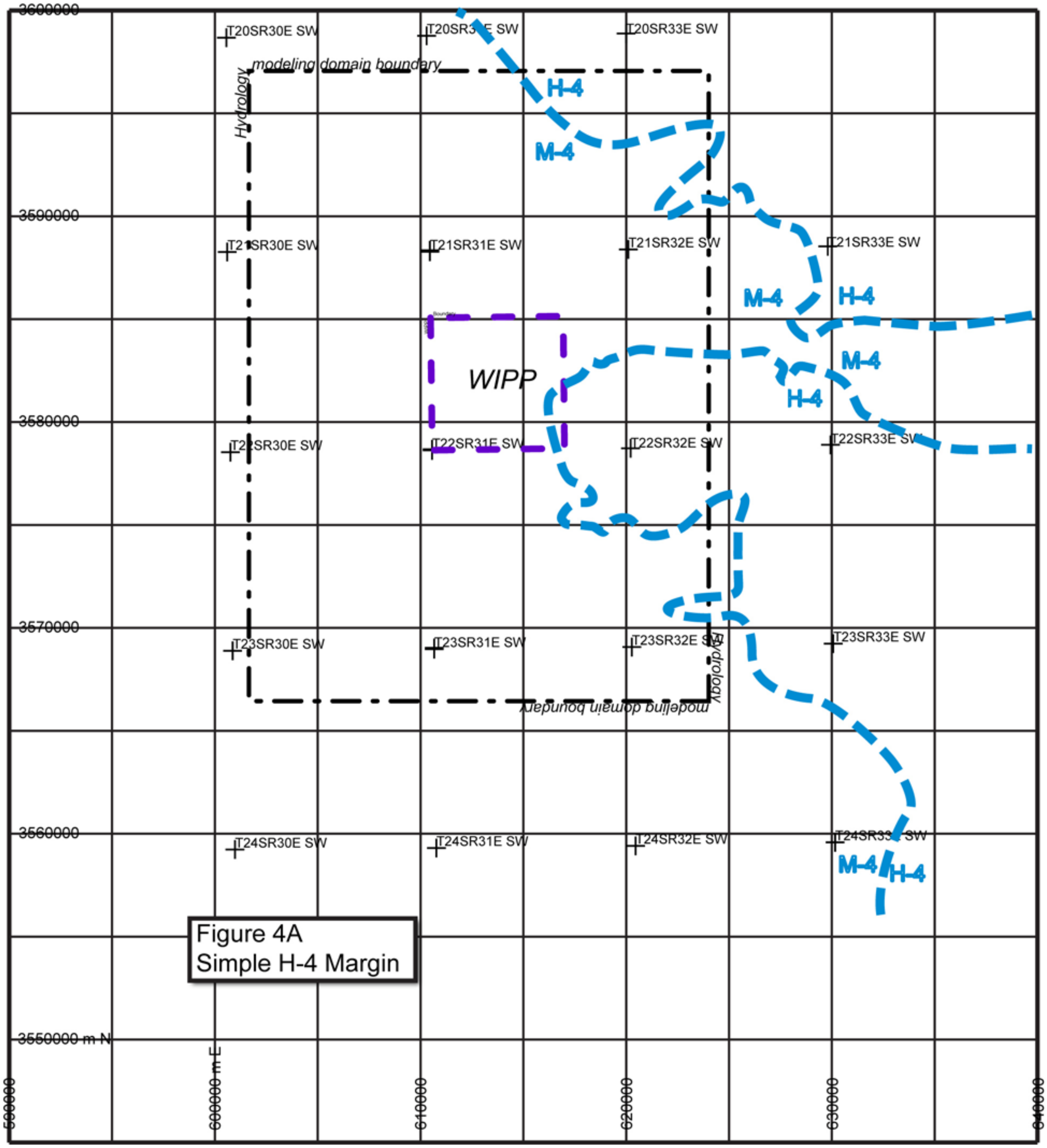


Figure 4A
Simple H-4 Margin

Figure 4A is a simplified version of Figure 4 without drillhole locations and H-4 thicknesses.

3.0 Understanding Rustler Halite Margins

3.1 Background

As reviewed in Holt and Powers (1988) and Powers and Holt (2000), Rustler halite margins were consistently interpreted until 1984 as a consequence of dissolution of halite from much more extensive original deposits. These conclusions rested on little direct evidence other than the fact that clastic (M-x) beds were thinner than equivalent halite (H-x) beds. Thus, the clastic unit was interpreted as the insoluble residue after halite had been removed. Direct studies of shafts and cores, however, revealed features that are consistent with depositional facies variations (e.g., Holt and Powers, 1988; Powers and Holt, 2000) with possible local effects along some margins (Beauheim and Holt, 1990). In addition, as pointed out by Lorenz (2006), the halite (H-x) beds contain far too little clastic material to be convertible to the clastic (M-x) beds by dissolution.

