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# AP-147 Analysis Report: Evaluation of WIPP Groundwater Compositions

## (AP-147: Analysis Plan for the Evaluation of WIPP Groundwater Compositions)

**Task Number 1.4.2.3**

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# 1. Introduction

This analysis report discusses the aqueous geochemistry of the waters from the geologic strata above the Salado Formation in the vicinity of the Waste Isolation Pilot Plant (WIPP). This report is focused on groundwaters from the Rustler Formation, the Dewey Lake Redbeds Formation, and the Santa Rosa Formation (Figure 1). Largely excluded from this analysis are groundwaters from the Culebra Dolomite Member of the Rustler Formation because those groundwaters have recently been studied under AP-125 (Domski and Beauheim, 2005; 2008). The only Culebra samples evaluated in this report are those that have been collected since January 2008, as well as historic data from non-WIPP wells that were not considered by Domski and Beauheim (2008).

In examining hydrochemical data from formations above the Salado, we determine how they fit with the classification schemes used by Domski and Beauheim (2008) to characterize the Culebra and develop new classification schemes as necessary. We also assess the consistency of the solute concentrations and groundwater classifications with the conceptualization of recharge and flow into and through the strata above the Salado Formation as developed by Corbet and Knupp (1996) and Corbet (1998), and propose modifications of that conceptualization as appropriate that might be investigated as the three-dimensional (3D) basin-scale model of Corbet and Knupp (1996) is updated under AP-139 (Kanney, 2008). In general, this analysis report has been prepared to meet the requirements of Tasks 1 – 4 of AP-147 (Beauheim and Domski, 2009). One deviation from the AP-147 requirements exists; the analytical data utilized for the analyses and plots discussed in this report were verified against their applicable references and routine calculation reports were not generated for the data verification task. The verified spreadsheet is entitled *AP-147_Hydrochemical_Data.xlsx* and will be stored in CMS. The data references exist in the Records Department in the forms of published data reports or laboratory analytical reports.

Trends in the aqueous geochemistry of the waters from above the Salado are identified by organizing the waters into groups based on several criteria. These criteria include the hydrochemical facies designations first proposed by Ramey (1985) and expanded by Siegel et al. (1991b), normative salt assemblages as calculated with the code SNORM (Bodine and Jones, 1986), and solution concentration as represented by ionic strength calculated using PHREEQCI (Charlton et al., 1997; Parkhurst and Appelo, 1999).

## 1.1 Geologic Setting

The Waste Isolation Pilot Plant (WIPP) is the U.S. Department of Energy's deep geologic repository for transuranic and mixed waste. The WIPP repository has been excavated 655 m below ground surface in Permian halite beds of the Salado Formation (Figure 1) in the Delaware Basin in southeastern New Mexico. The Salado Formation is overlain by the Permian Rustler Formation, which consists of five members. Figure 2 shows the stratigraphic subdivisions of the Rustler, including the informal stratigraphy of Holt and Powers (1988). The Culebra and Magenta are predominantly dolomites, with the Culebra being locally argillaceous and arenaceous while the Magenta is more gypsiferous. The other three members of the Rustler consist principally of beds of anhydrite (locally altered to gypsum) and mudstone (or other fine-

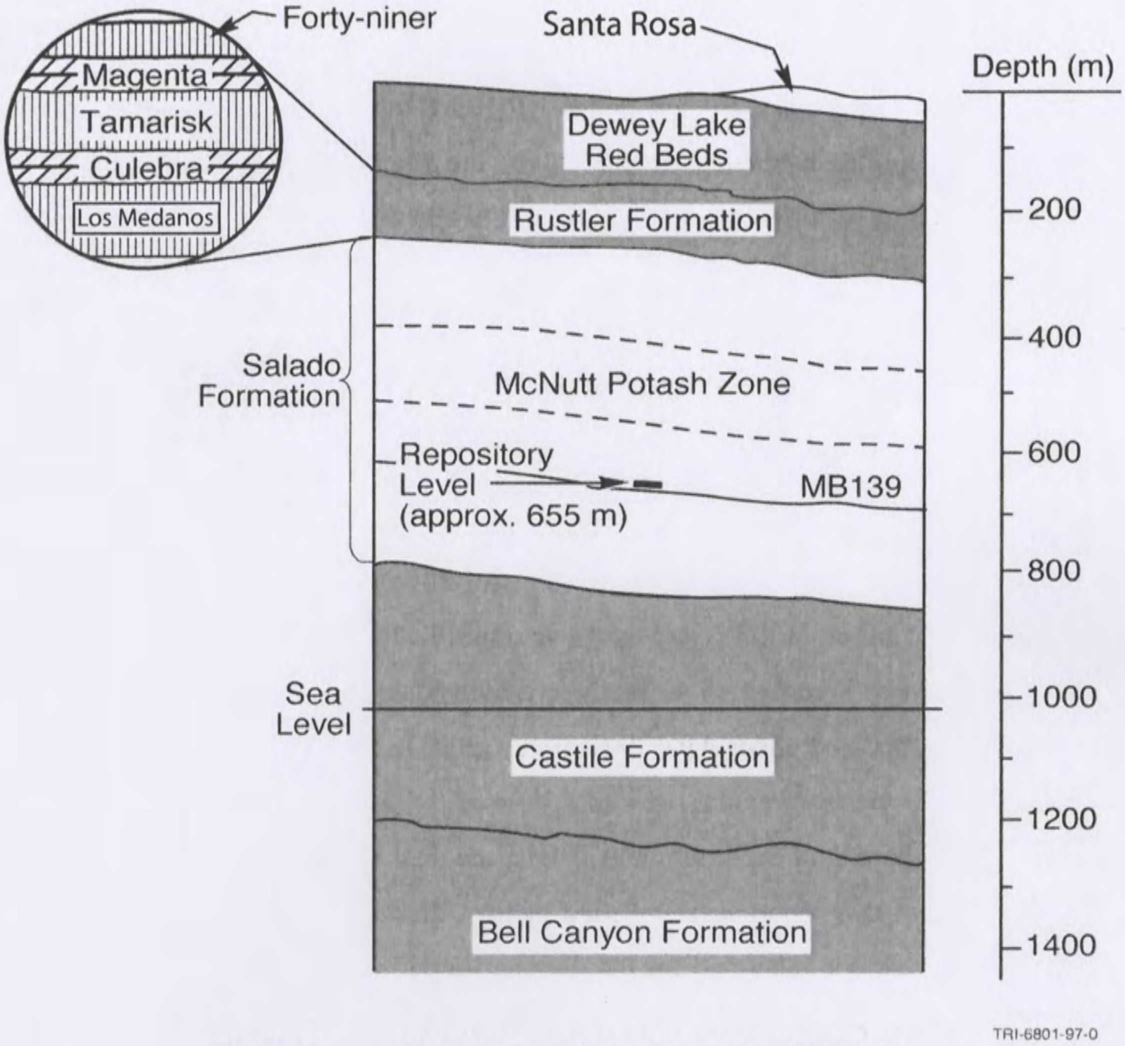


**Figure 1. General stratigraphy at the WIPP site.**

grained clastics). Halite beds are found in association with the mudstones east of the WIPP site, and halite beds and/or cements are found over much of the WIPP site in the lower Los Medaños mudstone and clastics. Using data from borehole geophysical logs, Powers (2007) has mapped the depositional margins of halite in the mudstone units of the Rustler (Figure 3).

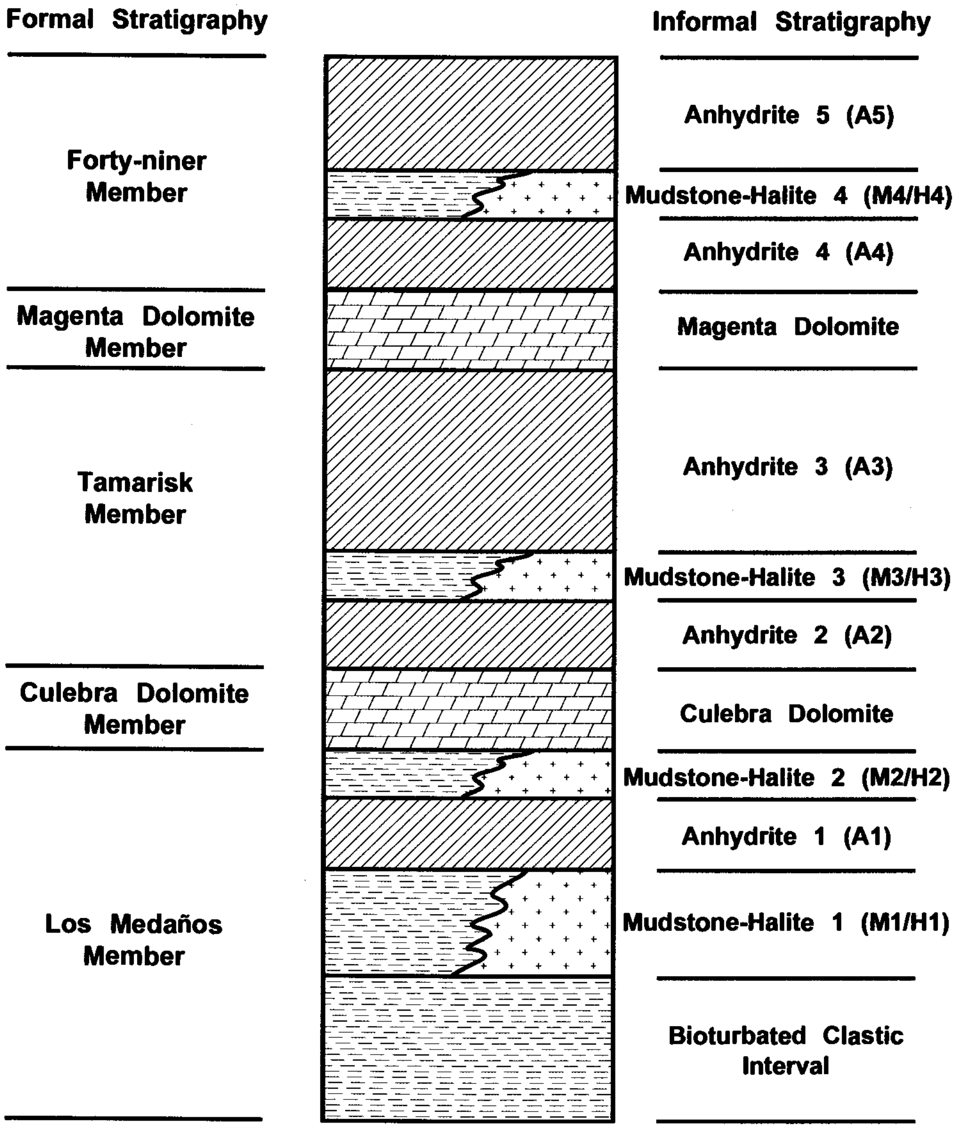


**Figure 2.** **Detailed stratigraphy of the Rustler Formation.**

The Permo-Triassic Dewey Lake is composed mainly of interbedded sandy siltstone, argillaceous siltstone, and fine-grained sandstone. The upper 30-60 m of the Dewey Lake are calcareous, while the lower portion of the Dewey Lake is tightly cemented with gypsum/anhydrite. The porosity and permeability of the upper, calcite-cemented portion of the

Dewey Lake are much higher than in the lower, sulfate-cemented portion. Water is found locally in the upper Dewey Lake, possibly perched on the surface where the cement changes from calcite to sulfate. The Dewey Lake tends to be fractured throughout, but the fractures in the lower portion are sealed with sulfate.

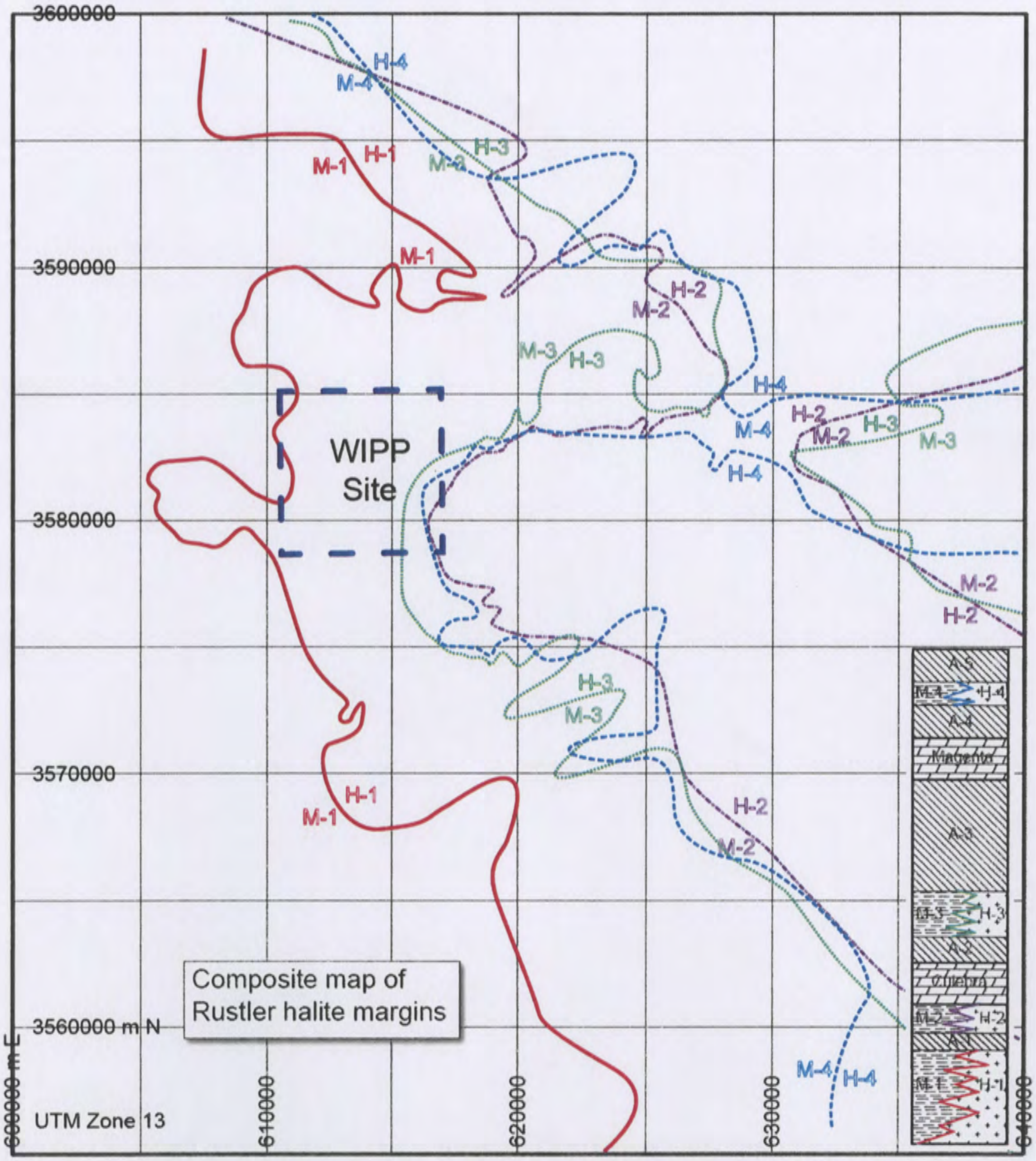


**Figure 3.** Mudstone-Halite (M-H) margins in the Rustler Formation.

The Triassic Santa Rosa consists primarily of moderately indurated sandstone with interbedded siltstone. The lower Santa Rosa is generally less calcareous than the upper part. The Santa Rosa has been completely removed by erosion from approximately the center of the WIPP site westward; it dips and thickens to the east.

Dissolution of the upper Salado Formation has created a large subsidence trough, known as Nash Draw, to the west of the WIPP site (Figure 4). Within Nash Draw, evaporite karst is present in the sulfatic members of the Rustler Formation, and the Culebra and Magenta, where present, are collapsed and broken. Portions, or all, of the Dewey Lake and various members of the Rustler have been locally eroded away in Nash Draw. A "brine aquifer" is found within dissolution residue at the Rustler-Salado contact in some parts of Nash Draw (Robinson and Lang, 1938).

## *1.2 Previous Studies*

Previous studies of the chemistry of the groundwaters above the Salado fall into two groups, data-based studies which examine the chemistry of water samples (Ramey, 1985; Lambert, 1991; Lambert and Carter, 1987; Chapman, 1988; Bodine and Jones, 1990; Myers et al., 1991; Siegel and Lambert, 1991; Siegel et al., 1991b; Domski and Beauheim, 2008), and flow-modeling-based studies which seek to explain the distribution of the water types (Corbet and Knupp, 1996; Kröhn and Schelkes, 1996; Corbet, 1998). All of these studies were largely focused on the Culebra and, except for Bodine and Jones (1990), involved minimal consideration of the water chemistry of other units. Siegel et al. (1991a) provide a comprehensive summary of the previous data-based studies, and only a brief overview is provided in this report.

Ramey (1985) recognized three hydrochemical facies within the Culebra and, based on the two-dimensional flow model in use at that time, concluded that flow was from regions of high total dissolved solids concentration to regions of lower concentration. Table 1 provides specific information on the hydrochemical facies identified by Ramey (1985). Subsequent studies sought to explain the compositional variations in the Culebra brines citing reasons such as climate change (Lambert, 1991; Lambert and Carter, 1987) and dilution or recharge (Chapman, 1988; Myers et al., 1991). Some of these later studies (Lambert, 1991; Lambert and Carter, 1987) supported the conceptual model of confined groundwater flow in the Culebra, and used several lines of argument against vertical flow into the Culebra. Among these were the prevalence of anhydrite over gypsum in the Rustler members above the Culebra (Siegel and Lambert, 1991), hydrogen and strontium isotope signatures of gypsum and sulfate and carbonate minerals (Lambert, 1991; Brookins and Lambert, 1988), and radiocarbon dates of Culebra waters (Lambert, 1987).

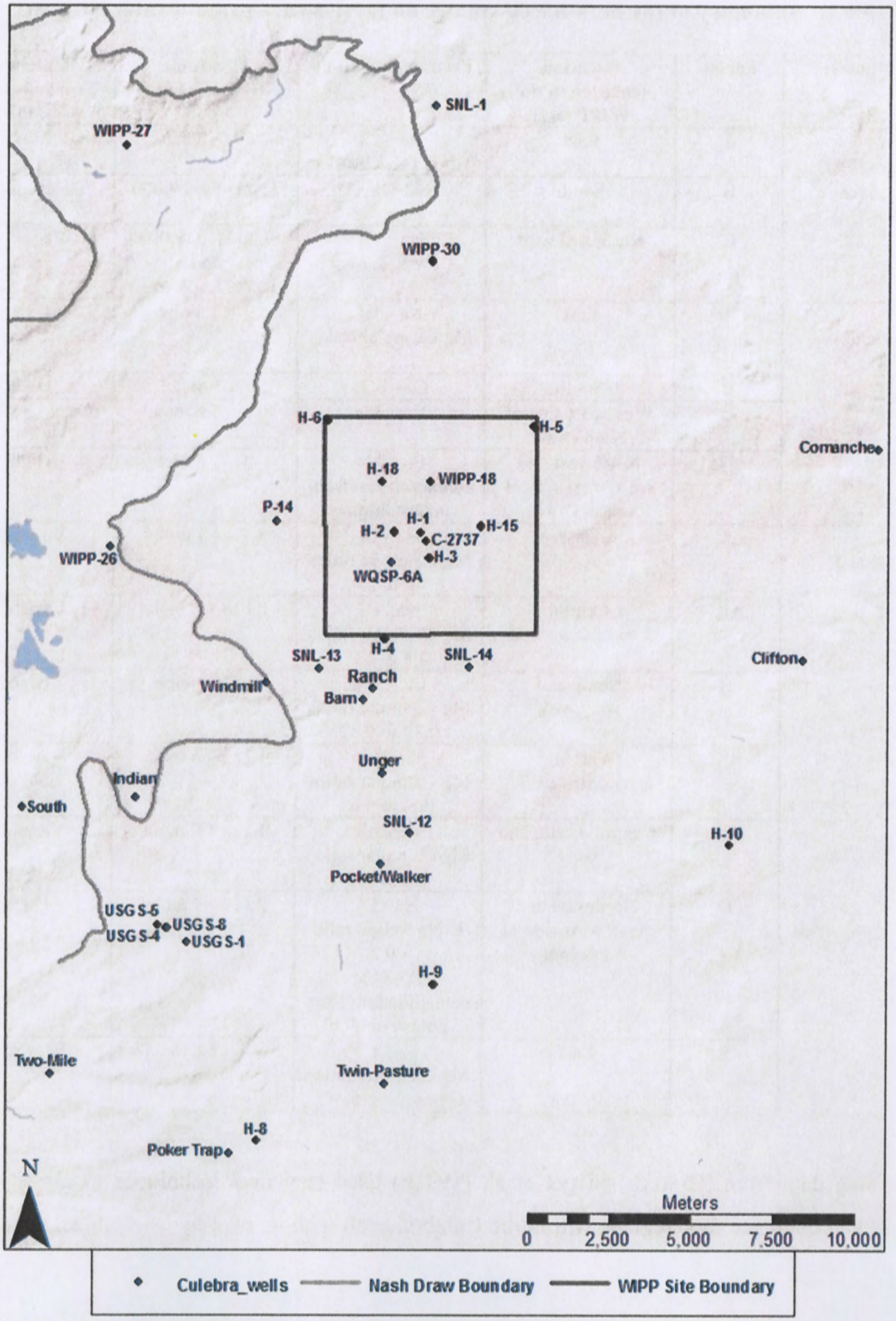


**Figure 4.** **WIPP site and surrounding area with the wells considered in this report.**

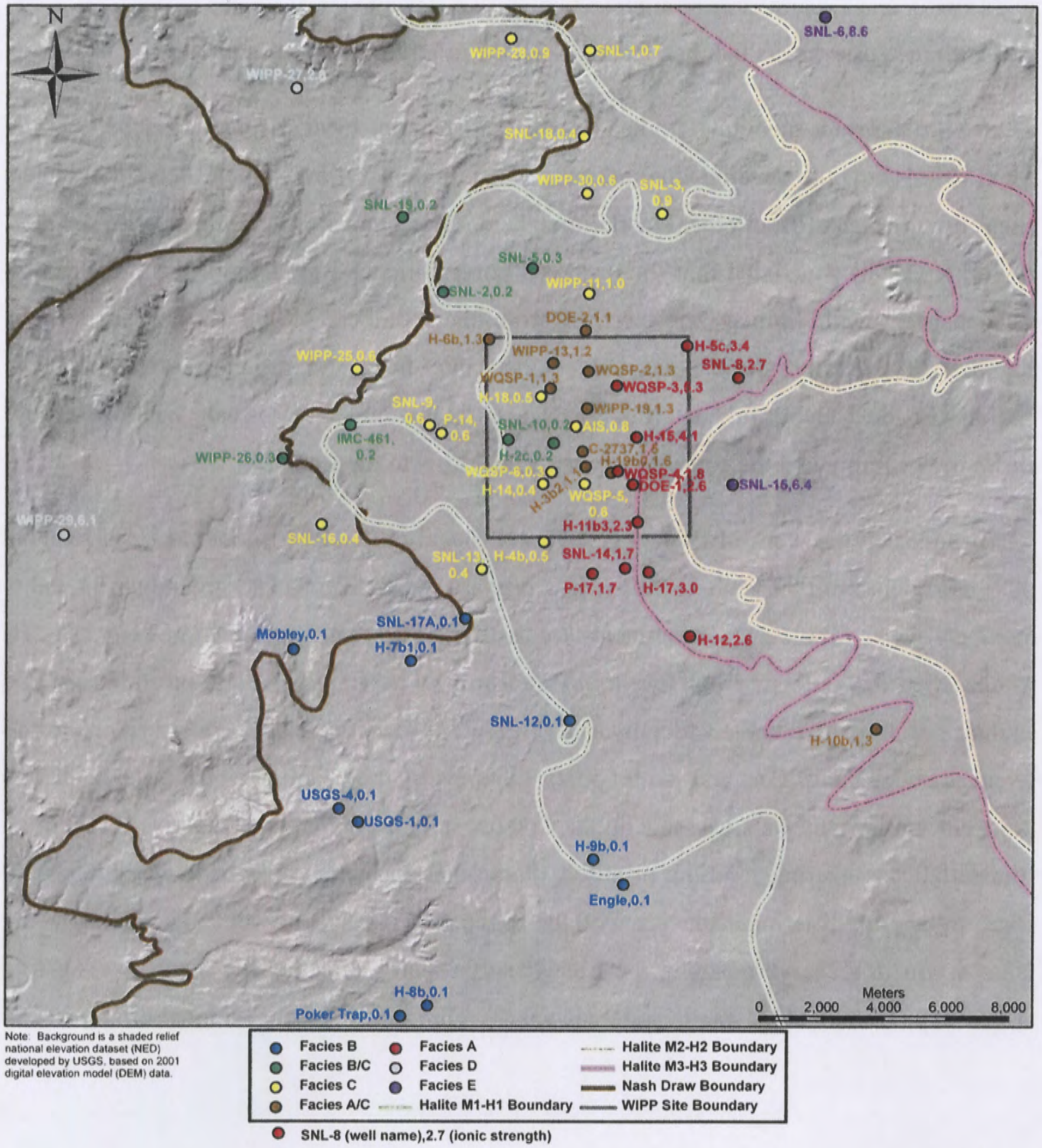
**Table 1. Summary of the data-based studies on the Culebra groundwater chemistry.**

| Author(s) | Facies | Location (relative to the WIPP site) | Predominant Ions | TDS/Ionic Strength Range | Culebra Transmissivity Condition |
|---|---|---|---|---|---|
| Ramey (1985) | A | East | Na – Cl<br>(high K & Mg) | >60,000 mg/L | Low |
| | B | South | Ca – $SO_4$ | Typically < 9,000 mg/L | High |
| | C | North and west | Na – Cl<br>(low K & Mg) | 9,000 – 239,000 mg/L<br>(increases W to E) | Variable |
| Siegel et al. (1991b) | A | East | Na – Cl<br>Mg:Ca molar ratios 1.2 - 2 | 2 – 3 molal | Low |
| | B | South | Ca - $SO_4$ | <0.1 molal | High |
| | C | West, east side of Nash Draw | Variable | 0.3 – 1.6 molal | Generally high |
| | D | Northwest and west, west side of Nash Draw | Possible contamination from potash mining | 3 – 7 molal | High |
| Domski and Beauheim (2008) | A | East | Na - Cl<br>Mg/Ca molar ratios 1.2 to 2.4 | 1.7 - 4.5 molal | Variable |
| | A/C | Central | Na - Cl<br>Mg/Ca molar ratios 0.5 to 1.2 | 1.1 to 1.6 molal | Variable |
| | B | South and southwest | Ca - $SO_4$<br>Mg/Ca molar ratios 0.32 to 0.52 | ≤0.1 molal | High |
| | B/C | West and northwest | Variable<br>Mg/Ca molar ratios 0.4 to 0.6 | 0.2 to 0.3 molal | Variable |
| | C | Central, north, and west | Variable<br>Mg/Ca molar ratios 0.4 to 1.1 | 0.3 to 1.0 molal | Variable |
| | D | Northwest and west, west side of Nash Draw | Na - Cl<br>K/Na weight ratio ~0.2<br>Possible contamination from potash mining | 2.6 – 5.9 molal | High |
| | E | East | Na - Cl<br>Mg/Ca molar ratios 4.1 – 6.6 | 6.4 – 8.6 molal | Very low |

Using data from 22 wells, Siegel et al. (1991b) used statistical techniques to classify the brines and delineate four regions within the Culebra, each with its own hydrochemical signature (see Table 1). Bodine and Jones' (1990) analyses supported the hydrochemical facies of Siegel et al. (1991b), and explained the complex chemistry of the Culebra brines as mixtures of connate brines with meteoric waters that had reacted with the overlying Rustler members.

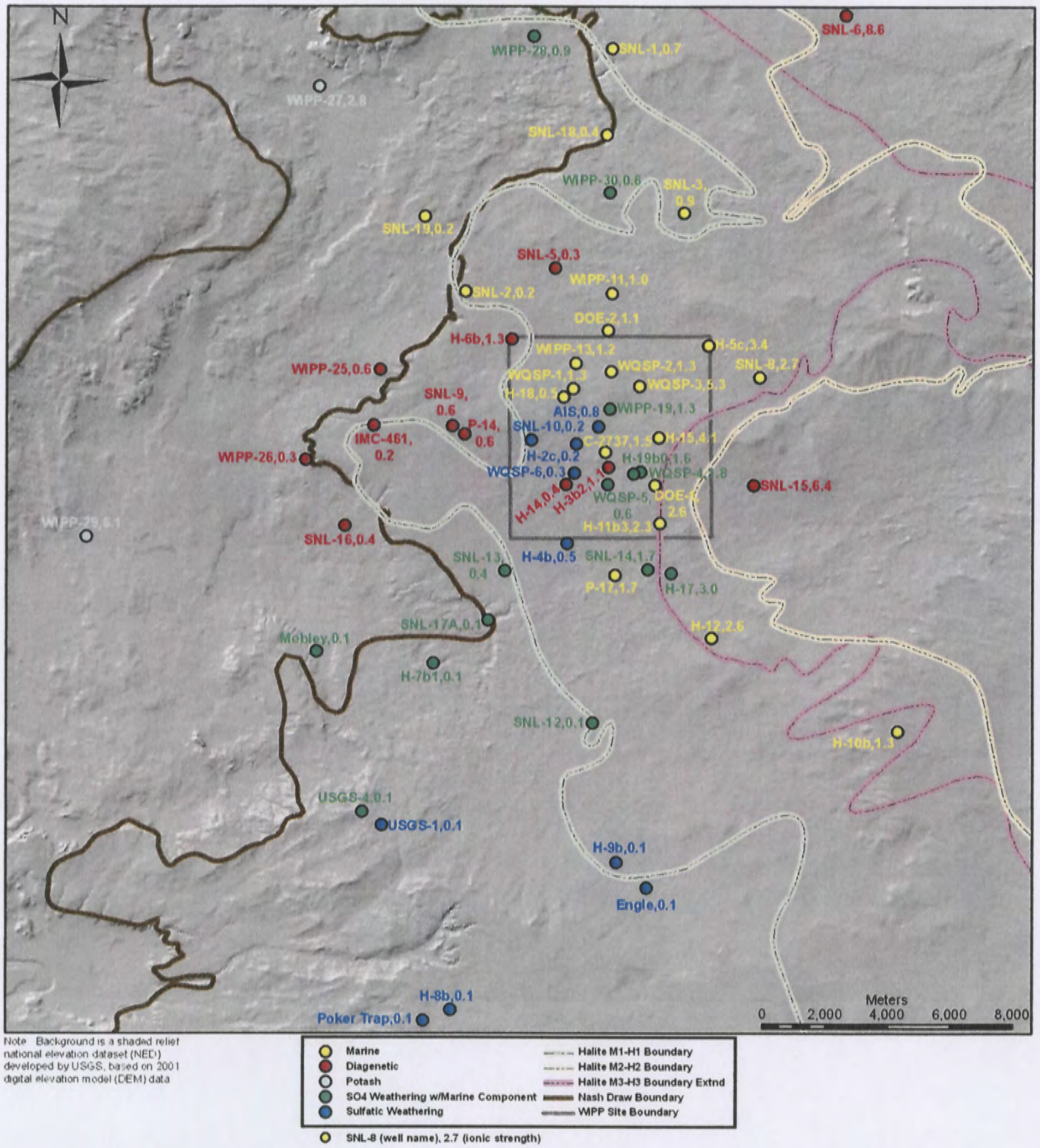
Later groundwater modeling studies (Corbet and Knupp, 1996; Kröhn and Schelkes, 1996; Corbet, 1998) sought to develop alternate conceptual models of flow in the Culebra that included vertical flow (leakage) from other Rustler members. The studies of Kröhn and Schelkes (1996) and Corbet (1998) concluded that the observed compositional variations of the Culebra brines were consistent with limited vertical flow from the members of the Rustler overlying the Culebra. Additionally, these studies concluded that flow and groundwater compositional variations in the Culebra are determined by a combination of large-scale heterogeneities in Culebra permeability and the contribution of vertical flow to the Culebra.

Expanding on the work of Ramey (1985) and Siegel et al. (1991b), Domski and Beauheim (2008) used data from 59 wells to define five primary facies for Culebra groundwaters and two transitional facies (Table 1). These facies are distributed spatially as shown in Figure 5. They also classified the Culebra groundwaters by salt norm type (Figure 6) and on the basis of the abundance of normative halite and anhydrite (Figure 7). They used these classifications to make inferences about the origins and evolutionary histories of the Culebra groundwaters. Through mixing calculations, they showed that all the Culebra salt norm types can be derived from mixing of the sulfatic weathering solution, primitive diagenetic, and dilute diagenetic water types. The sulfatic weathering solutions coincide with the southernmost facies B waters and appear to have a clear origin in recharge reaching the Rustler sulfate units directly, and then traveling to the Culebra. The primitive diagenetic water (facies E) represents a syndepositional brine present in the Culebra since the Permian. The origin of the dilute diagenetic water (a subset of the C family of facies) is the most poorly understood. This water probably flows into the WIPP site area from the north along long flowpaths where it has encountered a variety of minerals and mixing conditions.



Note: Background is a shaded relief national elevation dataset (NED) developed by USGS, based on 2001 digital elevation model (DEM) data.

**Figure 5.** Culebra wells color-coded on the basis of their hydrochemical facies (Domski and Beauheim, 2008).



Note Background is a shaded relief national elevation dataset (NED) developed by USGS, based on 2001 digital elevation model (DEM) data

**Figure 6. Culebra wells color-coded to water type based on SNORM output with corresponding ionic strength values (Domski and Beauheim, 2008).**

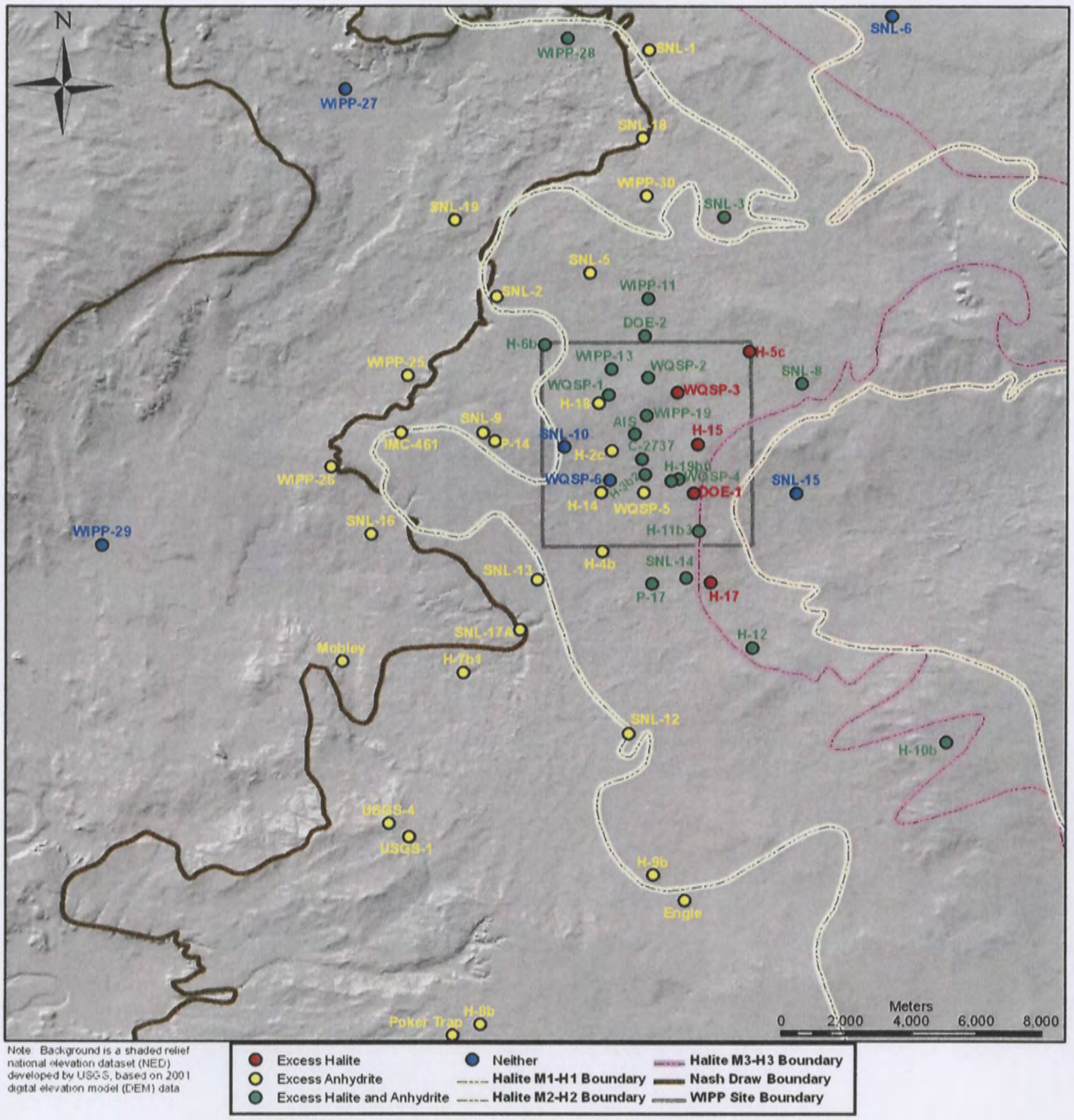


**Figure 7. Culebra wells color-coded based on the abundance of normative halite and anhydrite (Domski and Beauheim, 2008).**

Figure 8 presents a Piper plot showing how the facies and SNORM types differ in the relative percentages of major ions.

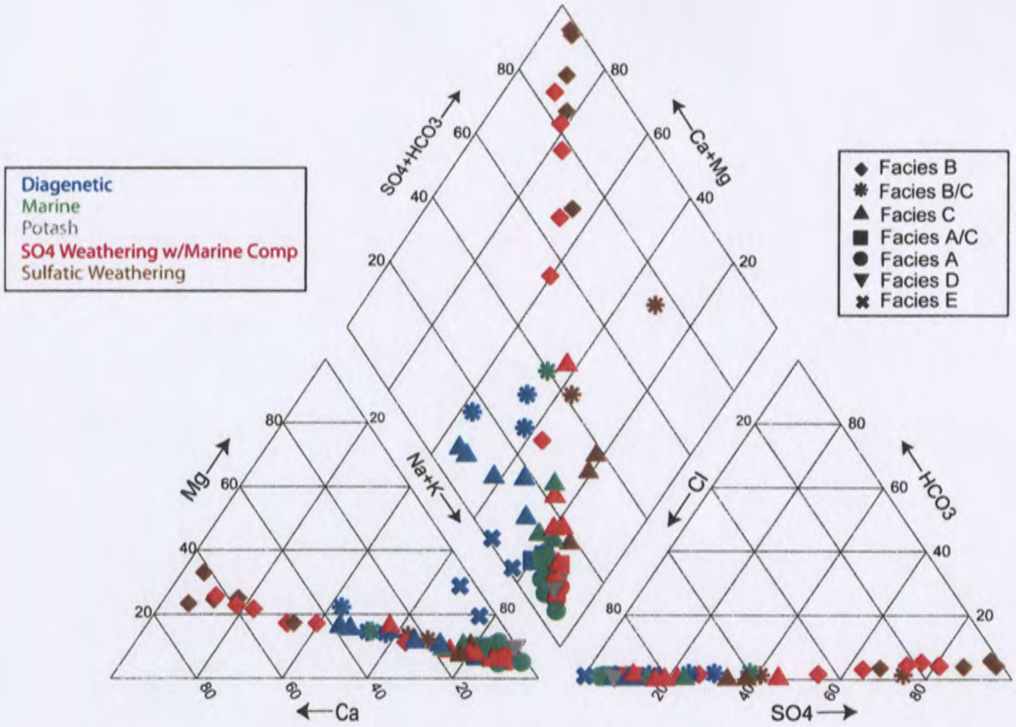


**Figure 8. Piper plot of the Culebra wells symbol-coded to reflect their hydrochemical facies and color-coded to reflect their SNORM type (Domski and Beauheim, 2008).**

Bodine and Jones (1990) and Siegel et al. (1991a) also studied the chemistry of groundwater samples that were then available from Rustler-Salado contact [21 samples], Magenta [13 samples], Dewey Lake [2 samples], and Santa Rosa [1 sample] wells. As the depositional environment and geologic history of the other members of the Rustler Formation were similar to that of the Culebra, similar processes have likely affected the groundwater chemistry of those other members. Hence, the same facies and SNORM types developed for the Culebra groundwaters were applied to other Rustler groundwaters. Bodine and Jones (1990) describe the Rustler-Salado contact waters as showing a trend from primitive diagenetic waters to the east to halite resolution waters to the west, consistent with dissolution of the upper Salado west of the WIPP site in Nash Draw. Magenta waters could be categorized using the same facies developed for the Culebra, although they showed more evidence of anhydrite resolution than the Culebra samples. In general, Bodine and Jones (1990) observed a decrease in salinity moving upward from the Rustler-Salado contact to the Culebra to the Magenta, along with a progression from primitive diagenetic waters to waters with more of an anhydrite resolution signature. Dewey Lake and Santa Rosa waters were considerably more dilute than the Rustler waters.

## 1.3 Data Sources

In an effort to be as comprehensive as possible and include data from as many wells as possible, we have assembled data collected over a span of 50 years. Groundwater samples have been collected, analyzed, and reported by a variety of laboratories and organizations since 1976 on behalf of the WIPP project. Analyses of groundwater samples collected by the U.S. Geological Survey (USGS) and Sandia National Laboratories (SNL) for the WIPP project between 1976 and 1986 are reported in a variety of publications, including Mercer and Orr (1979), Mercer et al. (1981), Dennehy and Mercer (1982), Dennehy (1982), Mercer (1983), Lambert and Robinson (1984), Bodine and Jones (1990), and Robinson (1997). Historic data from the region around WIPP dating as far back as 1960 have also been collected by the USGS, and analyses have been reported by Bodine and Jones (1990).

From 1985 until 1995, water samples were collected and analyzed by Westinghouse Electric Corporation (WEC; now known as Washington Regulatory and Environmental Services (WRES)) under the WIPP Water Quality Sampling Plan (WQSP; Colton and Morse, 1985) from most of the available Culebra wells and a small number of Magenta, Dewey Lake, and Santa Rosa wells (Uhland and Randall, 1986; Uhland et al., 1987; Randall et al., 1988; Lyon, 1989; WEC, 1991, 1992, 1993, 1994, 1995, 1996). Beginning in 1995, WEC began sampling only seven newly installed, fiberglass-cased wells designated WQSP-1 through WQSP-6 (Culebra wells) and WQSP-6A (a Dewey Lake well). Two rounds of sampling are performed in the WQSP wells each year, with 29 rounds being completed through December 2009 (Kehrman, 2002; U.S. DOE, 2010). All of the samples collected under the WQSP have been analyzed for an extensive list of anions, cations, trace metals, and organic compounds.

Since 2000, water samples have been collected by SNL under Test Plans (TP) 00-03 (Chace, 2003) and 03-01 (Chace and Beauheim, 2006) in non-WQSP wells. "Opportunistic" samples have also been collected during drilling of new wells when water was encountered at horizons other than the intended completion interval of the wells. These samples have been analyzed by Hall Environmental Analysis Laboratory (HEAL; Albuquerque, NM) for major ions ($Ca^{2+}$, $Mg^{2+}$, $K^+$, $Na^+$, $Cl^-$, $SO_4^{2-}$, $HCO_3^-$) as well as $Sr^{2+}$, $Fe^{3+}$, $Br^-$, $F^-$, and/or $NO_3^-$ in some cases. The laboratory reports are compiled in WIPP Records Package ERMS# 536041.

## 1.4 Data Screening

Representative samples and accurate chemical analyses are necessary to provide a valid interpretation of the aqueous geochemistry of the various strata considered. The water sample must be representative of the formation water and not influenced by the materials introduced during drilling or completion of the well. Lambert and Robinson (1984) developed a sampling protocol that involved serial analyses of various parameters to ensure that water quality had stabilized before final samples were collected. The sampling protocols established under Test Plans 00-03 (Chace, 2003) and 03-01 (Chace and Beauheim, 2006), as well as under the WIPP WQSP (Colton and Morse, 1985), were based on the work of Lambert and Robinson (1984) to ensure the representativeness of samples. Samples that were collected before these plans went into effect, however, may or may not be representative of the target formation. "Samples of opportunity" collected during the drilling of new wells where serial sampling or lengthy purging was not possible may also be of questionable representativeness.

To the extent possible, therefore, well conditions and sampling procedures have been evaluated to screen out samples not collected under formal protocols that might reasonably be expected to be non-representative of the formations from which they were purportedly derived (see Appendices A and B). Thus, we have discarded as unreliable many of the samples discussed by Bodine and Jones (1990) and Siegel et al. (1991b). Where possible, we include samples collected decades apart from the same wells (or from wells constructed on the same drilling pad) to evaluate the stability of the water chemistry. For wells that were sampled repeatedly over a few years under the WQSP, we have selected only the analyses with least analytical error (see below). All of the analyses we consider reliable and representative have been compiled into an Excel spreadsheet, *AP-147_Hydrochemical_Data.xlsx*, which provides the fundamental data source for the interpretations described in this Analysis Report.