Early in WIPP history, hydraulic properties of Rustler units, especially the Culebra, were thought to be a consequence of dissolution of Rustler and upper Salado halite. With the interpretation that dissolution of Rustler halite has limited application at WIPP, a new paradigm for explaining the distribution of Culebra hydraulic properties was necessary. Holt and Yarbrough (2002) showed that other factors (depth of Culebra and dissolution of Salado halite) explained most of the distribution of Culebra properties. The presence or absence of H-3 has been included probabilistically by Holt and Yarbrough (2002) to refine estimates of Culebra hydraulic properties.

Refined estimates of Rustler halite margins here provide potential for evaluating model differences based on these relationships developed by Holt and Yarbrough (2002).

3.2 Current Halite Margins

As noted in presenting each halite margin, significant sections of the margins adjacent to WIPP are little changed. New drillholes and re-evaluated logs provide data that increase local complexity to the margins as well as defining them more precisely. Basic patterns are generally preserved. There are four basic features that are exhibited to varying degrees by each of the halite beds and the halite margins that are useful to explore further to understand the origin of the halite margins and their significance for the hydrogeology of the Rustler. One feature is the thicker zone of halite in the southeastern sector of the hydrologic modeling domain (Figures 1-4 and 1A-4A). Another is thicker halite in the northeastern corner of the study area, although this is little represented in the hydrologic modeling domain. A third feature is the NW-SE trend dominated by mudstone or thin halite between these two areas of thicker halite. The last feature is the vast tract of mudstone for each unit to the west and southwest of the halite margin. The last feature has been more extensively treated in Holt and Powers (1988) and Powers and Holt (2000), reporting and interpreting the features that indicate these mudstone tracts developed as mudflats adjacent to the halite depositional basin. Here the first three features are discussed together for their significance in interpreting the depositional processes and any post-depositional dissolution that might affect hydraulic properties of Rustler units.

Data for each of the halite margins east of WIPP show halite tends to thicken from the halite margins toward the center of the zone southeast of WIPP as well as toward the northeast. H-1 shows the least evidence of thickening of the different intervals. Both halite zones in H-3 show some thickening toward these centers as indicated in cross-sections. There is general thinning toward the NW-SE mudstone trend shown for each interval. The area of halite for each unit tends to vary somewhat, but margins can also overlap; i.e., they do not systematically narrow upward everywhere. These relationships are evidence that the thicker halites southeast of WIPP and toward the northeast corner of the domain are depositional basins separated by a mudstone facies tract along the mudstone trend.

The most dramatic additional evidence that these lithologic relationships represent facies changes due to depositional processes comes from H-3. Cross-sections reveal that a polyhalite bed within M-3/H-3 can be traced across these basins and onto the flank of the mudstone tract. The polyhalite in some areas converges with the base of A-3 as the halite above the polyhalite completely disappears. In a few wells, no halite exists under the polyhalite or mudstone; this was previously noted in Holt and Powers (1988) and Powers and Holt (2000). Polyhalite dissolves incongruently in the presence of water (e.g., Lambert, 1983). If mudstone was the dissolution residue after halite was removed by circulating groundwater, the polyhalite should also have been altered to gypsum and not extend beyond halite margins. In areas such as Nash Draw, upper Salado halite has been dissolved, and reddish-brown gypsum is the residue after alteration of polyhalite marker beds by infiltrating water (Lambert, 1983).

Polyhalite persists beyond the area of overlying halite in H-3 and even, in a few cases, beyond any halite deeper in the M-3/H-3 interval as well. It is not reasonable to interpret the lateral M-3 as a residue of dissolution in view of these occurrences. Instead, the relationships are consistent with the core and shaft features previously interpreted by Holt and Powers (1988) and Powers and Holt (2000) as evidence that mudstone represents depositional facies and not a residue.

H-3 ranges to more than 10 m thick near the margin across much of the area, with significant segments displaying values of 3 m or less. It has been cored in few places. At well H-12, ~3 km south of the southeastern corner of the WIPP site (IDnum 1247, green star on layers Drillhole IDnums and Drillhole locations), muddy halite beds are equivalent to the lower part (H-3a) of the unit as it can be subdivided farther east in the depocenter (Holt and Powers, 1988). H-3b does not appear to have been deposited, and the overlying A-3 doesn’t show evidence of fracturing consistent with removal of H-3b by dissolution. Some cross-sections show the extension of H-3a, and cross-section A shows it in the presence of the polyhalite. The geophysical logs can be consistently interpreted consistent with the core evidence.