To have confidence in analytical accuracy, the charge-balance error (CBE) of the analysis should not exceed five percent. When the CBE for an analysis is above this threshold, the salt norm (SNORM) calculations described in this analysis report may result in non-representative normative assemblages; this is particularly important for highly concentrated waters and brines. The CBE is the difference in equivalents between the cations and anions divided by their sum and multiplied by 100.

The CBE was calculated for each sample that was judged, on the basis of sampling information, to be representative of the sampled formation to determine if it met the 5% CBE criterion or not. The screening was performed using PHREEQCI by entering the analysis, running the code, and outputting the percent error to an Excel spreadsheet. If multiple analyses from the same well over a period of less than 10 years met the 5% criterion, the analysis with the best CBE was retained for further evaluation and the others were discarded. For some wells, no analysis met the CBE criterion; in these cases, the analysis with the best CBE was retained, but flagged to denote greater uncertainty. Note that PHREEQCI uses the speciated water composition as opposed to the straight sum of the cations and anions to calculate the percent error. The speciated composition accounts for lower absolute ionic charge due to the association of cations and anions in solution, which more closely represents the natural state of the water. Table 2 provides the wells, sample dates, and CBE for each of the water analyses used in this Analysis Report. The well locations are shown in Figure 4. Samples that exceeded the 5% CBE threshold criterion are footnoted.

Several of the Magenta samples were collected after the lower portions of the wells, which had provided access to the Culebra, had been plugged back with cement so that the wells would have simple, single completions to the Magenta. Emplacement of the cement plugs raised the pH of the water in the wellbore, which could alter the water's chemistry. Although the sampling protocol used required that the pH be stabilized before a sample was collected, it is still possible that the chemistry of the water in the formation near the wellbore could be skewed from contact with the higher than normal pH water present in the wellbore. Additional screening was done on Magenta wells H-2a, H-3b1, H-4c, H-6c, H-15, H-18, and WIPP-18 to provide confidence the samples were representative of the Magenta. Based on the pH and calcium concentrations of the samples, it was determined that cement contamination was of no significance.

The water quality data set analyzed for this report consists of 58 samples collected from 44 wells completed in five geologic units, including 12 Culebra samples, 21 Magenta samples, 13 Dewey Lake samples, 9 Los Medaños samples, and 3 Santa Rosa samples. The data set consists of samples collected over an extended time period, from 1960 through 2010. Due to the age of the historical data, in many instances the process of researching the analytical results and

**Table 2. Wells, geologic units, sample dates, CBE, and sampling protocols followed for the analyses used in this report.**

| Well | Geologic Unit | Sample Date | CBE (%) | Sampling Protocol |
|---|---|---|---|---|
| Clifton | Santa Rosa | 10/28/1987 | 3.3 | Colton and Morse (1985) |
| Comanche | Santa Rosa | 10/26/1987 | 4.0 | Colton and Morse (1985) |
| H-5c[2,3] | Santa Rosa | 5/24/1978 | 3.8 | none |
| Barn | Dewey Lake | 7/13/1989 | 2.5 | Colton and Morse (1985) |
| Pocket | Dewey Lake | 11/2/1983 | -0.1 | none |
| Poker Trap | Dewey Lake | 12/19/1987 | -3.0 | Colton and Morse (1985) |
| Ranch[1] | Dewey Lake | 6/20/1990 | 7.5 | Colton and Morse (1985) |
| SNL-1[1,4] | Dewey Lake | 3/25/2004 | -7.4 | none |
| SNL-12[5] | Dewey Lake | 6/26/2003 | 0.7 | none |
| SNL-13[6] | Dewey Lake | 4/12/2005 | -0.9 | none |
| SNL-14[1,7] | Dewey Lake | 5/3/2005 | 8.8 | none |
| SNL-14[1,8] | Dewey Lake | 5/5/2005 | 6.1 | none |
| Twin-Pasture | Dewey Lake | 9/28/1989 | 4.9 | Colton and Morse (1985) |
| Unger | Dewey Lake | 1/26/1984 | -5.0 | none |
| Walker[2] | Dewey Lake | 7/31/1962 | 0.1 | none |
| WQSP-6A | Dewey Lake | 6/10/1998 | 0.7 | Colton and Morse (1985) |
| C-2737 | Magenta | 1/30/2007 | -0.2 | Chace and Beauheim (2006) |
| H-1 | Magenta | 5/10/1977 | 2.8 | none |
| H-2a | Magenta | 2/22/1977 | 2.2 | none |
| H-2b1 | Magenta | 2/8/2011 | -1.0 | Chace and Beauheim (2006) |
| H-3b1 | Magenta | 3/16/1989 | 1.1 | Colton and Morse (1985) |
| H-3b1[1] | Magenta | 7/30/2009 | -8.6 | Chace and Beauheim (2006) |
| H-4c | Magenta | 10/9/1991 | -4.4 | Colton and Morse (1985) |
| H-4c | Magenta | 3/1/2011 | -2.3 | Chace and Beauheim (2006) |
| H-5c | Magenta | 5/16/1990 | -3.8 | Colton and Morse (1985) |
| H-6c | Magenta | 3/15/1990 | 1.3 | Colton and Morse (1985) |
| H-6c | Magenta | 4/27/2010 | -5.4 | Chace and Beauheim (2006) |
| H-8a | Magenta | 2/12/1980 | -2.1 | none |
| H-8a[1] | Magenta | 4/20/2010 | -6.1 | Chace and Beauheim (2006) |
| H-9a | Magenta | 2/5/1980 | -0.7 | none |
| H-9c | Magenta | 5/22/2002 | -1.1 | Chace (2003) |
| H-9c | Magenta | 4/18/2011 | -4.4 | Chace and Beauheim (2006) |
| H-10a | Magenta | 3/21/1980 | -1.9 | none |
| H-15 | Magenta | 3/19/2008 | -0.6 | Chace and Beauheim (2006) |
| H-18 | Magenta | 4/17/2009 | -2.7 | Chace and Beauheim (2006) |
| USGS-5[2,9] | Magenta | 11/15/1961 | 0.02 | none |
| WIPP-27 | Magenta | 9/25/1980 | -0.7 | Lambert and Robinson (1984) |
| WIPP-18 | Magenta | 3/18/2010 | -4.0 | Chace and Beauheim (2006) |
| WIPP-30 | Magenta | 9/24/1980 | -3.4 | Lambert and Robinson (1984) |
| H-4bR[1] | Culebra | 8/13/2009 | -8.6 | Chace and Beauheim (2006) |
| H-6bR | Culebra | 12/10/2008 | -3.2 | Chace and Beauheim (2006) |
| H-15R | Culebra | 1/22/2009 | -1.1 | Chace and Beauheim (2006) |
| Indian[2] | Culebra | 1/22/1963 | 0.2 | None |
| South[2] | Culebra | 8/8/1962 | -0.2 | None |
| Two Mile[2] | Culebra | 8/8/1962 | -0.3 | None |

| | | | | |
|---|---|---|---|---|
| USGS-1[2] | Culebra | 8/18/1960 | 0.7 | None |
| USGS-4[2] | Culebra | 12/5/1961 | 1.6 | None |
| USGS-4[1] | Culebra | 7/30/2008 | 6.0 | None |
| USGS-8[2] | Culebra | 1/27/1963 | -3.9 | None |
| USGS-8 | Culebra | 7/30/2008 | 4.2 | None |
| Windmill[2] | Culebra | 9/14/1961 | -0.5 | None |
| H-1[2] | Los Medaños | 2/23/1977 | 0.4 | None |
| H-2c[2] | Los Medaños | 2/23/1977 | -0.5 | None |
| H-3b1[2] | Los Medaños | 2/23/1977 | -0.5 | None |
| H-5c[2] | Los Medaños | 5/16/1979 | -1.4 | None |
| P-14[2] | Los Medaños | 2/24/1977 | 0.9 | None |
| SNL-13[10] | Los Medaños | 4/26/2005 | -2.6 | None |
| USGS-5[2,11] | Los Medaños | 11/27/1961 | 0.1 | None |
| WIPP-26[2] | Los Medaños | 7/23/1980 | 0.3 | Lambert and Robinson (1984) |
| WIPP-30[2] | Los Medaños | 7/17/1980 | -0.02 | Lambert and Robinson (1984) |

[1] Analyses with CBE exceeding 5% threshold.
[2] Data from Bodine and Jones (1990).
[3] Sample collected when well was 69 m deep.
[4] Sample collected when well was 11 m deep.
[5] Sample collected when well was 53 m deep.
[6] Sample collected when well was 64 m deep.
[7] Sample collected when well was 63 m deep.
[8] Sample collected when well was 93 m deep.
[9] Sample collected when well was 127 m deep.
[10] Sample collected when well was 146 m deep.
[11] Sample collected when well was 212 m deep.

identifying citable references was extensive. During this process, a citable reference was identified for each set of analytical results and the data were determined to be verified.

To ensure consistency and accuracy in the dataset, the following procedure was used to verify the sample data.

- For recent samples and as available, the sample results were checked (verified) against the original laboratory analytical results.
- For historical samples, the sample results were verified against a WIPP-qualified and/or published report.
- In instances where sample results were published in more than one report, the data in both reports were verified against one another or it was determined that one report was more reliable and would therefore be the official reference for the sample.

- If a report was not available or multiple reports provided conflicting data, the raw laboratory analytical data were researched in the central WIPP Records Center and the sample results were verified against the laboratory data sheets.

## 1.5 Data Uncertainty

Domski and Beauheim (2008) presented a method for adjusting the concentrations of the major ions in a laboratory analysis to account for the analytical errors to achieve an electro-neutral solution composition. The purpose of performing such ionic adjustments is to increase our confidence in the interpretative methods used in classifying the waters. All laboratory analyses of natural waters samples carry some error, error which arises from precision of the instruments, and error introduced through sampling and/or handling techniques, e.g., not following the correct protocol for the analytes of concern. The magnitude of these errors is measured by calculation of the CBE, and should the CBE exceed 5%, then it becomes necessary to evaluate the reliability of the classification/interpretation of the water in light of these errors.

Of the 58 samples listed in Table 2, ten of the water analyses meet or exceed the 5% CBE threshold, and of those ten, five don't have duplicate samples to cross check the classifications. For Dewey Lake wells Ranch, SNL-1, SNL-14 at 63 m, SNL-14 at 93 m, and Unger, there were no duplicate chemical data to function as a cross check, making it necessary to re-evaluate the validity of their interpretations/classifications.

Examination of the data shows that the Ranch, SNL-1, SNL-14 (93 m), and Unger wells' analyses do not require correction because the samples are not close to any of the classification boundaries; thus, interpretation of their data was not affected. However, the SNL-14 (63 m) analysis was evaluated (see sheet "SNL-14 63m" in spreadsheet *DeweyLake_SantaRosa_Final.xls*) to determine if anything could be gained from correcting the error. The evaluation established that the errors were more or less spread equally among all of the major ions, and as such, correcting the errors would not change the interpretation.

# 2. Methods

The computer codes used to evaluate water compositions and the classification schemes used to differentiate among samples are described below.

## *2.1 Computer Codes*

Two geochemical codes were used in the analyses of the groundwater chemical data, PHREEQCI version 2.12.5-669, (Charlton et al., 1997; Parkhurst and Appelo, 1999) and SNORM version 2.1 (Bodine and Jones, 1986). PHREEQCI was used to perform basic speciation and saturation index calculations as well as theoretical reaction-path and mixing simulations. SNORM was used to calculate the normative salt assemblages (salt norms) for the waters and in some cases to calculate the salt norms from the PHREEQCI outputs.

PHREEQCI version 2.12.5-669 is a computer program written in the C programming language that is designed to perform a wide variety of low-temperature aqueous geochemical calculations. PHREEQCI is based on an ion-association aqueous model for dilute solutions, as well as the Pitzer virial-coefficient approach (expanded polynomial) for activity-coefficient corrections for high-ionic strength waters. PHREECQI has capabilities for (1) speciation and saturation-index calculations; (2) batch-reaction and one-dimensional (1D) transport calculations involving reversible reactions, which include aqueous, mineral, gas, solid-solution, surface-complexation, and ion-exchange equilibria, and irreversible reactions, which include specified mole transfers of reactants, kinetically controlled reactions, mixing of solutions, and temperature changes; and (3) inverse modeling, which finds sets of mineral and gas mole transfers that account for differences in composition between waters, within specified compositional uncertainty limits.

SNORM calculates an equilibrium normative salt assemblage (or salt norm) from the solute concentration data from a conventional water analysis. Although the salt norm can be visualized as the solid residuum that coexists with the small, last vestige of solution upon evaporation at 25°C and atmospheric carbon dioxide, the normative assemblage is computed directly from solute concentrations without proceeding along an evaporation path with its myriad succession of brine-solid interactions. Neither brine evolution nor character of the vestigial brine are considered; SNORM only distributes the solutes into the appropriate liquid-free salt assemblage. The program transforms 18 solutes into a normative salt assemblage (from a listing of 63 possible salts) and respective simple salts.

Quoting from the abstract for SNORM version 2.1 (Bodine and Jones, 1986):

> "The new computer program SNORM calculates the salt norm from the chemical composition of a natural water. The salt norm is the quantitative ideal equilibrium assemblage that would crystallize if the water evaporated to dryness at 25°C and 1 bar pressure under atmospheric partial pressure of $CO_2$. SNORM proportions solute concentrations to achieve charge balance. It quantitatively distributes the 18 acceptable solutes into normative salts that are assigned from 63 possible normative salts to allow only stable associations based on the Gibbs Phase Rule, available free energy values, and observed low-temperature mineral associations. Although most natural water compositions represent multiple solute origins, results from SNORM identify three major categories: meteoric or weathering waters that are characterized by normative alkali-bearing sulfate and carbonate salts; connate marine-like waters that are chloride-rich with a halite-bischofite-carnallite-kieserite-anhydrite association; and diagenetic waters that are frequently of marine origin but yield normative salts, such as Ca-bearing chlorides (antarcticite and tachyhydrite) and sylvite, which suggest solute alteration by secondary mineral reactions. The solute source or reaction process within each of the above categories is commonly indicated by the presence or absence of diagnostic normative salts and their relative abundance in the normative salt assemblage. For example, salt norms: (1) may identify lithologic source; (2) may identify the relative roles of carbonic and sulfuric acid hydrolysis in the evolution of weathering waters; (3) may identify the origin of connate water from normal marine, hypersaline, or evaporite salt resolution processes; and (4) may distinguish between dolomitization and silicate hydrolysis or exchange for the origin of diagenetic waters."

The PHREEQCI code was used to calculate the aqueous speciation, mineral saturation index values, percent error values, ionic strength, and specific element ratios for each analysis. Based on the percent error, each analysis was screened and those meeting the 5% CBE criterion were entered into SNORM. The SNORM code calculated the normative mineral assemblages for each analysis.

The resulting outputs from SNORM and PHREEQCI were imported into Excel for interpretive analysis. Interpretation of the model results was aided by the generation of plots (ion and ion-ratio values, solution properties) and categorization of wells based on the presence and abundance of normative mineral phases, ionic strength, and hydrochemical facies (Siegel et al., 1991b). The various categories were then plotted areally by well location to examine the spatial distribution of the data. Based on the spatial distribution, reaction-path and mixing simulations were created in PHREEQCI to test the feasibility of the evolution of water along a flow path.

A listing of all model input and output files as well as other electronic files used in preparation of this report is provided in Appendix C.

## 2.2 *Classifications*

As a means of distinguishing between different water types and for the purpose of gaining an understanding of their potential evolution and origins, three classification schemes were implemented: 1) hydrochemical facies; 2) normative mineral assemblages; and 3) the percentages of normative halite and anhydrite. In addition to the three classification schemes, mineral saturation index values and ionic strength values were also calculated as a further means of understanding the water chemistry of the samples.

### 2.2.1 Hydrochemical Facies

The definitions of the hydrochemical facies used by Domski and Beauheim (2008) and those defined in this report are listed in Table 3. The hydrochemical facies definitions have been expanded from the definitions of Domski and Beauheim (2008) to include two new facies, "F" and "G". These new facies were defined to accommodate the very dilute waters of the Santa Rosa and Dewey Lake Formations (facies F), and the concentrated waters of the Rustler-Salado contact (facies G). Note that the upper and lower limits of ionic strength and the Mg/Ca molar ratio often do not coincide exactly with the immediately adjacent facies because these limits were set by the data, i.e., compositional gaps exist in the data. Also note that the range of Mg/Ca ratios for facies B/C is wholly contained within the limits of the range for facies C; the ionic strength is the primary difference between these two facies.

The alkali to alkaline ratio is the total moles of sodium and potassium divided by the total moles of calcium and magnesium. This ratio is useful in distinguishing the low ionic strength waters having chemistry dominated by leaching of highly soluble alkali metals (sodium and potassium) that originated from alumino-silicate clastic sediments, which results in high values of the ratio, from those dominated by dissolution of carbonates (calcite and dolomite) and sulfates (such as gypsum), for which the ratio would be small. As the ionic strength of these waters increases, so does the contribution of dissolved halite to the total solute budget of the water and, likewise, the alkali:alkaline ratio also increases from the contribution of sodium from the halite.

**Table 3. Hydrochemical facies characteristics.**

| Facies | Ionic Strength (molal) | Mg:Ca | Alkali:Alkaline |
|---|---|---|---|
| F | <0.05 | 0.8 to 1.6 | 1.2 to 3.7 |
| B | <0.1 | 0.3 to 0.6 | 0.1 to 1.3 |
| B/C | 0.18 to 0.29 | 0.4 to 0.6 | 1.5 to 4.3 |
| C | 0.3 to 1.0 | 0.4 to 1.0 | 1.6 to 13.1 |
| A/C | 1.1 to 1.6 | 0.5 to 1.2 | 8.3 to 17.1 |
| A | 1.7 to 4.5 | 1.2 to 2.8 | 11.3 to 29.7 |
| D* | 2.6 to 6.4 | 1.0 to 22.6 | 12 to 23 |
| E | 6.7 to 13.6 | 2.3 to 64 | 0.3 to 8.3 |
| G | 4.2 to 8.6 | 1.9 to 10.5 | 29 to 83 |

* - facies D is distinguished by its high K:Na weight ratio of ~0.2

### 2.2.2 Salt Norm Classification

The output data from the SNORM calculations were compiled in Excel for sorting, plotting, and analysis. Based on the presence and abundance of key normative phases, inferences regarding the origins of the solutes and potential flow paths can be made. The work performed under AP-147 constitutes the examination of waters from three geologic formations, the relatively shallow Santa Rosa Formation, the Dewey Lake Redbeds, and the Rustler Formation including the Magenta, Culebra, and Los Medaños brines as well as the Rustler-Salado contact brines. Thus, compared to Domski and Beauheim (2008) which examined the waters of only the Culebra Member of the Rustler Formation, this report examines a more variable range of water types and a broader range of salt norm types have been identified.

Table 4 lists the salt norm types that have been identified and the diagnostic phases for each type.

**Table 4. Salt norm types and diagnostic phases.**

| **Salt Norm Type** | **Diagnostic Phases** |
|---|---|
| Carbonic acid | Presence of carbonate phases burkeite and trona, absence of anhydrite, less than 20% normative halite |
| Sulfur oxidation | Presence of sulfate phases epsomite, glauberite, thenardite, and aphthitalite, absence of anhydrite, less than 20% normative halite |
| Sulfatic weathering solution | Excess anhydrite (up to 60%) with polyhalite, bloedite, epsomite, and glauberite |
| Sulfatic weathering solution with marine component | Excess anhydrite (up to 75%) with carnallite, bischofite, and kieserite, and minor polyhalite in some instances |
| Diagenetic | Presence of tachyhydrite, carnallite, bischofite, with antarcticite possible |
| Potash | Sylvite |
| Halite resolution with diagenetic component | Halite in excess of 80% up to 95%, with tachyhydrite present |
| Halite resolution with meteoric component | Halite in excess of 80% up to 95%, with kieserite, magnesite, polyhalite (±bloedite and epsomite) |

### 2.2.3 Normative Excess Classifications

In addition to the detailed interpretation of the normative mineral assemblage, a more general interpretation of the salt norm based on the abundance of halite and anhydrite can provide a simple model of the flow path that a water may have traveled to reach a well. Given the unique geologic environment of the Rustler with sulfate beds above and below dolomite layers, and well-documented locations where halite is present in the stratigraphic section (Holt et al., 2005), a simple model for flow can be deduced from the halite and anhydrite values of the norms:

1) Excess anhydrite ($CaSO_4$) in the salt norm (>4%, Bodine and Jones, 1986) suggests dissolution of calcium sulfate, either anhydrite or gypsum, along the flowpath.

2) Excess halite (NaCl) in the salt norm (>78%, Bodine and Jones, 1986) suggests *in situ* dissolution of halite cements or of bedded halite.

3) Excess anhydrite (>4%) and halite (>78%) suggest potential vertical flow combined with lateral flow or mixing. Depending on whether this type of water dissolved halite or mixed with a halite-type water, this flow path could either be relatively long or relatively short.

4) Waters in which neither halite nor anhydrite exceed their threshold values could be either very old synsedimentary brines, e.g., SNL-13 Los Medaños, or of relatively recent

meteoric origin where dissolution reactions have not significantly altered their composition.

Four classifications were established based on this model: 1) *excess halite*; 2) *excess anhydrite*; 3) *excess anhydrite and halite*; and 4) *neither*. The *excess anhydrite* and *neither* classification schemes are potentially the quickest flow paths from the point of infiltration to the well, although truly primitive water samples, i.e., synsedimentary water, may also carry the *neither* classification. The classification for each well was plotted on a map to examine the spatial relationships of the classifications. These data will be discussed in Section 3.3.

### 2.2.4 Ionic Strength and Mineral Saturation Index

The ionic strength and mineral saturation index values for each water sample were calculated in PHREEQCI. Ionic strength ($\mu$) is given by:

$$\mu = \frac{1}{2}\sum_{i=1}^{n} b_i z_i^2$$

where: n = number of ions in solution

b = molality (moles of solute/kg of solvent)

z = charge number of ion

Ionic strength functions as a measure of concentration, and can be considered as reflecting the degree of interaction between water and rock. Ionic strength was used as a classification parameter in assigning waters to hydrochemical facies, as well as a standalone parameter used to observe concentration trends in the Culebra.

The mineral saturation index (*SI*) is calculated by PHREEQCI and is a measure of the degree of saturation of a mineral phase with respect to equilibrium. The saturation index is the log of the ratio of the ion activity product to the equilibrium constant for the phase of interest. Thus, as a log quantity, negative values of SI indicate undersaturation and positive values indicate supersaturation, while a value of zero indicates saturation conditions for the phase of interest. The PHREEQCI saturation index results are presented in Section 3 for each of the formations.

# 3. Results of Hydrochemical Classification

The results of the hydrochemical classification of the waters of each geologic unit are presented in the following sections.

## *3.1 Santa Rosa and Dewey Lake Waters*

Table 5 summarizes the results of the analyses for the Santa Rosa and Dewey Lake waters. Table 5 shows that all of the samples, with the exception of the contaminated SNL-1 sample (see discussion below), have very low ionic strength ranging from 0.01 molal to 0.11 molal. The low ionic strength is consistent with low levels of water-rock interaction due to these waters having been recently recharged. Aspects of the geology and mineralogy of the Santa Rosa and Dewey Lake that may be relevant to the water compositions are discussed below, followed by discussion of each of the different classifications.

**Table 5. Classification of Santa Rosa and Dewey Lake waters.**

| Well | Geologic Unit | Facies | μ (molal) | SNORM type | Normative Excess | Gypsum SI | Calcite SI | CO2 (g) SI |
|---|---|---|---|---|---|---|---|---|
| Comanche | Santa Rosa | F | 0.01 | Carbonic acid | Neither | -2.27 | -0.22 | -2.11 |
| Clifton | Santa Rosa | F | 0.02 | Sulfur oxidation | Neither | -1.50 | -1.02 | -1.38 |
| H-5c | Santa Rosa | F | 0.03 | Sulfur oxidation | Neither | -1.20 | -0.61 | -1.67 |
| Twin-Pasture | Dewey Lake | B | 0.01 | Carbonic acid/sulfatic weathering solution | Anhydrite | -1.83 | 0.0 | -2.30 |
| SNL-14 (63 m) | Dewey Lake | F | 0.01 | Sulfatic weathering w/marine component | Anhydrite | -1.46 | 0.47 | -2.78 |
| Barn | Dewey Lake | F | 0.02 | Sulfur oxidation | neither | -1.34 | -0.19 | -1.71 |
| SNL-12 | Dewey Lake | B | 0.05 | Sulfatic weathering w/marine component | Anhydrite | -0.41 | -0.21 | -1.94 |
| Pocket[1] | Dewey Lake | B | 0.06 | Sulfatic weathering w/marine component | Anhydrite | -0.28 | 0.58 | -2.64 |
| Poker Trap | Dewey Lake | B | 0.06 | Sulfatic weathering | Anhydrite | -0.16 | -0.14 | -2.16 |
| SNL-14 (93 m) | Dewey Lake | B | 0.07 | Sulfatic weathering w/marine component | Anhydrite | -0.24 | 0.57 | -2.63 |
| Ranch | Dewey Lake | B | 0.08 | Sulfatic weathering w/marine component | Anhydrite | -0.13 | 0.42 | -1.92 |
| Unger | Dewey Lake | B | 0.08 | Sulfatic weathering w/marine component | Anhydrite | -0.05 | -0.07 | -1.97 |
| Walker[1] | Dewey Lake | B | 0.09 | Sulfatic weathering w/marine component | Anhydrite | -0.02 | 0.10 | -2.06 |
| WQSP-6A | Dewey Lake | B | 0.1 | Sulfatic weathering w/marine component | Anhydrite | 0.00 | 0.35 | -2.56 |
| SNL-13 | Dewey Lake | B | 0.11 | Sulfatic weathering w/marine component | Anhydrite | 0.06 | 0.63 | -3.38 |
| SNL-1 | Dewey Lake | D | 6.35 | Potash | Halite | 0.08 | 0.54 | -1.83 |

1 – Note that the exact location of Pocket well is uncertain; Pocket may be the well known as Walker, or it may be close to Walker.

### 3.1.1 Geology and Mineralogy of the Santa Rosa and Dewey Lake

Holt and Powers (1990) observed the Triassic Santa Rosa Formation in the air-intake shaft from about 12 to 15 m depth, and characterized it as a calcareous siltstone/sandstone comprised of 80 percent quartz, 5 percent mafics, and 15 percent other grains, with very rare subvertical calcite-filled fractures. The unit dips and thickens to the east. Powers (2009) reports that at borehole SNL-8, the Santa Rosa is ~74 m thick, and is composed of interbedded siltstone and sandstone that is moderately indurated and contains mica in the sandstone layers.

Although the mineralogy of the Santa Rosa is not well documented, we infer from the reported presence of a mafic phase and mica, both of which are relatively unstable under atmospheric or near-surface conditions, that other high-temperature and more stable phases that occur in igneous and metamorphic rocks, such as the feldspar to plagioclase suite of phases, may also be present as clastics in the Santa Rosa. These potassium-sodium-calcium silicate phases, though sparingly soluble in groundwater compared to the common evaporite minerals (gypsum and halite) of the Rustler Formation, are the probable source of the solutes observed in the dilute waters of the Santa Rosa.

Holt and Powers (1990) studied the Dewey Lake in the air-intake shaft and characterized it as consisting of 145 m of interbedded siltstone, fine sandstone, mudstone, and claystone. They subdivided the formation into an upper (116 m) sequence and a lower (29 m) sequence on the basis of grain size and sedimentary structures, with the lower sequence having been deposited in a saline mudflat environment and the upper sequence deposited in a fine-grained ephemeral fluvial system. The transition from the lower to the upper sequence in the Dewey Lake marks the change from Rustler-style marine-influenced evaporite deposition to deposition on a broad fluvial plain of low relief (Holt and Powers, 1990).

Holt and Powers (1990) observed calcite-filled fractures and calcareous cements in the upper 38 m of the Dewey Lake, and abundant gypsum-filled fractures and sulfate-based cements in the Dewey Lake below 38 m in the air-intake shaft. For the most part, the fractures parallel bedding and differential unloading is considered to be the likely mechanism of their occurrence. These horizontal gypsum-filled fractures as well as mudstone/claystone interbeds could function as low-conductivity structures impeding vertical flow within the Dewey Lake. Although not as numerous, gypsum-filled fractures are also observed cross-cutting bedding. The gypsum infilling is considered to have occurred early in the post depositional history, or possibly syndepositionally, and includes both the lower saline mudflat deposits and the upper fluvial deposits of the Dewey Lake.

Powers (2002; 2003) reports core and geophysical log data showing vertical changes in natural mineral cements from calcite to gypsum/anhydrite in the Dewey Lake over the central and southeastern portions of the WIPP site. The sulfate-cemented lower Dewey Lake appears to have lower porosity and permeability than the upper calcite-cemented portion (TerraTek, 1996), and water appears to be perched on the upper contact of the sulfate-cemented portion. In areas where the Dewey Lake has been exposed to weathering after erosion of the overlying Santa Rosa, this cement boundary tends to generally parallel the eroded upper surface of the Dewey Lake, suggesting that weathering has affected the location of the boundary. Where the Dewey Lake has been protected by overlying rocks of the Santa Rosa, the cement change appears to be stratigraphically controlled, but the data points are too few to be certain. Holt and Powers (1990) suggested that the cement change might be related to infiltration of meteoric water.

### 3.1.2 Hydrochemical Facies

Figure 9 displays the Santa Rosa and Dewey Lake hydrochemical facies plotted on a Piper (1944) diagram. Piper diagrams plot the percentages of the major solutes (Ca, Mg, Na, K, Cl, $SO_4$, and $HCO_3$) with the cations plotting in the bottom left trilinear diagram, the anions in the bottom right trilinear diagram, and the cation-anion combined projection in the central diamond. Because the major element concentrations are expressed as percentages relative to each other and not as absolute concentrations, the degree of concentration of the waters cannot be discerned from this type of plot.

Figure 9 shows that the Santa Rosa and Dewey Lake groundwaters tend from sodium-potassium bicarbonate facies F to calcium sulfate facies B type waters, with a single sodium-potassium chloride water representing facies D (SNL-1). The occurrence of facies F bicarbonate type waters is indicative of shallow recharge where dissolved atmospheric carbon dioxide hydrolysis reactions leach sodium and potassium from siliciclastic sediments. The well containing facies D water, SNL-1, is located a few hundred meters south of the Intrepid East potash tailings pile and encountered brine in the upper Dewey Lake at a depth of 11 m. This water must be the product of potash-refining activities and does not reflect the groundwater chemistry of natural Dewey Lake water.

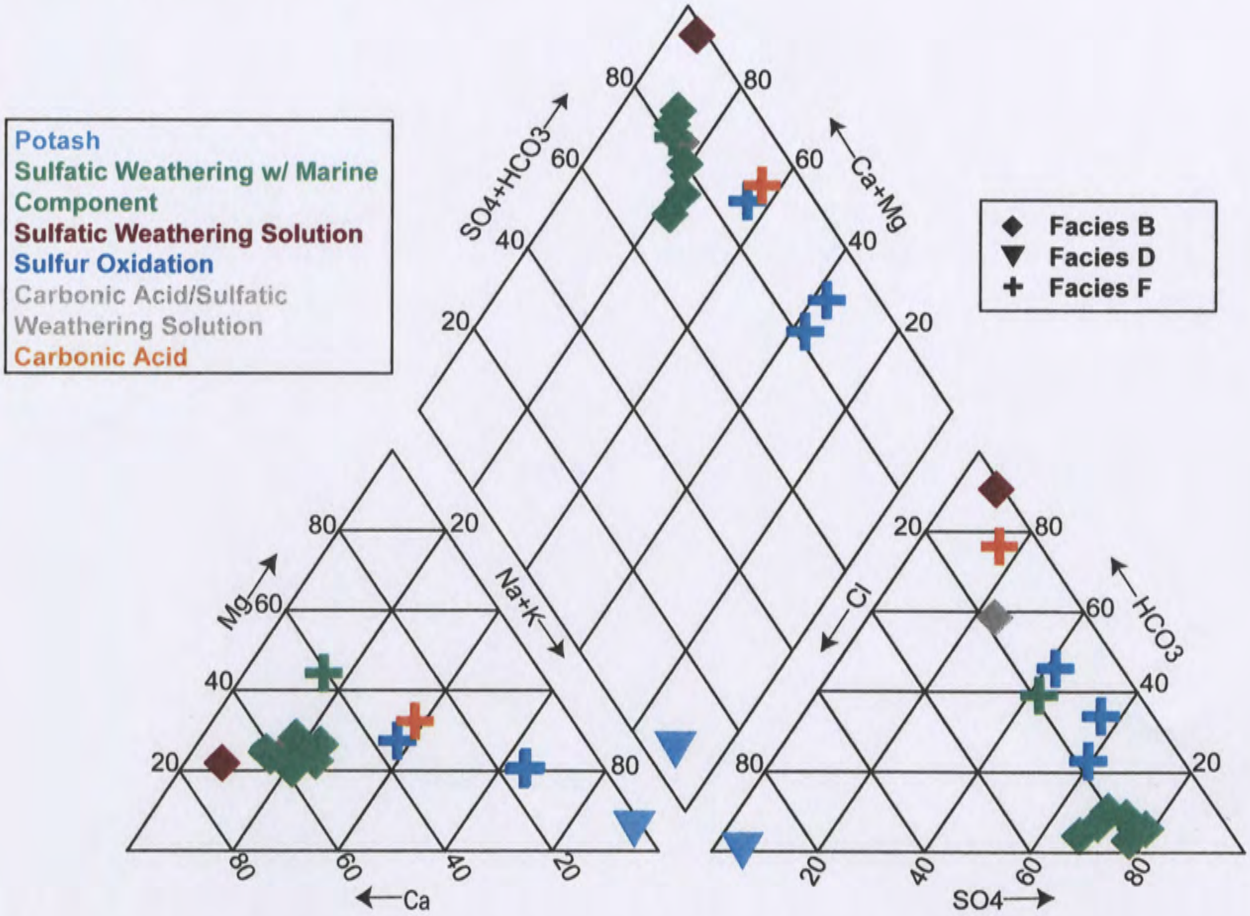


**Figure 9.** **Piper plot of the Santa Rosa and Dewey Lake waters symbol-coded to reflect their hydrochemical facies and color-coded to reflect their SNORM type.**

Figure 10 depicts the Santa Rosa and Dewey Lake wells plotted on a map of the WIPP site and surrounding area with the wells color-coded by facies. There is no geographic correlation between the facies and location, but there is a relationship between the facies and the position in the stratigraphic column from which the samples were taken. The five facies F samples come from the three Santa Rosa wells (all stratigraphically higher than the Dewey Lake) and Dewey Lake wells Barn and SNL-14 (63 m). The Barn well is only 42 m deep, whereas the nearby but facies B Dewey Lake Ranch well is 51 m deep. Similarly, the Dewey Lake sample from SNL-14 at 93 m is facies B, not F. Thus, the transition from facies F to facies B appears to occur as depth

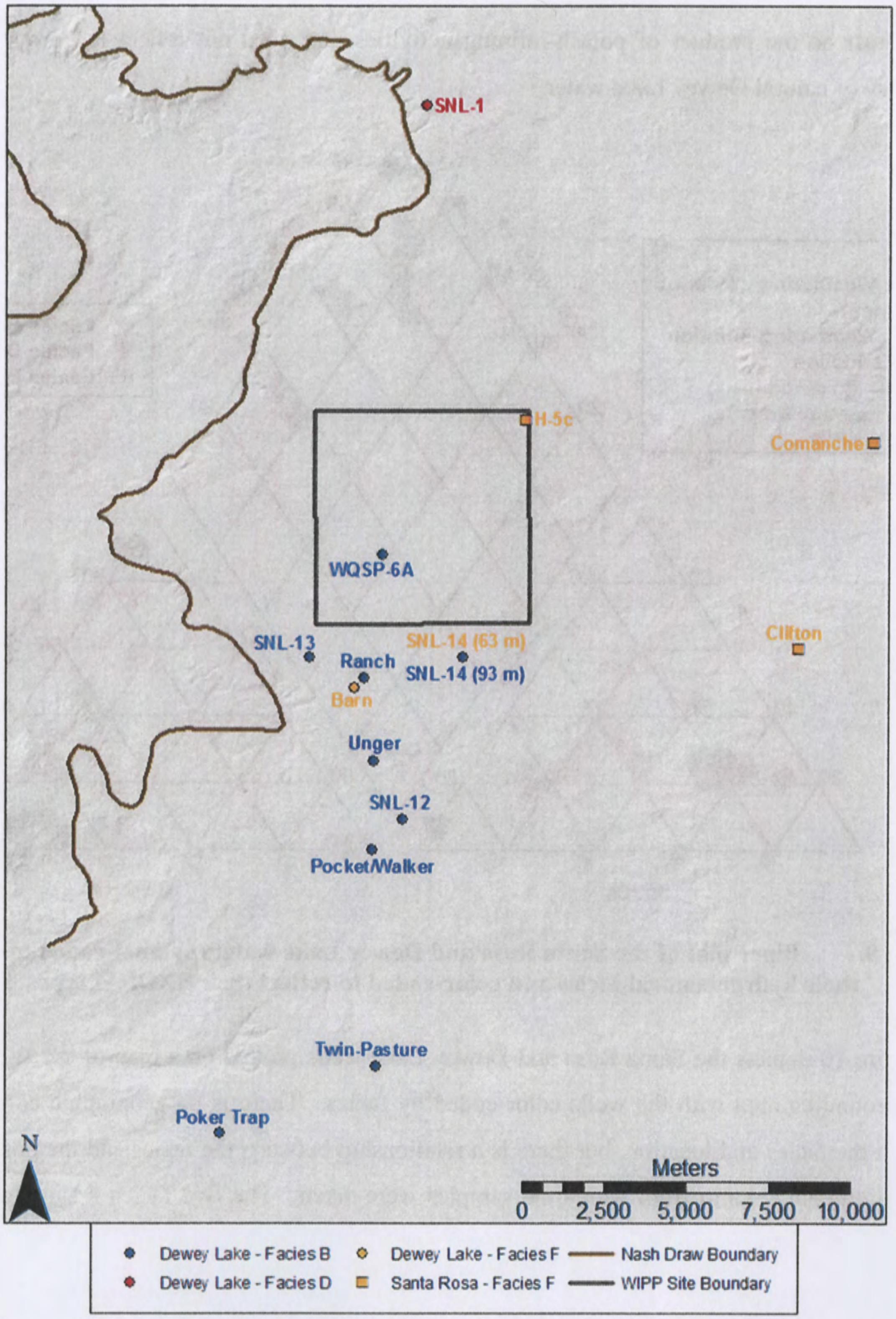


**Figure 10.** **Santa Rosa and Dewey Lake waters color-coded on the basis of hydrochemical facies.**

in the Dewey Lake increases, which may correlate with increased gypsum in the Dewey Lake with depth. The SNL-14 sample from 93 m was collected when the hole was directly (0.3 m) above the point at which Powers (2008) first noted gypsum in drill cuttings. Considering the inherent imprecision involved in establishing depths of provenance from drill cuttings, gypsum may very well be present in the Dewey Lake some distance above 93 m in SNL-14. Overall, given that the Santa Rosa and Dewey Lake occur at shallow depths, and they are not influenced by the presence of mudstone-halite margins, it is not surprising that there is less variation in their water chemistry compared to that seen in the deeper formations.

### 3.1.3 Saturation Indices and Ionic Strength

Figures 11 and 12 show the PHREEQCI-calculated calcite and gypsum saturation indices, respectively, for the Santa Rosa and Dewey Lake waters. Figure 11 shows that as dissolved carbon dioxide increases, the saturation of calcite decreases, and that the facies F waters have lower calcite saturation than the facies B waters. It makes sense both from a geochemical and hydrologic point of view that the deeper Dewey Lake waters, facies B, should have lower dissolved carbon dioxide than the shallower Santa Rosa waters, and, as a consequence, be closer to calcite saturation.

Figure 12 displays the gypsum saturation index versus ionic strength for each Santa Rosa and Dewey Lake sample. All of the Dewey Lake facies B samples, with the exception of Twin-Pasture, are close to, or saturated with respect to gypsum ($-0.4 < SI < 0.1$), while the facies F Dewey Lake and Santa Rosa samples are well below gypsum saturation ($-2.3 < SI < -1.2$). The difference in gypsum saturation and facies between these groups of waters suggests possibly different hydrologic flow regimes for the upper Santa Rosa/Dewey Lake and the lower Dewey Lake.

The Santa Rosa and upper Dewey Lake, i.e., the section of Dewey Lake devoid of gypsum, and possibly the overlying Gatuña could be part of a phreatic water-table aquifer system that receives vertical recharge across the study area. A shallow groundwater system such as this would account for the observed low gypsum saturation in the facies F waters as well as their meteoric salt norm signature, as will be discussed in Section 3.1.4.

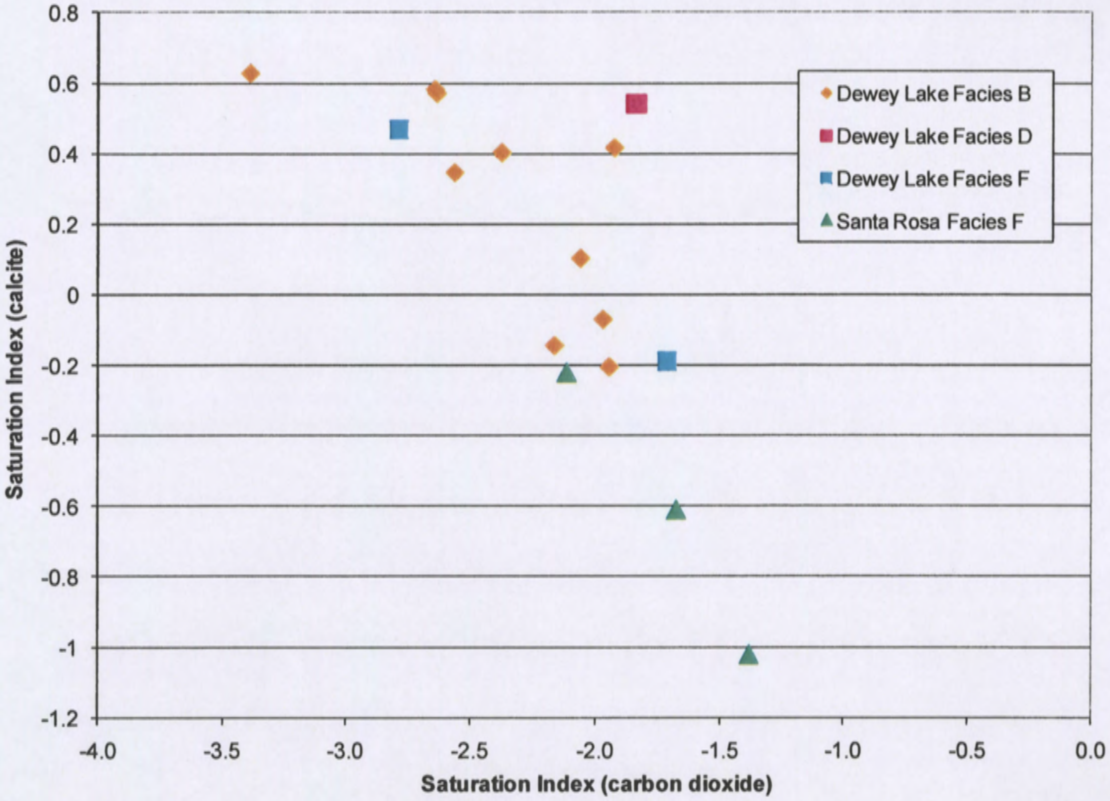


**Figure 11.** Calcite versus carbon dioxide saturation indices for the Santa Rosa and Dewey Lake waters color-coded on the basis of hydrochemical facies.

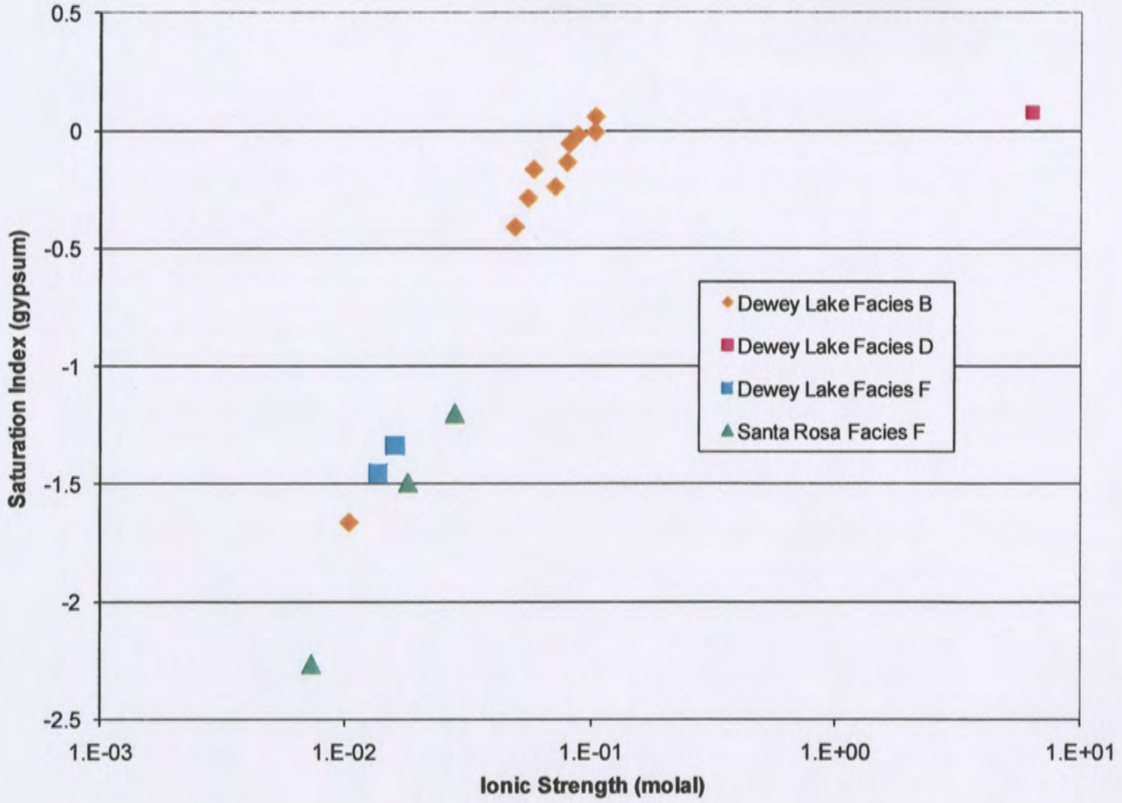


**Figure 12.** **Gypsum saturation index versus ionic strength for the Santa Rosa and Dewey Lake waters color-coded on the basis of hydrochemical facies.**

The lower Dewey Lake, on the other hand, with its calcium-sulfate cement, horizontal gypsum layers, and numerous low-conductivity interbeds, may be confined or partially confined, and have a leaky upper boundary at the base of the upper phreatic system. Thus, the waters of the lower system may originate either as direct recharge to the lower system, or water that has leaked from the upper system, or a combination of these two sources.