Core data from SNL-8, ~1.6 km east of the northern portion of the eastern WIPP site boundary (IDnum #20177, green star, layers Drillhole IDnums and Drillhole locations), indicate some fracturing of the lower A-3 that is inferred as evidence of dissolution of limited halite from H-3 (Powers et al., 2006). A diversion in the current margin shows halite in two drillholes surrounded by drillholes without any indications of halite (layer H3 Margin). Here I extend the zone of suspected or known dissolution of H-3 (green dotted line, layer H3 Margin) to include SNL-8 and the excursion of the current margin.

H-4 halite is generally less than 5-6 m thick, with a few points reaching about 10 m. Powers et al. (2006) inferred that halite in this unit in the north-central part of this study area is equivalent stratigraphically to the lower half of the complete M-4 unit. Higher-energy sedimentary features in the upper part of M-4 suggested a more distal depositional center relative to drillholes with this lower halite. Log data in cross-sections A and B indicate that halite exists both above and below the argillaceous section, but the lower halite extends beyond the upper halite. Thus, the interpretation of Powers et al. (2006) is consistent with more distal areas but these data reveal a more complete depositional sequence.

Core data support depositional facies changes with some syndepositional dissolution of halite in the mudflat for these variations in thickness (Holt and Powers, 1988; Powers and Holt, 2000; Powers et al., 2006). Each halite unit tends to show thinner halite approaching the margin, although there are also individual points with thicker intervals. SNL-8 indicates a zone of limited dissolution of H-3 similar to previous interpretations.

These relationships indicate that the mudstone facies along the NW-SE trend east-northeast of WIPP are depositional in origin, and Rustler halite deposits show evidence that smaller basins developed within the broader Delaware Basin system that is revealed in earlier evaporite beds.

Underlying structural elements coincide with the depositional patterns in the Rustler and are explored further here.

3.3 Relevant Structural Elements

There are two general structures that are coincident with Rustler depositional patterns and are explored here as factors in deposition. The first is the evaporite deformation that has developed on a gently sloping base and the second is the Capitan reef. The Capitan reef (layer Capitan outline) is a depositional feature, and it marks the edge of the Delaware Basin immediately before evaporites began to precipitate to fill the basin. Castile Formation evaporites filled much of the basin, and they are deformed in the area northeast of WIPP (e.g., Anderson and Powers, 1978). The deformation propagated upward through the evaporite section, including the Rustler Formation. The elevation of the top of Culebra is a convenient marker for evaluating the extent of deformation for the Rustler (layers Culebra elevation (m) and Culebra elevation contours (m)). The general eastward dip of the top of the Bell Canyon Formation (layers Bell Canyon elev (m) and Bell Canyon elev contours (m)), which is also the base of the Castile Formation, shows that the evaporite deformation did not arise from basement tectonics.

The anticline indicated by top of Culebra is similar to the mudstone facies trends in each of the halite-bearing intervals (layer Halite Margins composite). Based on the earlier conclusion that the halite-mudstone lateral differences in thickness represent depositional facies changes, I suggest that the underlying evaporite-bearing Salado and Castile Formations deformed episodically, creating the conditions for the more restricted environments leading to halite deposition and the attendant facies changes. It is likely that salt withdrawal in the Castile and possibly Salado from the area southeast of WIPP dropped base level, and the halite migrated to the northeast and perhaps east to form the core of the anticline. The uplift of existing Rustler units likely further restricted inflow of water. Non-halite-bearing units of the Rustler show very limited or no similar trends in thickness relative to the anticline (see layer MH1 Thickness, A3 Thickness, Culebra thickness, and Culebra thickness contours). Rustler units other than mudstone-halites generally indicate greater water depth, and the thickness is less affected by minor basin relief. Instead of considering it a remarkable coincidence that halite units deposited during these events, it is more likely that we should think of the halite units being a consequence of the mini-basin formation after salt withdrawal.

The elevation difference for the Culebra between the axis of the depositional basin southeast of WIPP and the top of the anticline along sections A-A' and B-B' is 80-100 m. Overlying units are deformed as well, indicating that some deformation occurred after the Rustler was deposited. Halite thickness may, however, indicate the amount of deformation while halite was being deposited, as other informal units of the upper Rustler show little difference in thickness across the anticline, as previously discussed. The combined thickness of halite in H-3 and H-4, both above the Culebra, is at least 40 m in the depocenters on both sides of the anticline, while there is little or no halite in the equivalent mudstones across the top of the anticline. In view of the argument that the halite-mudstone relationships indicate facies changes across the anticline rather than dissolution, I infer that the 40+ m of halite represents as much as half of the deformation that occurred after the Culebra was deposited. Furthermore, this portion of the deformation occurred as the halite was being deposited, first in H-3 and somewhat later in H-4.