The waters of both the upper and lower system share a common trait of very low ionic strength, which suggests that the lower system may be receiving water from the upper system. If the two systems were completely isolated, then the ionic strength of water from the lower system would be higher than that of the upper system due to greater water-rock interaction from traveling a longer horizontal flow path from its source area.

As noted in Section 3.1.1, gypsum does not occur in either the Santa Rosa or the upper Dewey Lake, while it is common in the lower Dewey Lake. Thus, water entering the Dewey

Lake through the Santa Rosa would be below gypsum saturation, while the water of the lower Dewey Lake where gypsum is present would be gypsum-saturated. The impediment to flow between the gypsum-free upper Dewey Lake and the lower Dewey Lake where gypsum is common would act to minimize mixing and maintain the observed stratification of water composition. Additional evidence of the depth stratification within the Dewey Lake is provided by the two SNL-14 samples; the first sample from 63 meters depth is a facies F water and undersaturated with respect to gypsum (SI = -1.5), while the deeper SNL-14 sample from 93 meters depth is close to gypsum saturation (SI = -0.2). The gypsum-saturation data demonstrate that water in the Dewey Lake may be stratified but do not unambiguously explain the cause of the stratification.

### 3.1.4 Salt Norm Types

The salt norm types for the Santa Rosa and Dewey Lake waters are shown on the Piper plot in Figure 9. The detailed results of the SNORM runs are displayed in Figure 13 with each bar representing the salt norm mineral assemblage for a particular well. The data are sorted by salt norm type and each salt norm type is sorted by ionic strength. The Santa Rosa wells, Comanche, Clifton and H-5c, and the Dewey Lake Barn well all appear to be waters of meteoric origin dominated either by carbonic acid or weak sulfuric acid hydrolysis of alumino-silicate minerals present in clastic sediments of the formation. These four wells all share a unique salt norm feature in that they do not contain any normative anhydrite, which suggests that these waters may never have contacted gypsum or other sulfates along their flow path. As was discussed in Section 3.1.3, these waters belong to the shallow water-table system, where meteoric water recharges vertically to the Santa Rosa and upper Dewey Lake. The Dewey Lake Twin-Pasture well represents a unique water type that reflects both a carbonic acid hydrolysis and a sulfate dissolution signature. Though not saturated with respect to gypsum, the presence of normative anhydrite along with the carbonates, calcite and dolomite, suggest both sulfate and carbonate interaction.

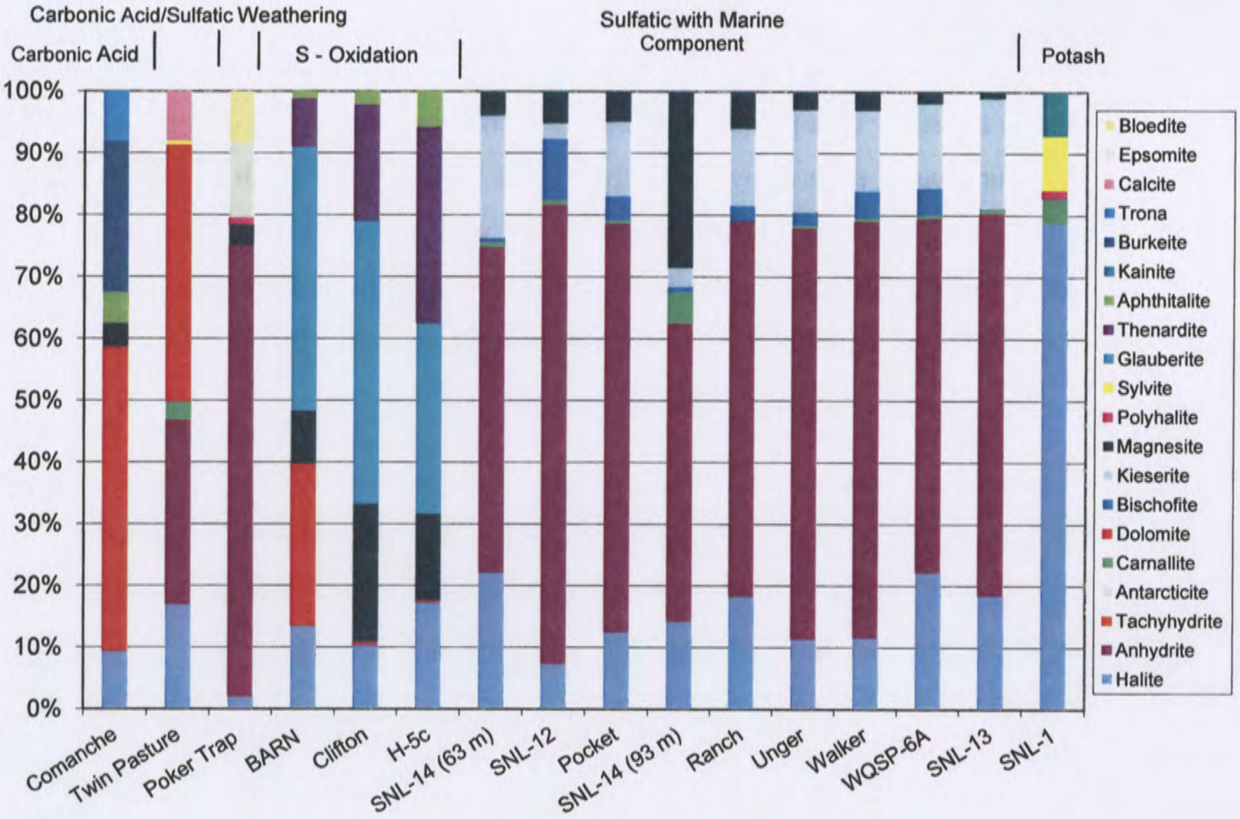


**Figure 13. Santa Rosa and Dewey Lake salt norms.**

The carbonic acid hydrolysis signature is reflected in the Comanche well norm by the presence of the carbonate phases dolomite ($CaMg(CO_3)_2$), magnesite ($MgCO_3$), and the alkali-bearing phases trona ($Na_3H(CO_3)_2 \cdot 2H_2O$) and burkeite ($Na_6CO_3(SO_4)_2$), and in the Twin-Pasture norm by the presence of dolomite, calcite ($CaCO_3$), and trace sylvite (KCl). Bodine and Jones (1990) state that "…alkali (sodium and potassium) bearing carbonate salts in the norm reflect atmospheric carbon dioxide – water interaction forming carbonic acid and accompanying hydrolysis of silicate minerals." The high percentage of the mixed alkali carbonate-sulfate salt, burkeite, in the Comanche norm may suggest a level of sulfur oxidation.

Three wells, Clifton, H-5c, and Barn, all have normative assemblages which include glauberite ($Na_2Ca(SO_4)_2$), thenardite ($Na_2SO_4$), and aphthitalite ($K_3Na(SO_4)_2$) – alkali-sulfate salts – in addition to normative magnesite and dolomite. Bodine and Jones (1990) state that "...alkali-bearing sulfate salts in the norm reflect sulfide mineral oxidation forming sulfuric acid with consequent hydrolysis of silicate minerals." We do not know if sulfide phases such as pyrite, which is a potential source of reduced sulfur, exist in the Santa Rosa Formation, though pyrite has been observed in the Culebra Dolomite Member of the Rustler Formation, and pyrite is a common early diagenetic phase in sedimentary rocks. The shallow depth of burial of the Santa Rosa across the study area permits oxygenated recharge to reach the Santa Rosa and react with reduced sulfur phases, such as pyrite, to form weak sulfuric acid which in turn reacts with the matrix siliciclastic sediments to create the observed water compositions and calculated salt norms. Though the number of water samples from the Santa Rosa Formation is small, the chemistry of the available samples is consistent with the geology and hydrologic setting of the formation.

The hydrochemical facies classification, facies F, for Comanche, Barn, Clifton, and H-5c matches well with their salt norm type where the diagnostic phases are alkali-bearing salts. Thus, the high alkali to alkaline ratio of the facies F waters reflects the chemical interaction between the water and clastic phases that the salt norm identified.

The salt norms of the Dewey Lake waters reflect the geology and the influence of the gypsum-filled fractures. The predominant salt norm type is sulfatic weathering solution with a small marine component. The primary phase of this salt norm type is anhydrite followed by kieserite ($MgSO_4 \cdot H_2O$), bischofite ($MgCl_2 \cdot 6H_2O$), and carnallite ($KMgCl_3 \cdot 6H_2O$) in order of decreasing abundance. The marine component most likely originates from the dissolution of trace evaporite minerals present at the time of deposition. The Poker Trap well was included in Domski and Beauheim (2008) as a Culebra well, but has since been found to be completed in the Dewey Lake. The Poker Trap salt norm is that of a sulfatic weathering solution with a large excess of anhydrite (73%) and diagnostic epsomite ($MgSO_4 \cdot 7H_2O$) and bloedite ($Na_2Mg(SO_4)_2 \cdot H_2O$). The salt norms of these lower Dewey Lake waters reflect fresh water interaction with Rustler-style marine-influenced evaporites, and represent the shallowest occurrence of a water type that is observed in the Magenta and Culebra Members of the Rustler Formation.

The salt norm from SNL-1 has a potash signature with the diagnostic phases including high halite (~79%), sylvite (KCl), and kainite ($KMgClSO_4 \cdot 3H_2O$). As discussed above, this water must be the product of potash-refining activities and does not reflect the groundwater chemistry of natural Dewey Lake water.

The salt norm results for the Santa Rosa and Dewey Lake waters are plotted on a map of the WIPP site and surrounding area in Figure 14. Due to the small number of wells, we cannot establish any correlation of the SNORM results with geomorphic or geologic features.

### 3.1.5 Normative Excesses

The normative excess results for the Santa Rosa and Dewey Lake waters are plotted on a map of the WIPP site and surrounding area in Figure 15. The waters of the three Santa Rosa wells and the Dewey Lake Barn well all have normative halite and anhydrite below excess levels. This lack of excess normative halite and anhydrite is a reflection of the dilute and relatively low reacted nature of these waters, and the high probability that these are young newly recharged waters. The remainder of the Dewey Lake wells contain waters with excess anhydrite, which signals dissolution of gypsum and greater water to rock reaction, and water that is further along a potential flowpath compared to the waters of the Santa Rosa. As discussed above, the excess halite in the SNL-1 water reflects contamination from potash refining.

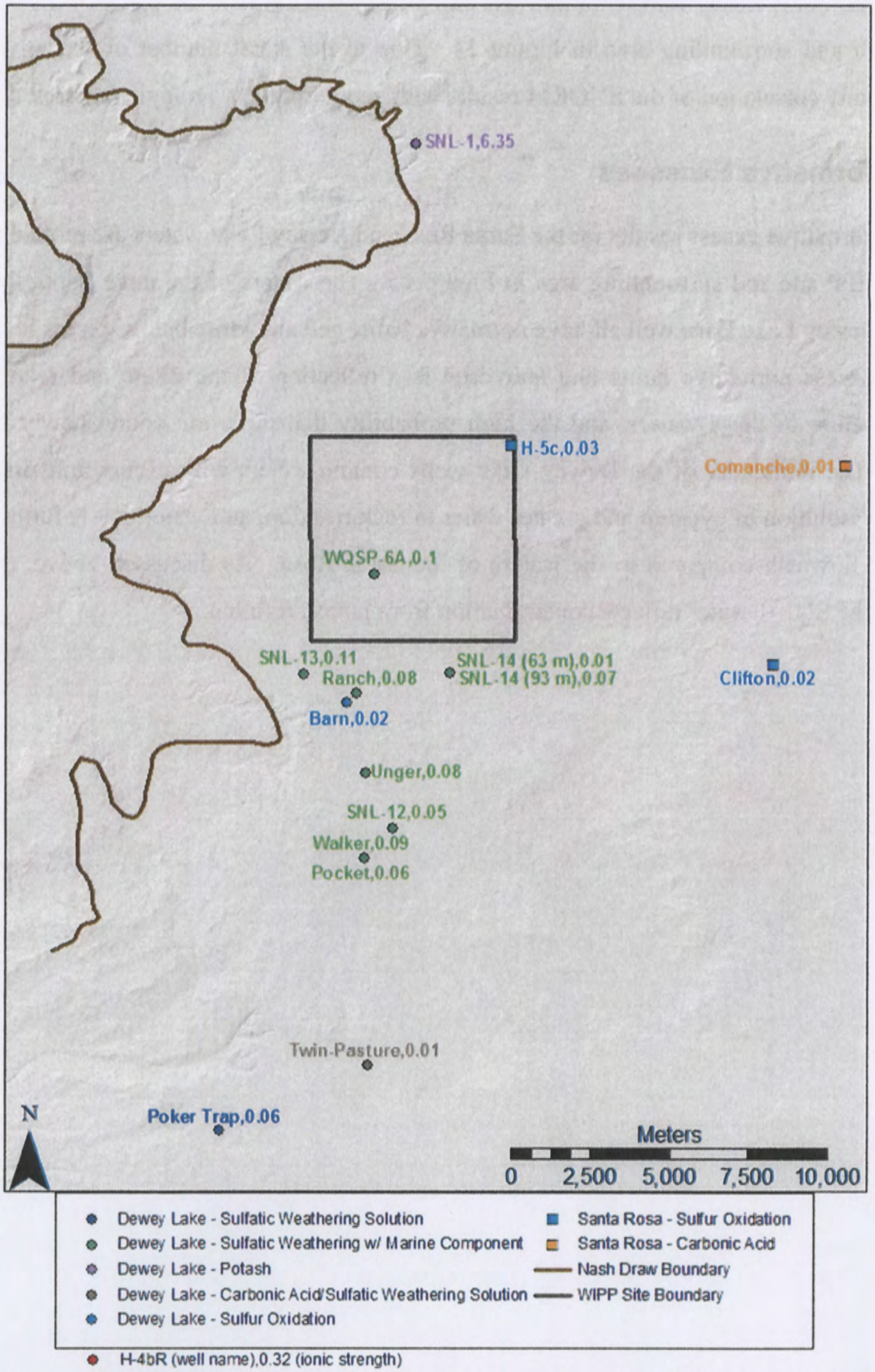


**Figure 14.** Santa Rosa and Dewey Lake waters color-coded on the basis of salt norm type.

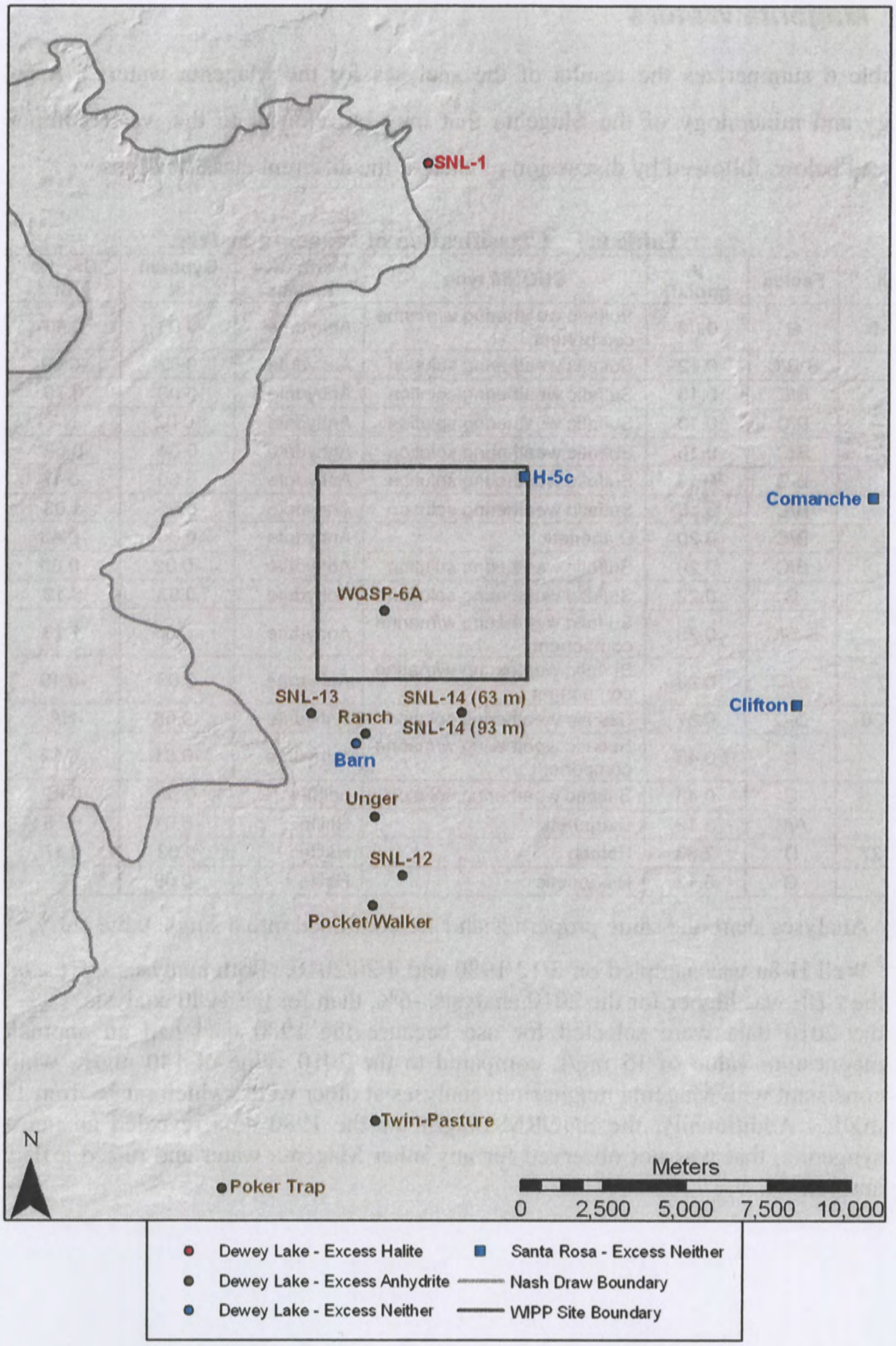


**Figure 15.** **Santa Rosa and Dewey Lake waters color-coded on the basis of normative excess.**

## 3.2 Magenta Waters

Table 6 summarizes the results of the analyses for the Magenta waters. Aspects of the geology and mineralogy of the Magenta that may be relevant to the water compositions are discussed below, followed by discussion of each of the different classifications.

**Table 6. Classification of Magenta waters.**

| Well | Facies | μ (molal) | SNORM type | Normative Excess | Gypsum SI | Calcite SI | $CO_2$ SI |
|---|---|---|---|---|---|---|---|
| USGS-5 | B | 0.09 | Sulfatic weathering w/marine component | Anhydrite | 0.03 | 0.49 | -2.68 |
| H-6c | B-B/C | 0.12 | Sulfatic weathering solution | Anhydrite | 0.02 | -0.09 | -2.85 |
| H-9a | B/C | 0.13 | Sulfatic weathering solution | Anhydrite | 0.00 | 0.76 | -4.06 |
| H-9c[1] | B/C | 0.13 | Sulfatic weathering solution | Anhydrite | -0.02 | NA | NA |
| H-5c | B/C | 0.15 | Sulfatic weathering solution | Anhydrite | 0.04 | 0.62 | -3.84 |
| H-18 | B/C | 0.16 | Sulfatic weathering solution | Anhydrite | 0.00 | -0.17 | -2.95 |
| H-2b1 | B/C | 0.18 | Sulfatic weathering solution | Anhydrite | 0.05 | 1.03 | -4.83 |
| H-3b1[1] | B/C | 0.20 | Diagenetic | Anhydrite | 0.00 | -0.43 | -2.45 |
| WIPP-18 | B/C | 0.20 | Sulfatic weathering solution | Anhydrite | -0.02 | -0.86 | -2.92 |
| H-8a[2] | B | 0.22 | Sulfatic weathering solution | Anhydrite | 0.03 | 0.19 | -3.10 |
| H-2a | B-B/C | 0.23 | Sulfatic weathering w/marine component | Anhydrite | -0.04 | 1.18 | -3.99 |
| C-2737 | B/C | 0.23 | Sulfatic weathering w/marine component | Anhydrite | 0.00 | -0.19 | -2.90 |
| WIPP-30 | B/C | 0.37 | Sulfatic weathering solution | Anhydrite | -0.08 | NA | NA |
| H-1 | C | 0.46 | Sulfatic weathering w/marine component | Anhydrite | -0.01 | -0.02 | -2.41 |
| H-4c[1] | C | 0.48 | Sulfatic weathering solution | neither | 0.06 | 0.89 | -3.46 |
| H-15 | A/C | 2.13 | Diagenetic | Halite | -0.01 | 0.58 | -3.56 |
| WIPP-27 | D | 2.83 | Potash | Halite | 0.02 | 0.17 | -1.27 |
| H-10a | G | 5.12 | Diagenetic | Halite | -0.09 | NA | NA |

[1] Analyses share the same properties and are combined into a single table entry.

[2] Well H-8a was sampled on 2/12/1980 and 4/20/2010. Both analyses were evaluated and the CBE was higher for the 2010 analysis, -6%, than for the 1980 analysis, -2%. However, the 2010 data were selected for use because the 1980 data had an anomalously low magnesium value of 15 mg/L compared to the 2010 value of 140 mg/L, which is more consistent with Magenta magnesium analyses at other wells, which range from 122 to 2600 mg/L. Additionally, the SNORM output for the 1980 data revealed an unusual phase, syngenite, that was not observed for any other Magenta water and raised a flag about the analysis.

### 3.2.1 Geology and Mineralogy of the Magenta

The Magenta Member of the Rustler Formation is a 7- to 8-m-thick unit with features that are vertically consistent over the study area, including a lower algal-dominated section overlain by a strongly cross-laminated section and a thin nodular gypsum bed near the top of the Magenta.

The transition from deposition of the sulfate Tamarisk A-3 to the carbonate Magenta represented a freshening of the waters of the northern Delaware Basin (Powers et al., 2006). The deposition of the nodular gypsum near the top of the Magenta marked the chemical divide from carbonate to sulfate deposition with increasing salinity and the transition to deposition of the Forty-niner A-4 anhydrite. Powers et al. (2006) observed halite fracture fillings near the top of the Magenta from core removed from borehole SNL-6 and SNL-15 and hypothesized that the halite-saturated brine that deposited the halite was the same as that which deposited the Forty-niner H-4 halite. The Magenta is hydraulically isolated by the Tamarisk A-3 sulfate below and by the Forty-niner A-4 sulfate bed above.

### 3.2.2 Hydrochemical Facies

Figure 16 is a Piper plot of the waters of the Magenta symbol-coded on the basis of hydrochemical facies. It shows that the Magenta water chemistry tends from calcium sulfate to sodium chloride solutions. The single occurrence of facies D water is from WIPP-27, which is near the Intrepid West potash tailings pile.

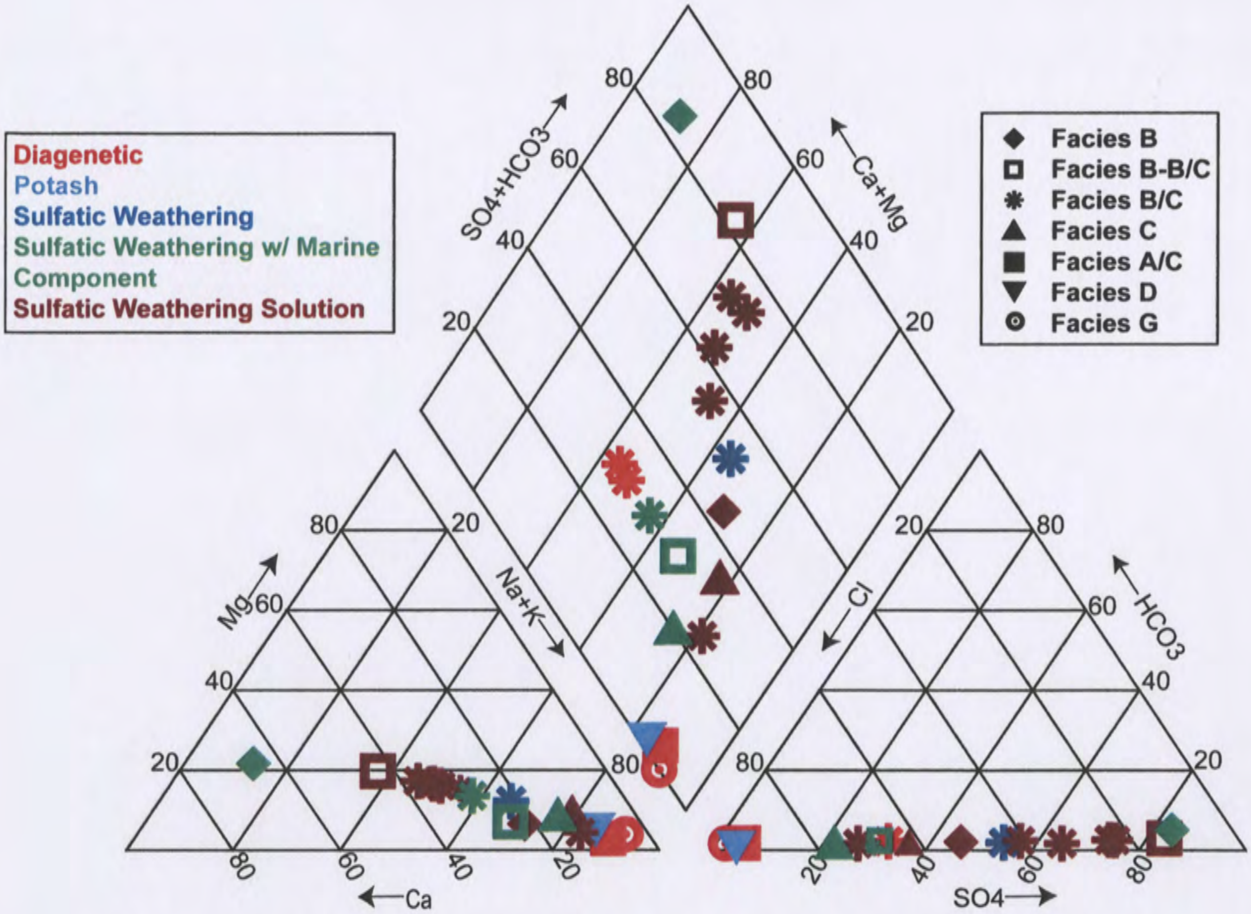


**Figure 16. Piper plot of the Magenta waters symbol-coded to reflect their hydrochemical facies and color-coded to reflect their SNORM type.**

Figure 17 shows the areal distribution of the Magenta hydrochemical facies on a map of the WIPP site and surrounding area. Given the sparse data, it is difficult to draw any conclusions on the distribution of the facies with regard to any geomorphic features such as Nash Draw, or geologic features such as the halite/mudstone margins. However, in the broadest sense, the most dilute facies B waters tend to occur along the western margin of the study area and in Nash Draw, while the more concentrated waters (H-15 and H-10a) lie along the eastern portions of the study area. As a specific example, the H-10a well lies furthest to the east of all the Magenta wells, and it is the most concentrated of all the Magenta waters at 5.12 molal.

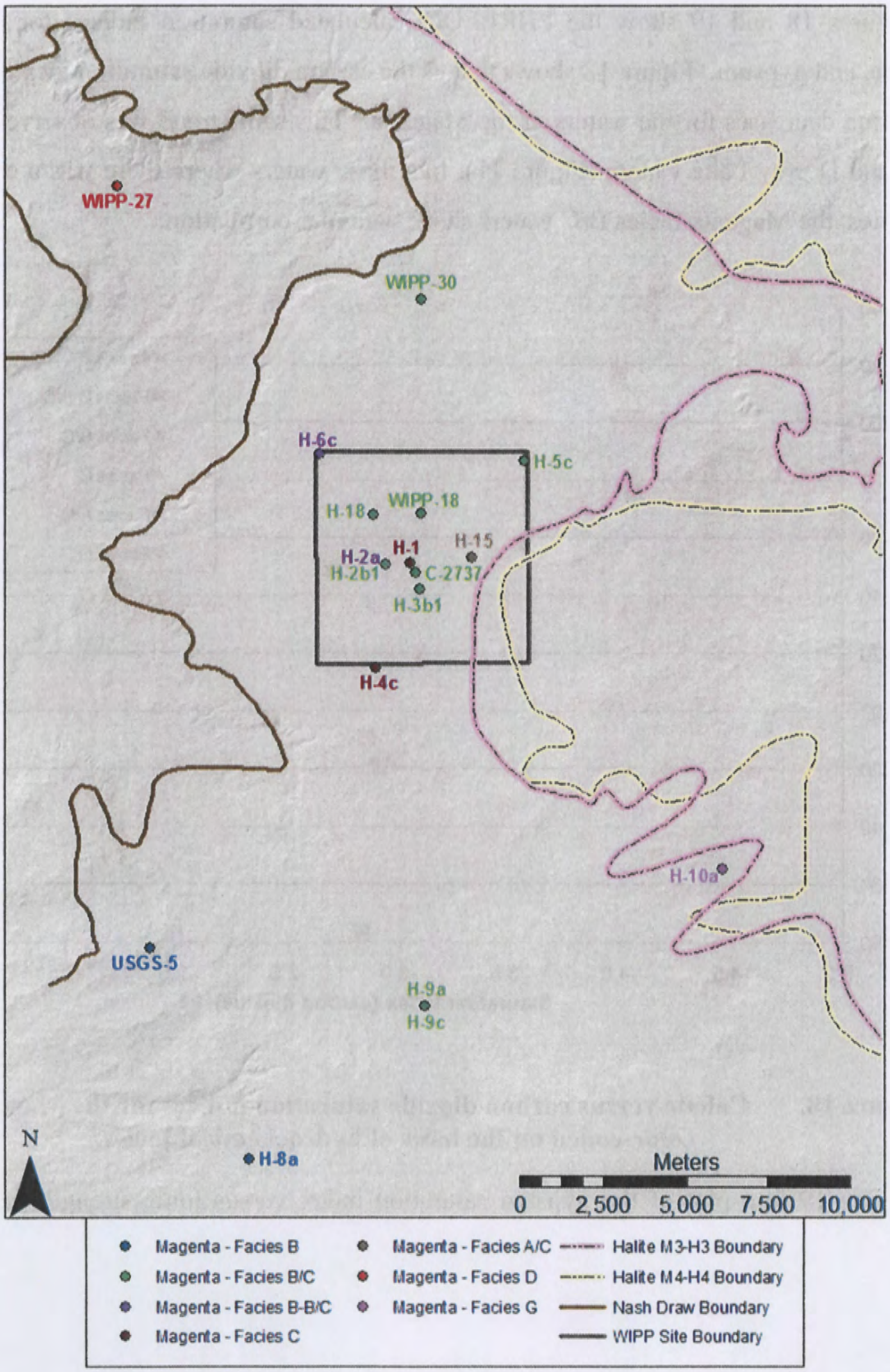


**Figure 17.** **Magenta waters color-coded on the basis of hydrochemical facies.**

### 3.2.3 Saturation Indices and Ionic Strength

Figures 18 and 19 show the PHREEQCI-calculated saturation indices for calcite, carbon dioxide, and gypsum. Figure 18 shows that as the carbon dioxide saturation increases, the calcite saturation decreases for the waters of the Magenta. This same trend was observed for the Santa Rosa and Dewey Lake waters (Figure 11); like those waters where there was a correlation with the facies, the Magenta facies B/C waters show a similar correlation.

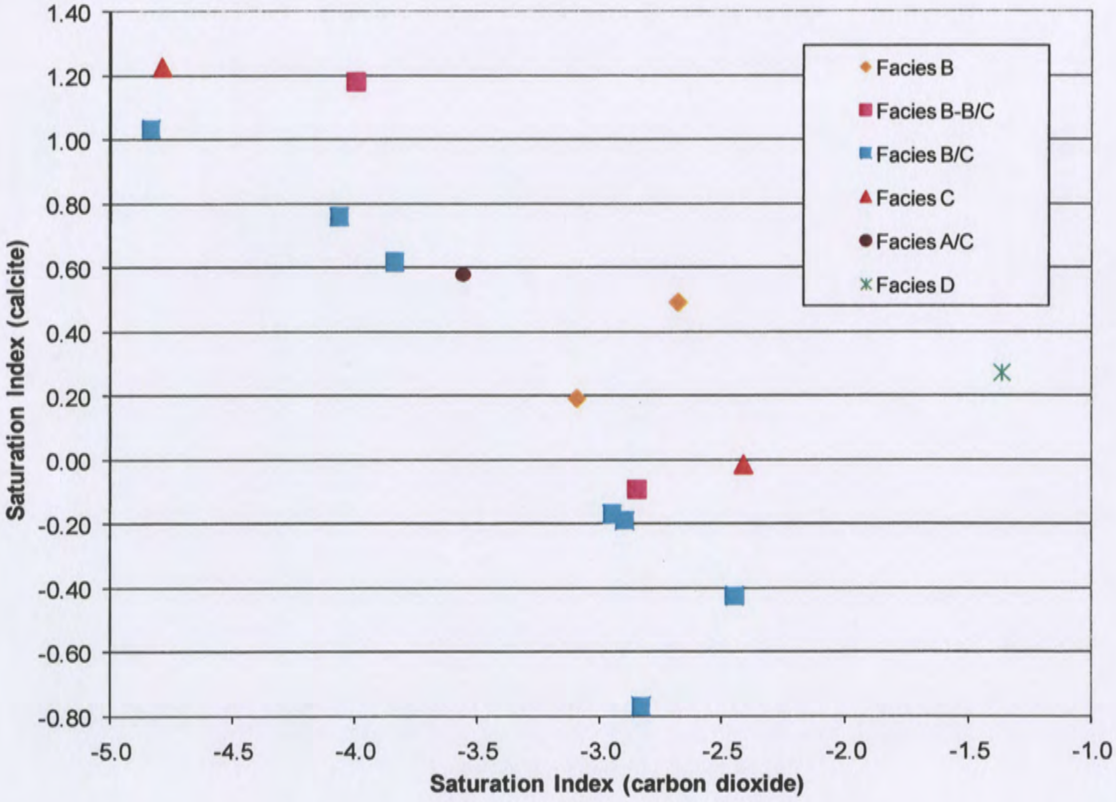


**Figure 18. Calcite versus carbon dioxide saturation indices for the Magenta waters color-coded on the basis of hydrochemical facies.**

Figure 19 is a plot of the gypsum saturation index versus ionic strength for the Magenta waters. This plot shows that all of the Magenta waters are essentially saturated with respect to gypsum and that there is no variation in gypsum saturation with ionic strength. Gypsum saturation is expected for the Magenta waters because of its occurrence within this unit and the units above and below the Magenta, and because gypsum has a relatively high solubility. The waters of the Magenta range in ionic strength from 0.1 to 5.1 molal (Table 6). Of the 18 samples discussed in this report, however, 14 have ionic strengths less than 0.5 molal.

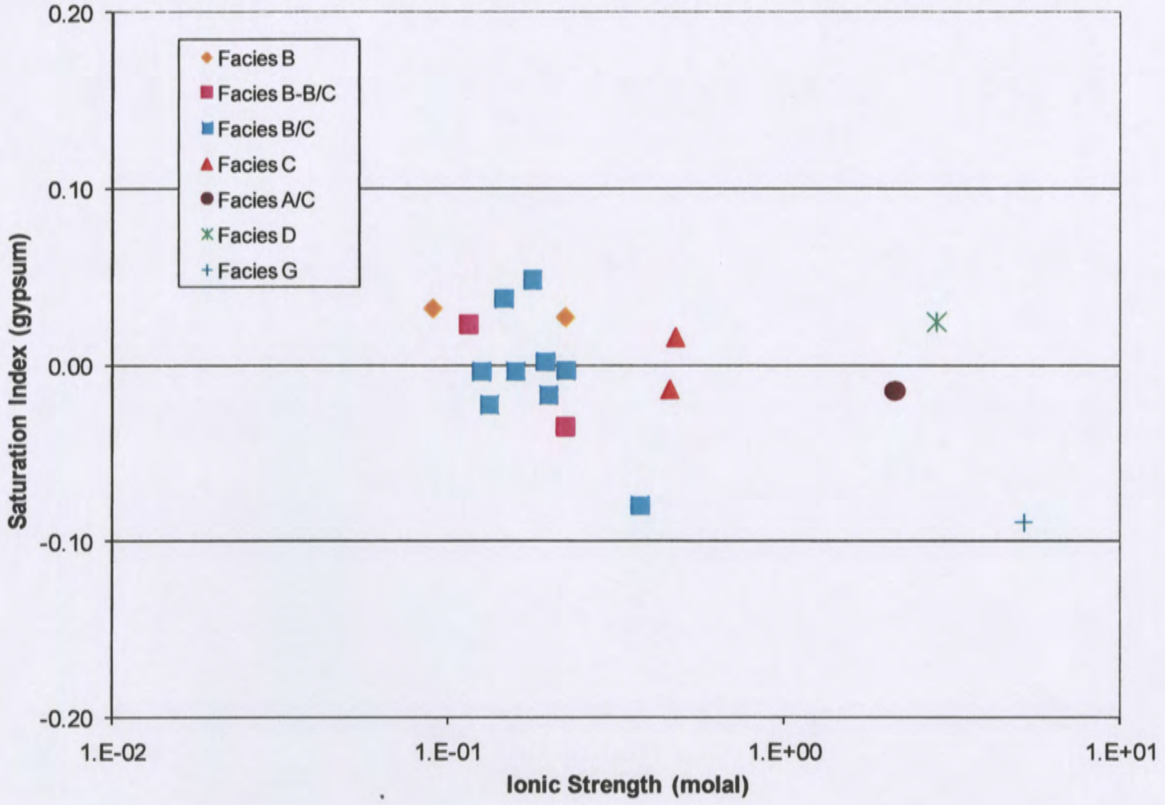


**Figure 19.** **Gypsum saturation index versus ionic strength for the Magenta waters color-coded on the basis of hydrochemical facies.**

### 3.2.4 Salt Norm Types

The salt norm types for the Magenta waters are shown on the Piper plot in Figure 16. Detailed salt norm results for the Magenta waters are shown in Figure 20. In the waters of the Magenta, four salt norm types were observed: 1) sulfatic weathering solutions with ionic strengths from 0.12 to 0.48 molal; 2) sulfatic weathering solutions containing a marine component from 0.09 to 0.46 molal ionic strength; 3) diagenetic with ionic strength from 0.20 to 6.34 molal; and 4) potash salt norm at 2.83 molal.

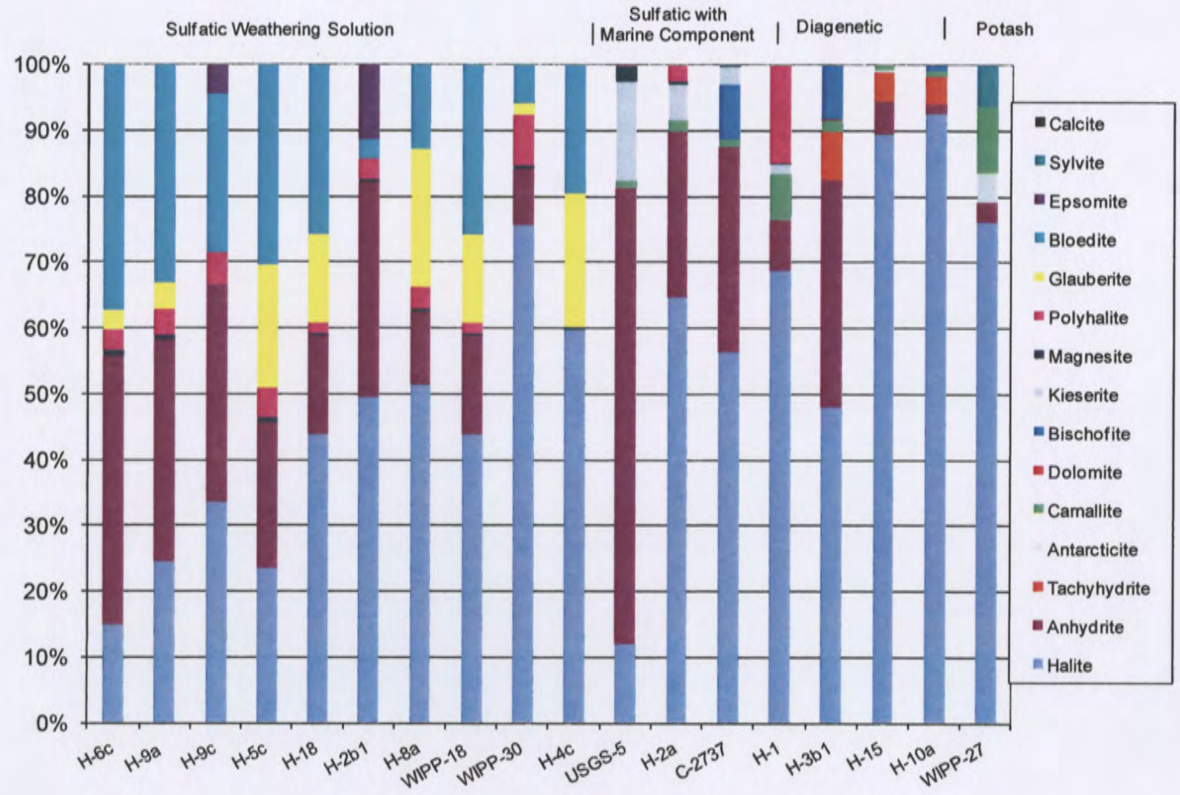


**Figure 20. Magenta salt norms.**

The sulfatic weathering solutions are characterized by low to moderate ionic strength (0.12 to 0.48 molal) and are composed of facies B, B/C, and C. All of the norms for these waters contain excess anhydrite with the exception of H-4c, for which neither halite nor anhydrite are in excess. The normative assemblages are heavy in sulfate phases (anhydrite – polyhalite – bloedite – glauberite ± epsomite). The mixed alkali/alkaline sulfate phases bloedite ($Na_2Mg(SO4)_2 \cdot H2O$) and glauberite ($Na_2Ca(SO_4)$) are indicative of continental recycling of sulfate phases, i.e., weathering and dissolution of sulfate-bearing minerals (Bodine and Jones, 1986). None of the other salt norm groups have either bloedite or glauberite in their normative assemblages, thus making these phases diagnostic minerals of this group. It is worthy to note that well H-2b1 lacks normative glauberite and only contains minor normative bloedite (~3%), for this well all of the sodium is coordinated with chloride as halite, and the diagnostic phase of this norm is espsomite (~11%).

The sulfatic weathering solutions with a marine component group of waters is characterized by ionic strengths that vary between 0.1 to 0.5 molal, and includes facies B, B/C, and C. The normative mineral assemblages are composed of halite, excess anhydrite, the mixed alkali/alkaline chloride, carnallite ($KMgCl_3•6H_2O$), and also include alkaline sulfates as kieserite ($MgSO_4•H2O$) and polyhalite ($K_2Ca_2Mg(SO_4)_4•2H_2O$). In the norms of these waters, the diagnostic marine assemblage of halite-bischofite-kieserite-carnallite-anhydrite has been altered by the input of additional sulfate, which sacrifices bischofite ($MgCl_2•6H_2O$) in favor of additional kieserite and polyhalite. Bodine and Jones (1986) state that the presence of polyhalite in an otherwise marine-like norm is strong evidence for meteoric-marine water mixing. Compared to the sulfatic weathering type waters, this group lacks normative bloedite, while the diagnostic marine phase carnallite persists in these norms as a product of their relative greater chloride compared to sulfate concentrations.

In the Magenta, we observe three wells, H-3b1, H-15, and H-10a, with the diagenetic salt norm type. The waters range from low ionic strength (0.2 molal) calcium sulfate water at H-3b1 to concentrated (6.3 molal) sodium chloride brine at H-10a. The salt norms of these waters all share the diagnostic mineral suite of tachyhydrite ($Mg_2CaCl_6•12H_2O$), carnallite ($KMgCl_3•6H_2O$), and bischofite ($MgCl_2•6H_2O$) or antarcticite ($CaCl_2•6H_2O$), signaling that they contain a fraction of primitive fluid in their makeup.