Additional work on this aspect is not needed for this study. The principal objective of this study was to define the halite margins. Understanding the processes by which the margin of halite units developed and estimating the effects on hydraulic properties because of these processes are interpretive processes that build on the basic data and previous studies. The mudstone facies northeast of WIPP do not indicate post-depositional dissolution, and the hydraulic properties of Rustler units in this area have not been enhanced by this process. In fact, even in the mudstone trend over the top of the Culebra anticline, it is possible that the mudstone facies of one or more of the intervals is cemented by halite that is not easily detected by these methods. The strain on the Culebra through deformation is relatively small, and it may be less important for having developed early in the post-depositional history of the Culebra and in the presence of adjacent halites – at least on the flanks of the anticline.

4.0 Quality Assurance

Data for the drillholes included in this study came from two sources: commercially available geophysical logs (purchased or downloaded from the New Mexico Oil Conservation Department web site) and core investigations of recently drilled wells for WIPP. Data were entered in an electronic database for the drillholes or wells. The principal items of interest for quality are: location (UTM coordinates) and an indicator of the presence of halite for each of four intervals in the Rustler. Location data mainly come from an export of data held in the drillhole database maintained by David Hughes (WRES). Additional wells drilled for WIPP have been added, with locations from well surveys and absence/presence of halite established on the basis of my core and log interpretations. Halite data were recorded as a value of 0 (no halite indicated) or a number (halite present; value represents an estimate of halite thickness). The value 1 indicates some evidence of halite, but not a good estimate of thickness.

Individual data points for location and absence/presence (thickness) of halite are not routinely checked. Plotted data overlain on previous maps show correspondence with earlier locations for drillholes in common. There are minor variations to individual locations as Hughes' database is modified regularly. There also may be minor variations in locations of WIPP wells due to resurveys underway. These are expected to be insignificant for this study. There are also individual drillhole locations where the current interpretation on the absence/presence of halite may differ from earlier studies, but these are not common. A data set has been provided of the wells in my database that are 1) within the study area, and 2) might be a source of data, even if none are plotted here. Maps of halite thickness, for example, only show well locations for which there is a specific data entry – either 0 (zero) or a value. Wells with null values are not plotted.

Data exported from the database were checked initially for outliers that might indicate major typographical errors. Extremes were checked individually and corrected as appropriate. In addition, low and high values that were not extreme were individually checked for consistency. Each plot of data for a mudstone-halite unit was then further checked for anomalies and outliers. Color coding for ranges of values helped identify outliers or truly anomalous data. This is the most practical way to check the data for gross location, typographical, or interpretive errors. Thickness estimates are helpful in identifying such issues. Most attention is paid to the data near the margin. It is irrelevant for this study whether, for example, an estimate of halite thickness well away from the margin should be 20 or 25 m.

Additional data identifying the drillhole (especially API number for oil and gas wells) are imported from Hughes' database. They are accepted as accurate, although general checking occurs in the process of accessing geophysical logs for interpretation. Here, an internal, unique identifier is assigned within my database to each well that is 5 digits or less. This is a more efficient identifier than a lengthy API number or well name.

One mathematical operation was performed on the data during export – thicknesses or elevations were computed in metric units from feet. The multiplier 0.3048 m/ft was always used for this conversion; for each export, a few of the computed values were checked with a hand calculator to determine that the set up of the command line was correct. Normal spreadsheet and database operations were used to sort data for plotting.

5.0 Computers and Software

The software used in this report was for data recording, preparation of illustrations, and report writing. Location and drillhole data supplied by Hughes in an Access table were imported into a Visual FoxPro (VFP) 9.0 data table to form the framework of the geology. Data on halite units were recorded in the VFP data table using a form to reduce potential for processing errors in a spreadsheet. The data for each halite unit (including basic well identifiers and UTM coordinates) were exported to a table in *Microsoft® Excel® 2003* SP2 in preparation for plotting. Graphic plots of each halite unit were developed with *Golden Software Grapher 5.03.19.* Plots were copied directly into *Adobe® Illustrator® CS* for figure preparation. Contour lines, halite margins, and other figure elements were done using *Illustrator*. *Microsoft® Word 2003* SP2 was used to prepare the report, and the final report file was prepared as a pdf using *Adobe® Acrobat® 7.0* version 7.0.9. All software has been registered to Dennis W. Powers.

All software was used on a personal computer containing an Intel® Core®2 Duo running at 1.86GHz with 3.25 GB of RAM. The operating system is *Microsoft® Windows® XP* version 2002 with Service Pack 2 installed and registered to Dennis W. Powers.

Electronic files attached to this report are in Excel® 2003, Acrobat® 7.0, or Word 2003 formats.

6.0 Discussion

Additional data points and some re-evaluation of drillhole data have added some local complexity to the estimated margin locations of halite within Rustler subunits. Margins near WIPP remain nearly unchanged. This additional complexity to the margins does not change the basic interpretation that the margins are the result of deposition and local syndepositional dissolution of halite (Holt and Powers, 1988; Powers and Holt, 2000; Powers et al., 2006). Core evidence from well SNL-8 shows limited brecciation of A-3 that I interpret as an extension of a narrow margin along the H-3 margin where a limited amount of halite was dissolved after deposition.