The unique high ionic strength and diagenetic signature of the water from well H-10a, with its location in an embayment of the M3-H3 and M4-H4 mudstone/halite margins, suggests that the margins exert a strong influence on the chemistry of the wells in their proximity. Like H-10a, the proximity of wells H-3b1 and H-15 to the M3-H3 and M4-H4 mudstone/halite margins is considered the potential cause for their diagenetic signature where solutes may be diffusing from the Magenta east of the mudstone/halite margins.

A single Magenta well, WIPP-27, has a potash normative signature. The diagnostic phase for this norm is sylvite (KCl). Siegel et al. (1991b) attributed the unusually high potassium levels to contamination from potash refining activities at the nearby potash mining facilities.

The distribution of salt norm types across the study area is plotted in Figure 21. Although the sample size is small, some valuable observations can still be made. The wells closest to the mudstone/halite margins are diagenetic, and wells slightly further west of the margins are sulfatic weathering with a marine component, and finally even further west are sulfatic weathering solution wells. Domski and Beauheim (2008) demonstrated that the salt norm type sulfatic weathering with a marine component was an intermediate composition resulting from mixing

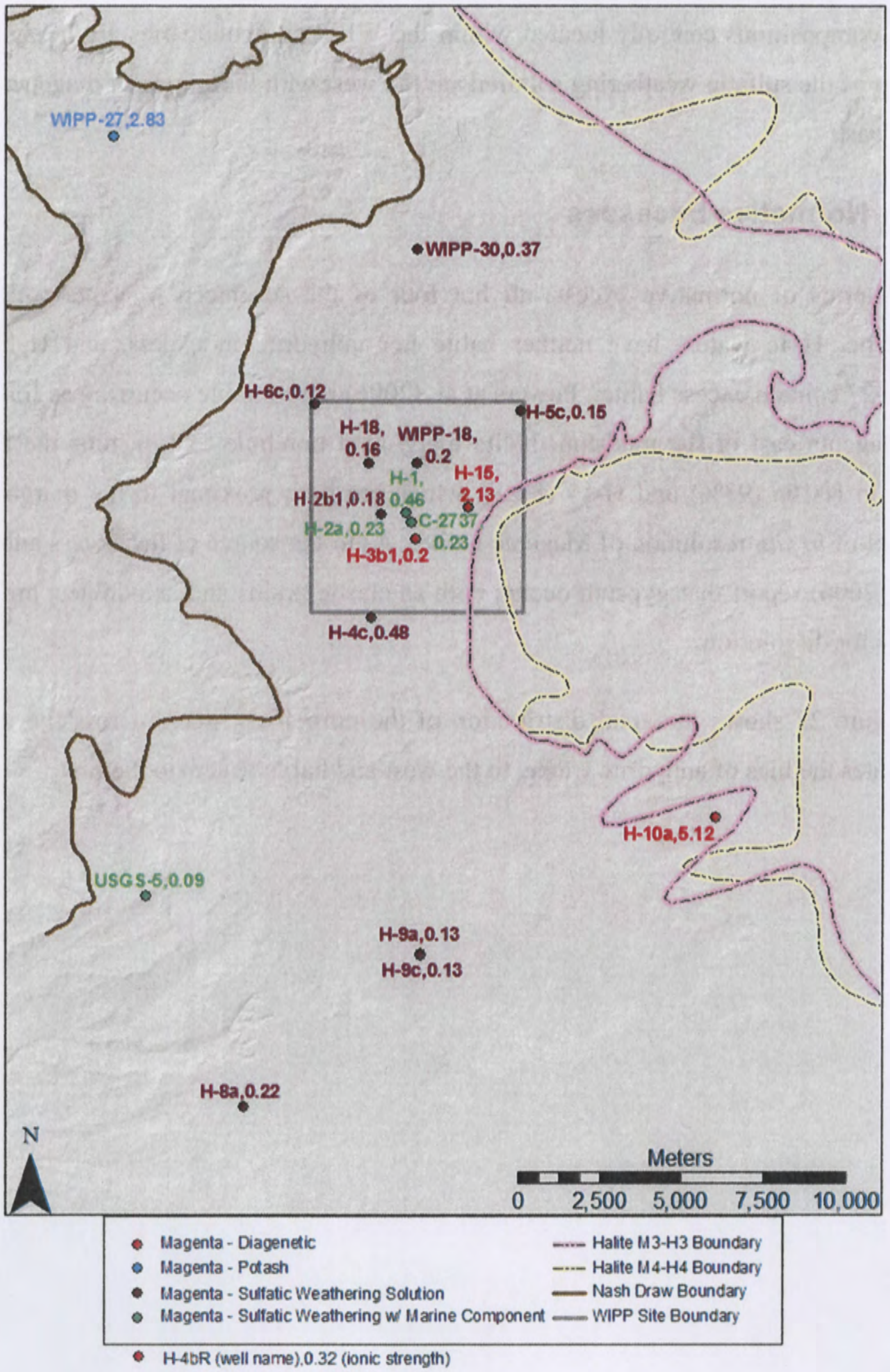


**Figure 21.** Magenta waters color-coded on the basis of salt norm type.

waters of diagenetic composition with those of sulfatic weathering solutions. Thus, the Magenta wells' compositions centrally located within the WIPP site boundaries are likely the product of mixing of the sulfatic weathering solutions to the west with the waters of diagenetic composition to the east.

### 3.2.5 Normative Excesses

In terms of normative excess, all but four of the seventeen Magenta wells have excess anhydrite, H-4c waters have neither halite nor anhydrite in excess, and H-10a, H-15, and WIPP-27 contain excess halite. Powers et al. (2006) report halite occurring as fracture fillings in the Magenta east of the mudstone/halite margins at borehole SNL-6, thus the high normative halite in H-10a (93%) and H-15 (89%), which are both proximal to the margins, may be the product of *in situ* resolution of Magenta halite. As to the source of the excess anhydrite, Powers et al. (2006) report that gypsum occurs both as clastic grains and as nodules, providing a ready supply for dissolution.

Figure 22 shows the areal distribution of the normative excess across the study area, and illustrates the bias of anhydrite waters to the west and halite waters to the east.

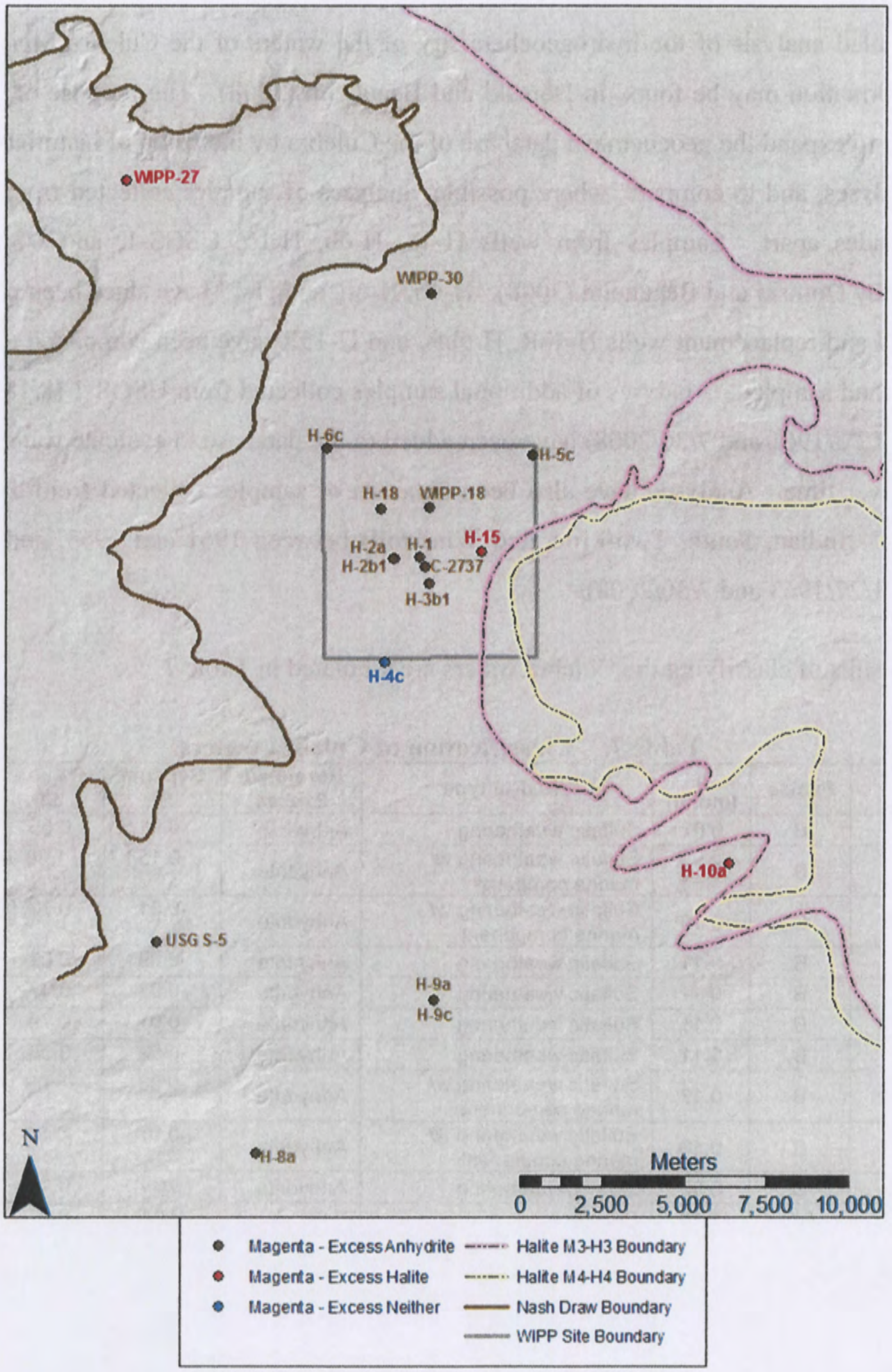


**Figure 22.** **Magenta waters color-coded on the basis of normative excess.**

## 3.3 Culebra Waters

A detailed analysis of the hydrogeochemistry of the waters of the Culebra Member of the Rustler Formation may be found in Domski and Beauheim (2008). The purpose of the current analysis is to expand the geochemical database of the Culebra by inclusion of historical and more recent analyses, and to compare, where possible, analyses of samples collected from individual wells decades apart. Samples from wells H-4b, H-6b, H-15, USGS-1, and USGS-4 were evaluated by Domski and Beauheim (2008). H-4b, H-6b, and H-15 have since been plugged and abandoned and replacement wells H-4bR, H-6bR, and H-15R have been completed on the same well pads and sampled. Analyses of additional samples collected from USGS-1 (8/18/1960) and USGS-4 (12/5/1961 and 7/30/2008) have been added to the database to evaluate water chemistry stability over time. Analyses have also been obtained of samples collected from a number of stock wells (Indian, South, Two-Mile, and Windmill) between 1961 and 1963, and from well USGS-8 (1/27/1963 and 7/30/2008).

The results of classifying the Culebra waters are tabulated in Table 7.

**Table 7. Classification of Culebra waters.**

| Well | Facies | μ (molal) | SNORM type | Normative Excess | Gypsum SI | Calcite SI | CO2 (g) SI |
|---|---|---|---|---|---|---|---|
| South | B | 0.07 | Sulfatic weathering | Anhydrite | -0.01 | 0.55 | -2.21 |
| USGS-4[1] | B | 0.10 | Sulfatic weathering w/ marine component | Anhydrite | -0.15 | -1.28 | -2.00 |
| Indian | B | 0.10 | Sulfatic weathering w/ marine component | Anhydrite | -0.01 | 0.72 | -2.43 |
| USGS-8[1] | B | 0.11 | Sulfatic weathering | Anhydrite | -0.09 | 0.08 | -3.32 |
| USGS-1 | B | 0.11 | Sulfatic weathering | Anhydrite | -0.03 | 0.47 | -2.66 |
| Windmill | B | 0.11 | Sulfatic weathering | Anhydrite | -0.01 | 0.79 | -3.08 |
| USGS-4[2] | B | 0.11 | Sulfatic weathering | Anhydrite | -0.02 | 0.38 | -2.56 |
| USGS-8[3] | B | 0.12 | Sulfatic weathering w/ marine component | Anhydrite | -0.03 | -0.09 | -2.22 |
| Two-Mile | B | 0.16 | Sulfatic weathering w/ marine component | Anhydrite | -0.07 | -0.81 | -2.11 |
| H-4bR | C | 0.32 | Sulfatic weathering | Anhydrite | 0.00 | 0.12 | -3.21 |
| H-6bR | A/C | 1.10 | Diagenetic | Both | 0.04 | 0.67 | -3.12 |
| H-15R | A | 4.18 | Marine | Halite | 0.00 | 0.59 | -3.16 |

[1] 7/30/2008 sample (see Table 2)
[2] 12/5/1961 sample (see Table 2)
[3] 1/27/1963 sample (see Table 2)

The classification results for wells H-15R, H-4bR, H-6bR, USGS-1, and USGS-4 are consistent with those presented in Domski and Beauheim (2008). However, decreases in ionic strength were observed for H-4bR relative to H-4b (0.45 molal in 1992 (Domski and Beauheim, 2008) to 0.33 molal in 2009) and for H-6bR relative to H-6b (1.27 molal in 1994 (Domski and Beauheim, 2008) to 1.10 molal in 2008). Future sample analyses will be required to determine if the apparent freshening of these waters is an actual trend or an anomaly.

### 3.3.1 Geology and Mineralogy of the Culebra

The Culebra is a locally argillaceous and arenaceous, well- to poorly indurated dolomicrite approximately 7-8 m thick. It exhibits significant spatial heterogeneity in the types of porosity, the amount of fracturing, and the amount of porosity-filling cements (primarily gypsum, with some halite) that are present. It contains minor amounts of clay and silt-sized clastic material. After dolomite, Sewards et al. (1991) report that clay is the most abundant mineral of the Culebra. Clay minerals include corrensite, illite, serpentine, and chlorite. Clay occurs in bulk rock and on fracture surfaces.

### 3.3.2 Hydrochemical Facies

The Culebra data are plotted in the Figure 23 Piper plot. The chemistry ranges from dilute facies B calcium carbonate/sulfate waters to facies C waters of slightly higher ionic strength to more concentrated facies A/C and high ionic strength facies A sodium chloride waters.

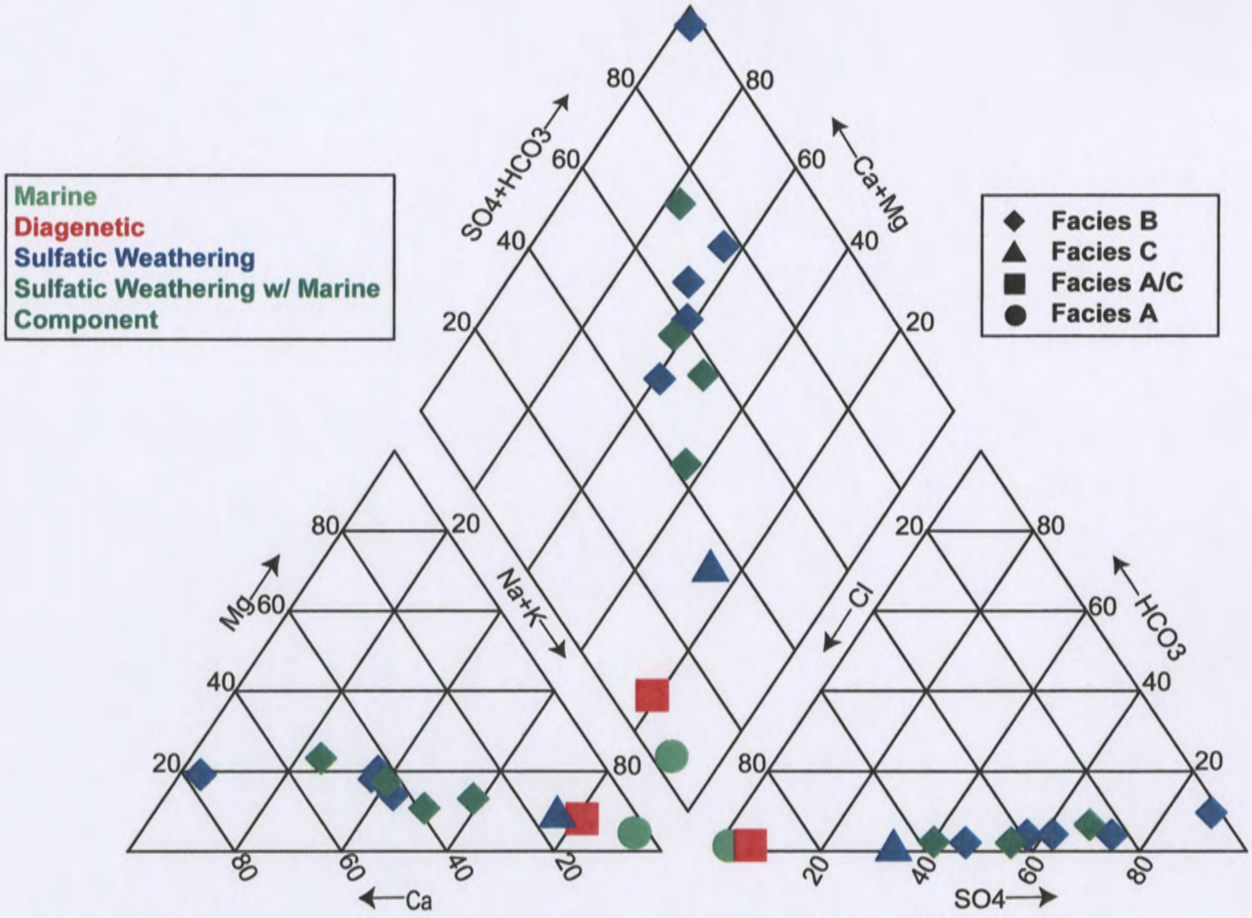


**Figure 23.** **Piper plot of the Culebra waters symbol-coded to reflect their hydrochemical facies and color-coded to reflect their SNORM type.**

Figure 24 shows the areal distribution of the hydrochemical facies for the Culebra wells. The wells not included in Domski and Beauheim (2008), Windmill, Indian, South, USGS-8, and Two-Mile, all are located southwest of the WIPP site and belong to facies B, and are consistent with the other Culebra wells in that region which are also facies B wells (Figure 5). The replacement wells on or close to the WIPP site, H-6bR, H-15R, and H-4bR, retain the facies designations given to the original wells at those locations in Domski and Beauheim (2008).

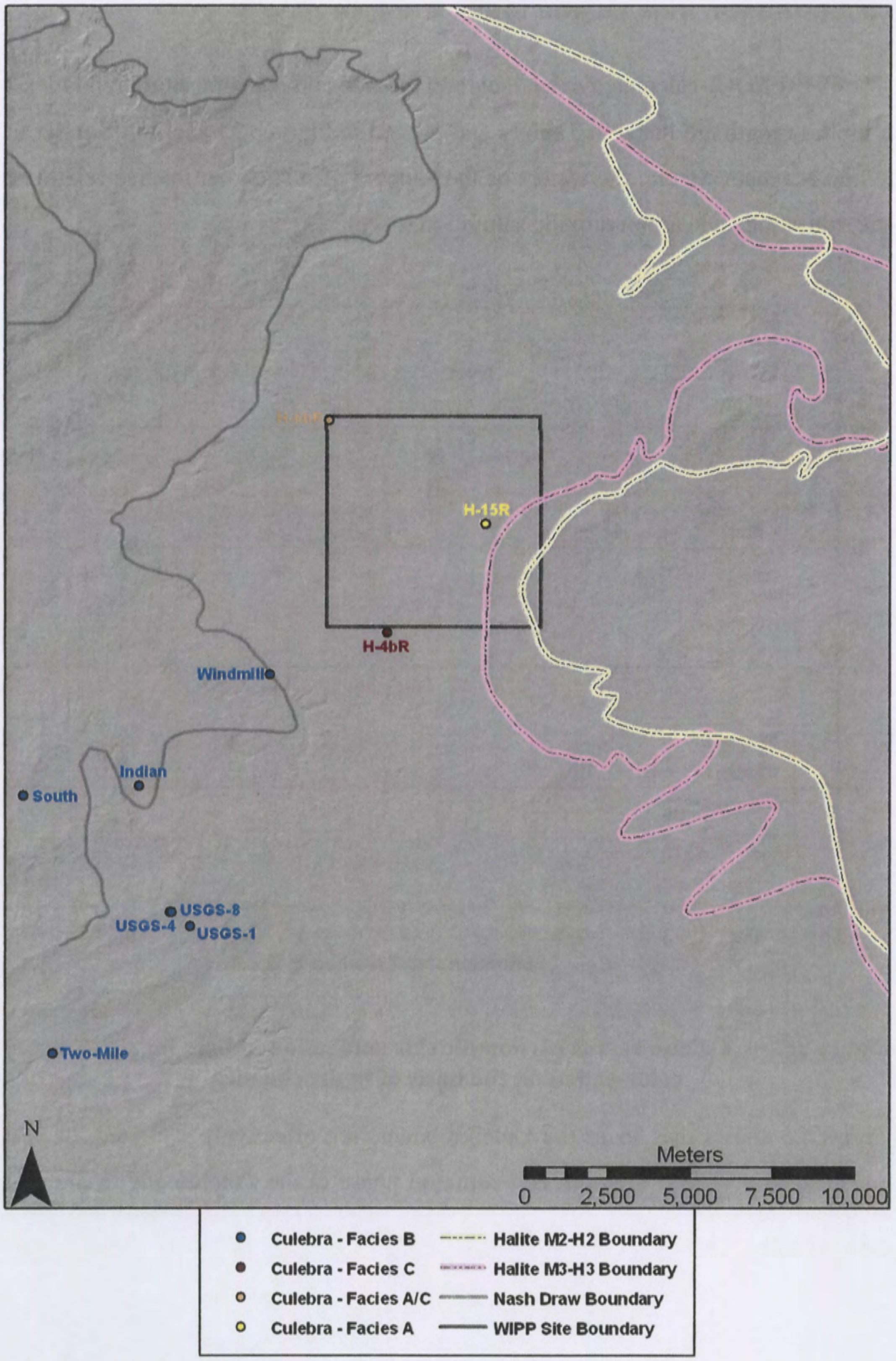


Figure 24. Culebra waters color-coded on the basis of hydrochemical facies.

### 3.3.3 Saturation Indices and Ionic Strength

The PHREEQCI-calculated calcite, carbon dioxide and gypsum saturation index values along with ionic strength are listed in Table 7 and plotted in Figures 25 and 26. Similar to the Dewey Lake and Magenta waters, the waters of the Culebra also show an inverse relationship between calcite saturation and carbon dioxide saturation (Figure 25).