The more interesting result of adding data points and estimates of thickness is that all margins show some gross trends that are similar. Southeast of WIPP, halite thickens and the margins resemble the outline of a depocenter that is elongate roughly northwest to southeast. In the northeast quadrant of the study area, halite tends to thicken as well. Between these two areas, three of the halitic units are divided by mudstone facies. H-1 thickness is not a similar datum because the estimate includes log signatures that may be halite cement, but there is a similar mudstone "embayment" for M-1/H-1 farther northwest.

The gross trends of these margins are similar to the trend in the elevation of the top of Culebra. As previously described (e.g., Holt and Powers, 1988; Powers et al., 2003), this anticlinal feature was called "Divide anticline". Mudstone dominates along this trend in three of the mudstone-halite units of the Rustler, and the evidence presented for depositional facies rather than dissolution leads to the proposition that halite facies were deposited in mini-basins formed by nascent salt withdrawal in underlying formations and halite migration into the anticline.

This hypothesis is not new, although it has not previously been applied to the Delaware Basin and it has not been proposed in an area where evaporites are the response to mini-basin formation. The more common literature deals with thick clastics that form in conjunction with diapiric processes. Recent literature includes such explanations for the remarkable preservation of lycopsid trees in Pennsylvanian coal-bearing strata in Nova Scotia (Waldron and Rygel, 2005) and deposits around the diapiric structures in northeastern Mexico (Giles and Lawton, 1999).

Mini-basins in the Paradox Basin (Utah) formed where salt withdrawal and halite anticlines are more nearly equivalent to the Delaware Basin structures. A detailed study of overlying siliciclastic beds of the Chinle Formation revealed that the distribution and development of paleosols could be used to detect and unravel the development of these halokinetic mini-basins (Prochnow et al., 2006). The concept of these halokinetic mini-basins is clearly established. It is not established whether study of the evaporite facies of the Castile, Salado, and Rustler Formations as well as fluvial facies of the clastic Dewey Lake can unravel the Delaware Basin halokinetic mini-basins in similar detail. Such a study is not a part of this project and is generally unnecessary to estimating hydraulic properties in such an area.

7.0 Personnel

Dennis W. Powers interpreted geophysical logs, entered data, prepared illustrations, and wrote this Task 1A report. Glen Garrett imported data from the Hughes data set into VFP, set up the basic VFP table, and created a form for entering Rustler halite thickness data into the VFP table.

8.0 References Cited

Anderson, R.Y., and Powers, D.W., 1978, Salt anticlines in Castile-Salado evaporite sequence, northern Delaware Basin, *in* Austin, G.S., ed., Geology and Mineral Deposits of Ochoan Rocks in Delaware Basin and Adjacent Areas: New Mex. Bur. Mines and Min. Res. Circ. 159, p. 79-84.

Beauheim, R.L., 2004, Analysis Plan for Evaluation and Recalibration of Culebra Transmissivity Fields, AP-114: Sandia National Laboratories, 19 p.

Beauheim, R.L., and Holt, R.M., 1990, Hydrogeology of the WIPP site, *in* Powers, D.W., Holt, R.M., Beauheim, R.L., and Rempe, N., eds., Geological and Hydrological Studies of Evaporites in the Northern Delaware Basin for the Waste Isolation Pilot Plant (WIPP): Geological Society of America (Dallas Geological Society) Guidebook 14, p. 45-78.

Giles, K.A., and Lawton, T.F., 1999, Attributes and evolution of an exhumed salt weld, La Popa basin, northeastern Mexico: *Geology*, v. 27, p. 323-326.

Holt, R.M., and Powers, D.W., 1988, Facies variability and post-depositional alteration within the Rustler Formation in the vicinity of the Waste Isolation Pilot Plant, southeastern New Mexico: WIPP-DOE-88-004, Department of Energy, Carlsbad, NM.

Holt, R.M., and Yarbrough, L., 2002, Analysis report, Task 2 of AP-088, Estimating base transmissivity fields, Sandia National Laboratories, Carlsbad, New Mexico (Copy on file in the Sandia WIPP Records Center under ERMS# 523889).

Holt, R.M., Beauheim, R.L., and Powers, D.W., 2005, Predicting fractured zones in the Culebra Dolomite, *in* Faybishenko, B, Witherspoon, P.A., and Gale, J., eds., Dynamics of Fluids and Transport in Fractured Rock: AGU Geophysical Monograph Series, v. 162, p. 103-116.

Lambert, S.J., 1983, Dissolution of evaporites in and around the Delaware Basin, southeastern New Mexico and west Texas: SAND82-0461, Sandia National Laboratories, Albuquerque, NM.

Lorenz, J.C., 2006, Assessment of the geological evidence for karst in the Rustler Formation at the WIPP site, *in* Caves & Karst of Southeastern New Mexico, L. Land et al., eds., NM Geological Society Fifty-seventh Annual Field Conference Guidebook, p. 243-251.

McKenna, S.A., and Hart, D.B., 2003, Analysis report, Task 4 of AP-088, Conditioning of base T fields to transient heads, Sandia National Laboratories, Carlsbad, New Mexico (Copy on file in the Sandia WIPP Records Center under ERMS# 531124).

Powers, D.W., 2002, Analysis report Task 1 of AP-088, Construction of geologic contour maps: report to Sandia National Laboratories, April 17, 2002 (ERMS # 522085).

Powers, D.W., 2003, Addendum 2 to Analysis report Task 1 of AP-088, Construction of geologic contour maps: report to Sandia National Laboratories, January 13, 2003 (ERMS # 522085).

Powers, D.W., and Holt, R.M., 1995, Regional geological processes affecting Rustler hydrogeology: IT Corporation report prepared for Westinghouse Electric Corporation, 209 p.

Powers, D.W., and Holt, R.M., 1999, The Los Medaños Member of the Permian Rustler Formation: *New Mexico Geology*, v. 21, no. 4, p. 97-103.

Powers, D.W., and Holt, R.M., 2000, The salt that wasn't there: mudflat facies equivalents to halite of the Permian Rustler Formation, southeastern New Mexico: *Journal of Sedimentary Research*, v. 70, no. 1, p. 29-36.

Powers, D.W., and Richardson, R.G., 2003, Basic data report for drillhole SNL-2 (C-2948) (Waste Isolation Pilot Plant): DOE/WIPP 03-3290, US Department of Energy, Carlsbad, NM.

Powers, D.W., Holt, R.M., Beauheim, R.L., and McKenna, S.A., 2003, Geological factors related to the transmissivity of the Culebra Dolomite Member, Permian Rustler Formation, Delaware Basin, southeastern New Mexico, *in* Johnson, K.S., and Neal, J.T., eds., Evaporite karst and engineering/environmental problems in the United States: Oklahoma Geological Survey Circular 109, p. 211-218.

Powers, D.W., Holt, R.M., Beauheim, R.L., and Richardson, R.G., 2006, Advances in depositional models of the Permian Rustler Formation, southeastern New Mexico, *in* Caves & Karst of Southeastern New Mexico, L. Land et al., eds., NM Geological Society Fifty-seventh Annual Field Conference Guidebook, p. 267-276.

Prochnow, S.J., Atchley, S.G., Boucher, T.E., Nordt, L.C., and Hudecs, M.R., 2006, The influence of salt withdrawal subsidence on palaeosol maturity and cyclic fluvial deposition in the Upper Triassic Chinle Formation: Castle Valley, Utah: *Sedimentology*, v. 53, p. 1319-1345.

Waldron, J.W.F., and Rygel, M.C., 2005, Role of evaporite withdrawal in the preservation of a unique coal-bearing succession: Pennsylvanian Joggins Formation, Nova Scotia: *Geology*, v. 33, p. 337-340.

9.0 List of Electronic Files Submitted

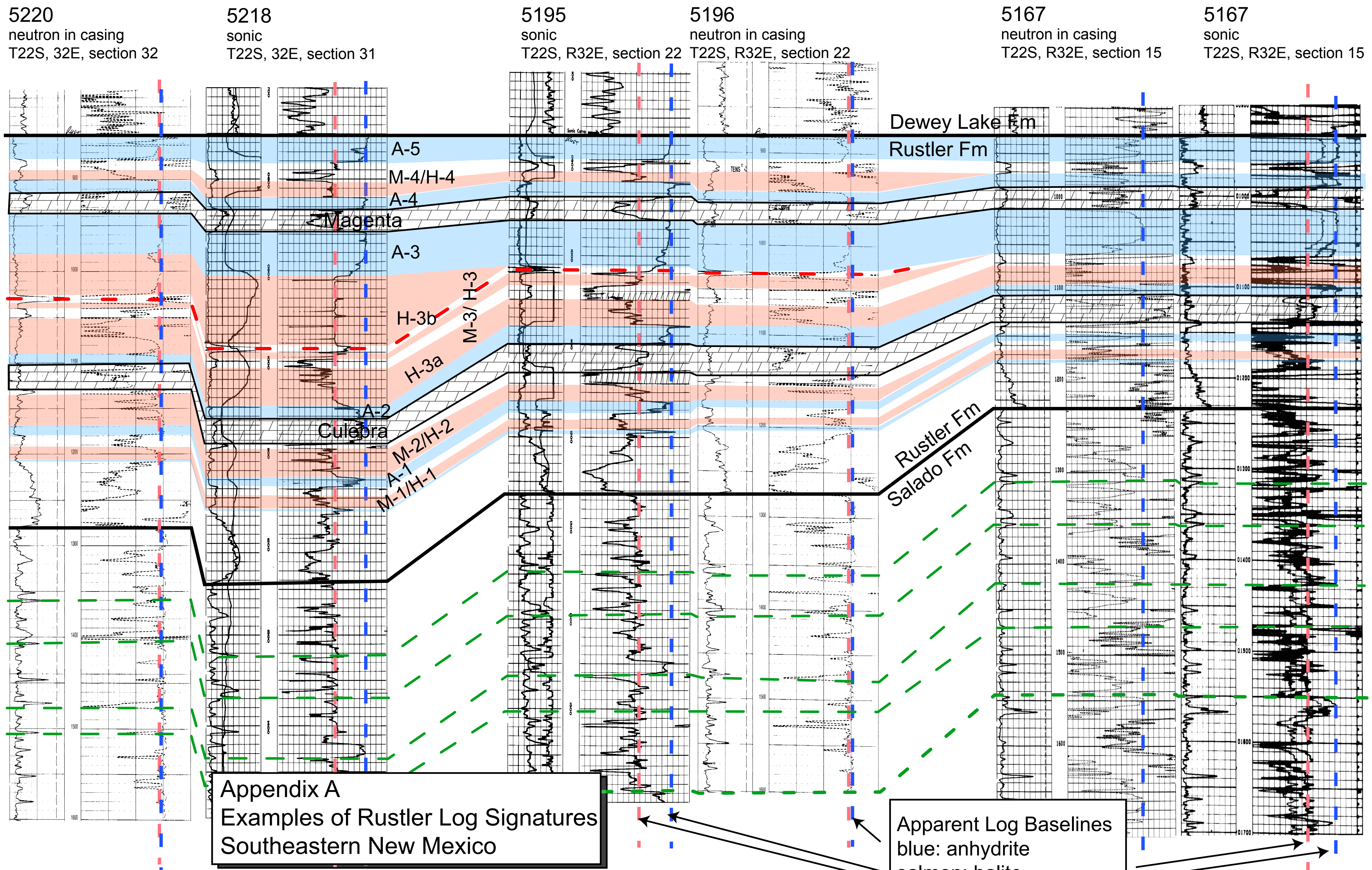
The following electronic files have been submitted for Task 1A:

Main report files: Analysis_Report_for_Task_1A_AP-114_10-5-07final.doc (Word 2003)
Analysis_Report_for_Task_1A_AP-114_10-5-07final.pdf (Acrobat® 7.0)

Figures as separate files: Task_1A_for_AP-114_Figure_1.pdf (Acrobat® 7.0)
Task_1A_for_AP-114_Figure_2.pdf (Acrobat® 7.0)
Task_1A_for_AP-114_Figure_3.pdf (Acrobat® 7.0)
Task_1A_for_AP-114_Figure_4.pdf (Acrobat® 7.0)
Task_1A_for_AP-114_AppendixA.pdf (Acrobat® 7.0)
Cross_sectionABC10-5-07.pdf (Acrobat® 7.0)
Cross_sectionDEF10-5-07.pdf (Acrobat® 7.0)
Rustler_mh_margins_10-5-07.pdf (Acrobat® 7.0)

Data source table: Task1A_for_AP-114_Composite_Excel_Files_10-4-07.xls (Excel® 2003)

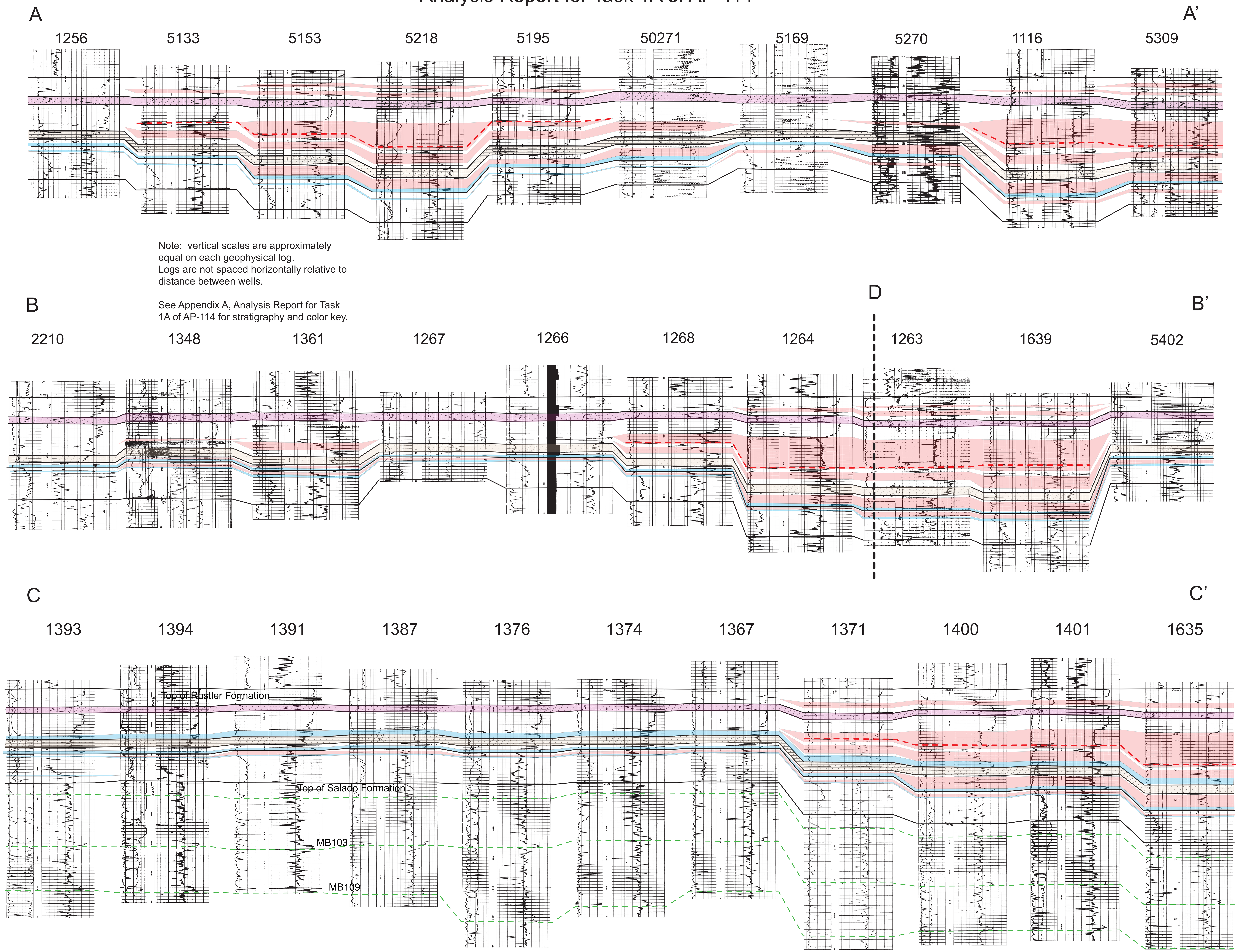
Résumé for Dennis W. Powers (Acrobat® 7.0)



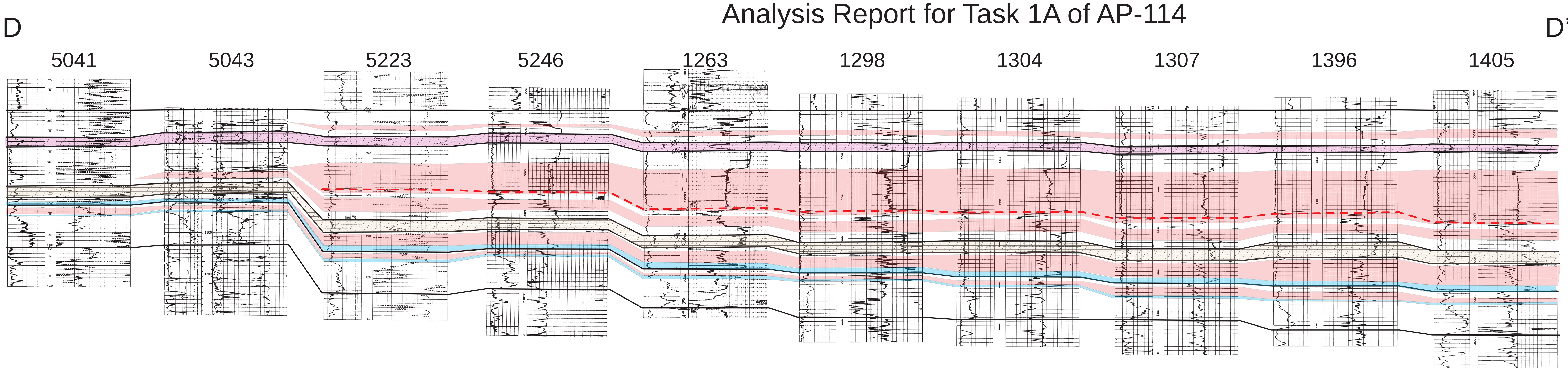
Appendix A
Examples of Rustler Log Signatures
Southeastern New Mexico

file name: Task_1A_for_AP-114_Figure_1.pdf

Cross Sections ABC
Analysis Report for Task 1A of AP-114



Cross Sections DEF
Analysis Report for Task 1A of AP-114



Note: vertical scales are approximately
equal on each geophysical log.
Logs are not spaced horizontally relative to
distance between wells.

See Appendix A, Analysis Report for Task
1A of AP-114 for stratigraphy and color key.