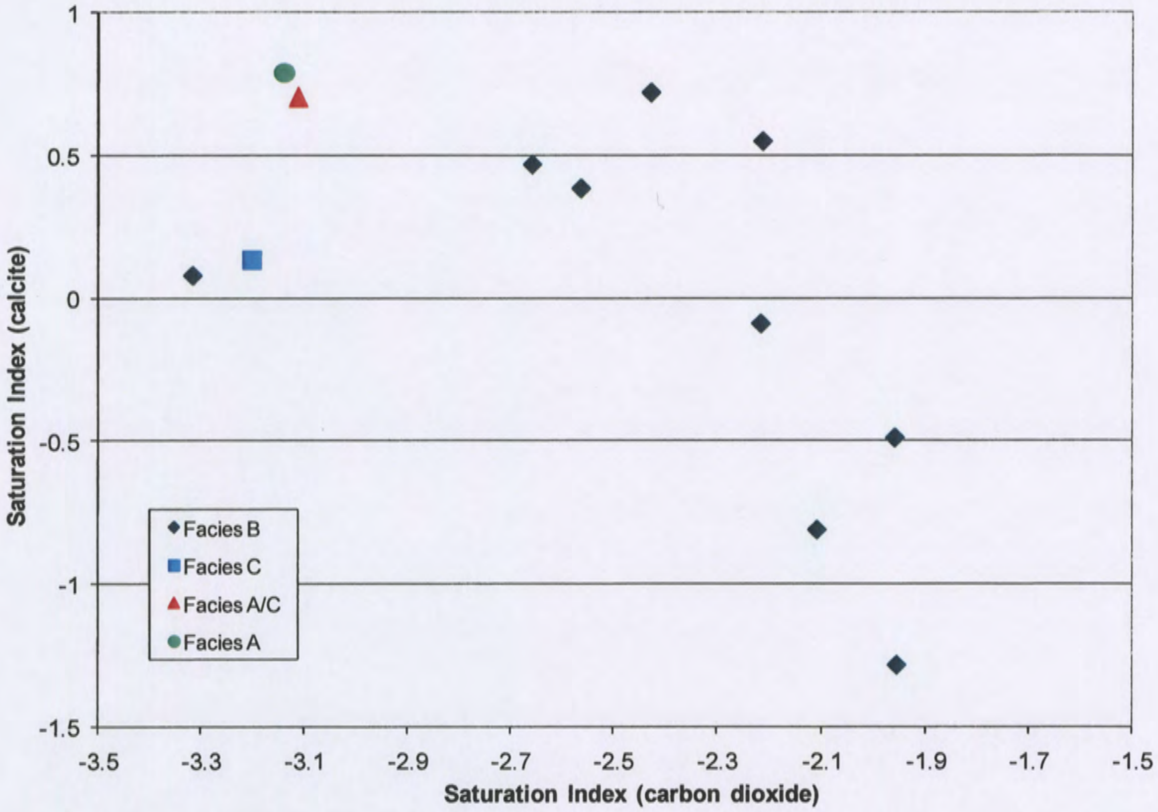


**Figure 25.** **Calcite versus carbon dioxide saturation indices for the Culebra waters color-coded on the basis of hydrochemical facies.**

Figure 26 shows that all of the Culebra waters are effectively saturated, or very nearly so, with respect to gypsum. Gypsum is a common phase in the Culebra and in the units above the Culebra, so gypsum saturation is expected, and was observed by Domski and Beauheim (2008) for a wider set of Culebra waters.

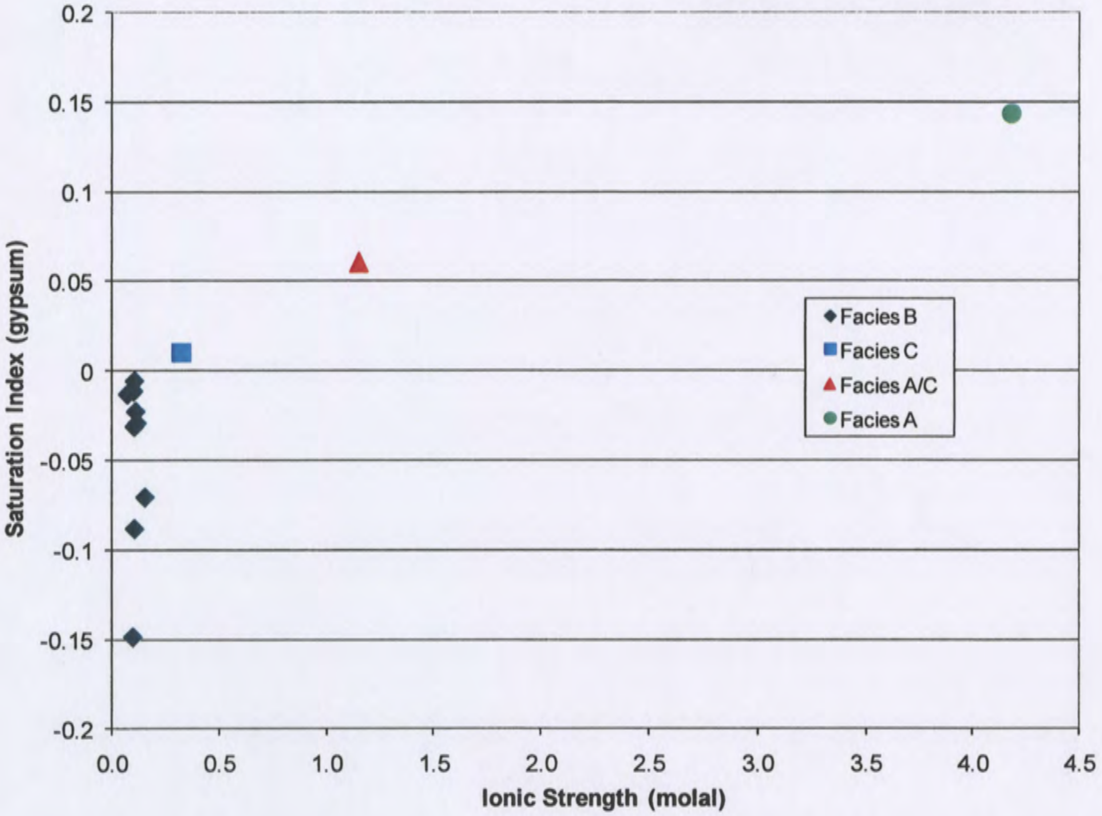


**Figure 26.** **Gypsum saturation index versus ionic strength for the Culebra waters color-coded on the basis of hydrochemical facies.**

### 3.3.4 Salt Norm Types

The salt norm types for the Culebra waters are shown in the Piper plot in Figure 23. The detailed SNORM output for the Culebra waters is plotted in Figure 27. The salt norms for H-4bR, H-6bR, H-15R, and USGS-1 are the same as those reported in Domski and Beauheim (2008). The salt norm type for USGS-4 changed from a sulfatic weathering solution in 1961 to a sulfatic weathering solution with a marine component in 2006 (Domski and Beauheim, 2008), and maintains that designation for the 2008 data. Similarly, USGS-8 changed from a sulfatic weathering solution with a marine component in 1963 to just a sulfatic weathering solution in 2008. These changes in the USGS-4 and USGS-8 reflect very subtle changes to the water chemistry, and with dilute waters, such as those in this region of the study area, small changes to chemistry (possibly analytical error) have a more pronounced influence on the SNORM output.

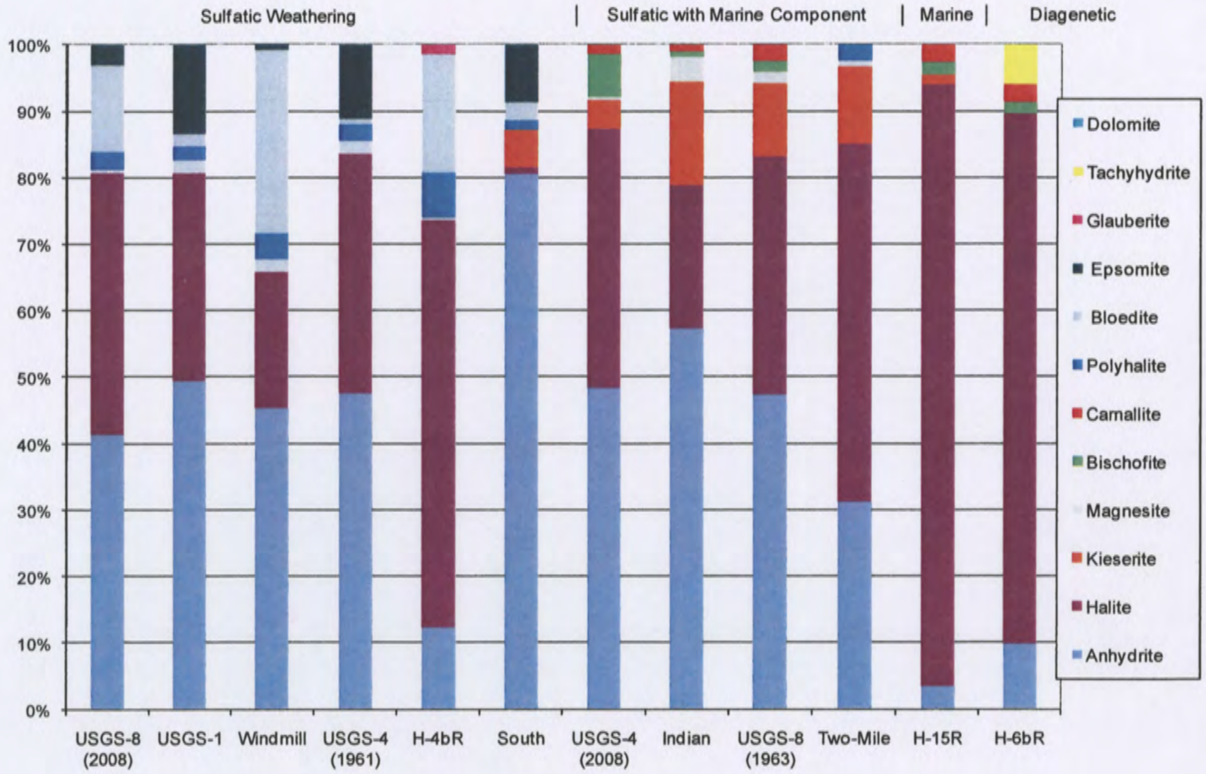


**Figure 27. Culebra salt norms.**

Figure 28 shows the areal distribution of the salt norms over the study area for the current analyses, and those reported in Domski and Beauheim (2008) are shown in Figure 6. The addition of wells southwest of the WIPP site boundary adds resolution to this area and draws a more heterogeneous picture of the salt norm types present there. With the addition of Windmill and South, both of which are sulfatic weathering types in an area previously dominated by mixed sulfate/marine (see Figure 6), and with Two-Mile a mixed sulfate/marine well in an area otherwise sulfatic weathering, the picture has changed to suggest the probability of encountering either of these types is more or less the same. Furthermore, it may suggest that these salt norm types are sufficiently close to one another that the distinction between them may not be as meaningful as the distinctions among more concentrated waters of these types such as occur further to the north (Domski and Beauheim, 2008).

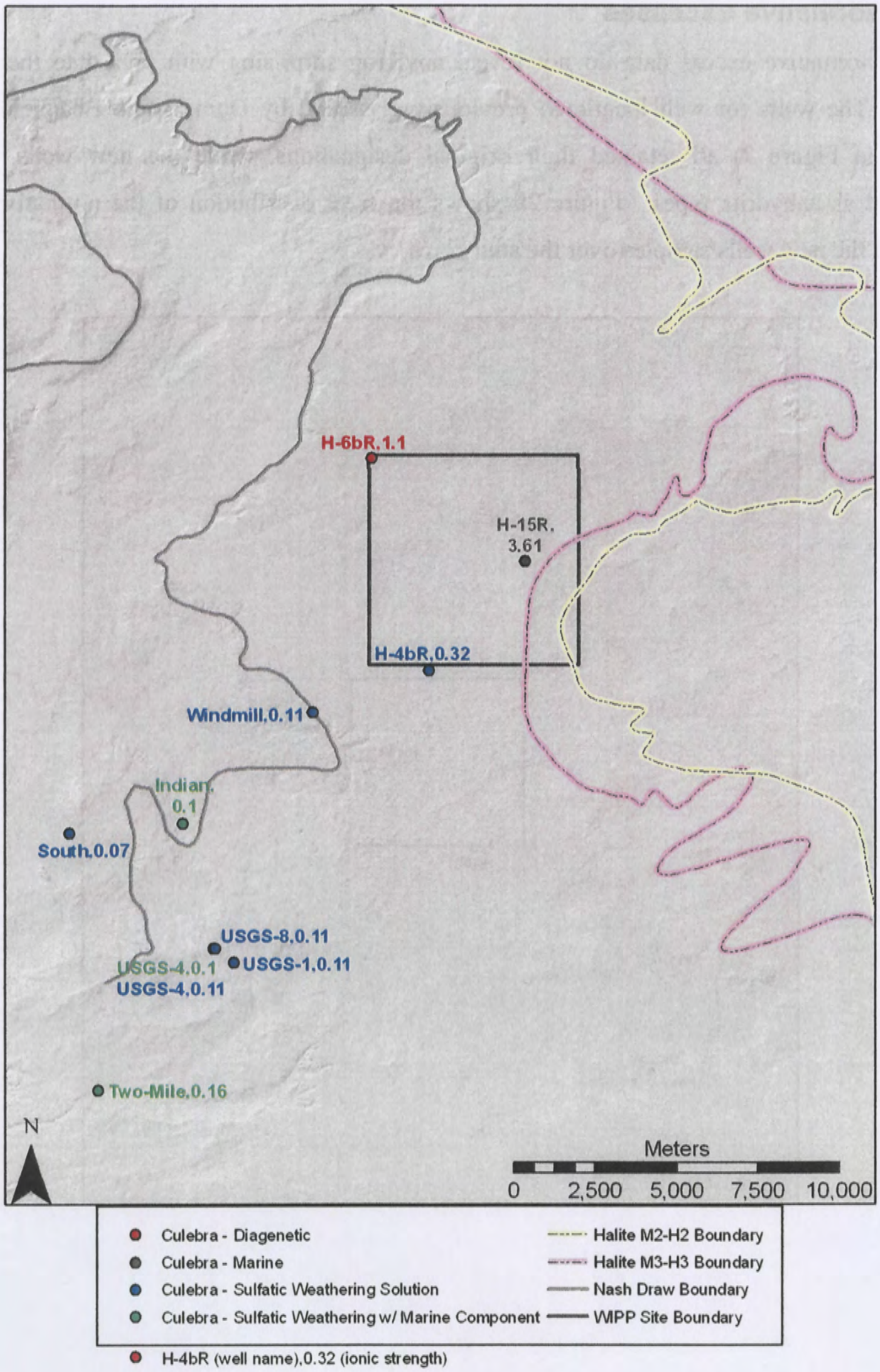


**Figure 28.** **Culebra waters color-coded on the basis of salt norm type.**

### 3.3.5 Normative Excesses

The normative excess data do not reveal anything surprising with regard to the Culebra waters. The wells (or well locations) previously classified by Domski and Beauheim (2008) (shown in Figure 7) all retained their original designations, while the new wells were all classified as anhydrite types. Figure 29 shows the areal distribution of the normative excess types for the new wells/samples over the study area

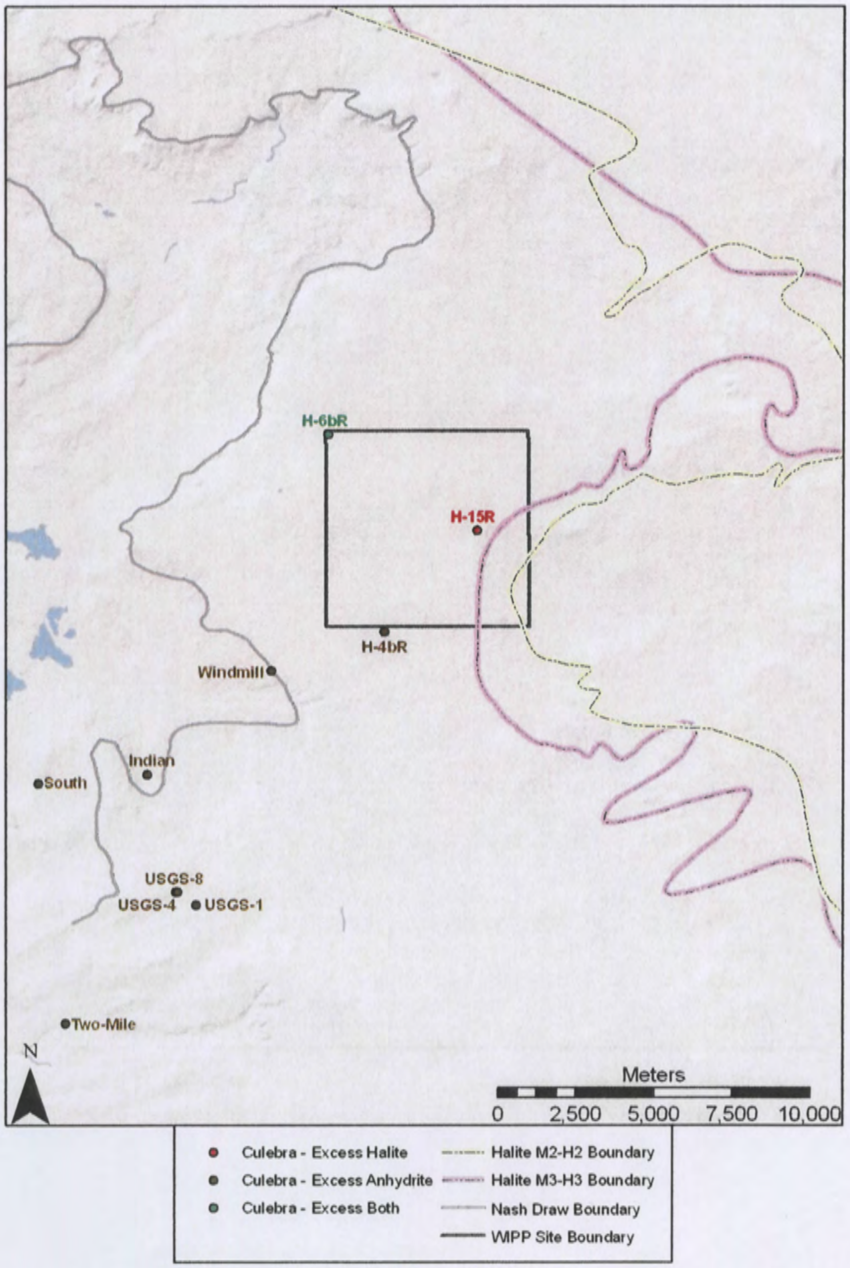


**Figure 29. Culebra waters color-coded on the basis of normative excess.**

## *3.4 Los Medaños and Rustler-Salado Contact Waters*

The only location from which only the Los Medaños, and not the combined Los Medaños-upper Salado interval, was sampled was SNL-13. All other samples discussed in this section were taken from intervals spanning the Rustler-Salado contact. The evaluation results for the Los Medaños and Rustler-Salado contact waters are summarized in Table 8, which reveals that there are two primary groups of waters represented: 1) diagenetic facies E waters; and 2) halite resolution facies G waters.

**Table 8. Classification of Los Medaños and Rustler-Salado contact waters.**

| Well | Geologic Unit | Facies | μ (molal) | SNORM type | Normative Excess |
|---|---|---|---|---|---|
| WIPP-26 | Rustler-Salado | G | 4.2 | Halite - M Comp | Halite |
| USGS-5 | Rustler-Salado | G | 4.8 | Halite - D Comp | Halite |
| P-14 | Rustler-Salado | G | 8.0 | Halite - M Comp | Halite |
| WIPP-30 | Rustler-Salado | G | 8.6 | Halite - M Comp | Halite |
| SNL-13 | Los Medaños | E | 6.7 | Diagenetic | Halite |
| H-2c | Rustler-Salado | E | 10.0 | Diagenetic | Neither |
| H-3b1 | Rustler-Salado | E | 11.0 | Diagenetic | Neither |
| H-1 | Rustler-Salado | E | 11.2 | Diagenetic | Neither |
| H-5c | Rustler-Salado | E | 14.8 | Diagenetic | Neither |

### 3.4.1 Geology and Mineralogy of the Los Medaños Member and Rustler-Salado Contact

Before 1999, the Los Medaños Member of the Rustler Formation was referred to simply as the unnamed lower member. The unit had not previously been named due to the lack of good surface exposure that would allow proper description. However, with the construction of the shafts at the WIPP site, it became possible to observe pristine sections of the lower member directly and to correlate cores and geophysical logs to the observations. Based on their characterization of the lower member of the Rustler, Powers and Holt (1999) proposed the formal name of "Los Medaños".

Powers and Holt (1999) summarized the Los Medaños geology as follows:

> The stratotype consists of 34.4 m of siliciclastics, halitic mudstones, muddy halite, and sulfates (mainly anhydrite). Bedding, invertebrate fossil remains, and bioturbation indicate a saline lagoon with connections to open marine water, in contrast to the shallow-water, desiccating evaporite cycles of the underlying Salado

> Formation. The lagoon was generally drying up, with some periods of subaerial exposure, as the Los Medaños was deposited. The uppermost claystone marks the transgression that deposited the overlying Culebra Dolomite.

Thus, during its deposition, the waters of the Los Medaños had attained concentrations where carbonates, sulfates (anhydrite and polyhalite), and halite were deposited, and had done so on several occasions as shown in the stratigraphic column (Powers and Holt, 1999). Thus, with multiple cycles of inundation and desiccation, the waters of the Los Medaños should reflect a mixture of residual brines left over from the periods of basin desiccation.

Holt and Powers (1988) provide a description of the Rustler-Salado contact as a "thin stratigraphically distinct sulfate unit immediately underlying the siliciclastics of the lower Rustler." They further describe the Rustler-Salado contact as more related to Salado deposition than Rustler, and consisting of anhydrite and sometimes polyhalite that is commonly laminated with the lower sections being argillaceous.

West of the WIPP site, erosion and dissolution of portions of the Rustler Formation led to dissolution of portions of the upper Salado Formation, forming a dissolution trough. The surface expression of the dissolution trough is known as Nash Draw, while the margin of where dissolution has occurred has formed an escarpment known as Livingston Ridge. Robinson and Lang (1938) observed that a "brine aquifer" had formed in Nash Draw in the disrupted residue at the Rustler-Salado contact. Like the Culebra and Magenta and their relationship with the mudstone-halite margins, the composition of the Los Medaños and the Rustler-Salado samples is dependent on their location relative to the Salado dissolution margin. Connate brines should exist east of the margin, while halite resolution brines should be present west of the margin.

### 3.4.2 Hydrochemical Facies

A Piper plot of the Los Medaños and Rustler-Salado contact waters symbol-coded on the basis of hydrochemical facies is shown in Figure 30. The plot shows that they range from magnesium chloride to sodium/potassium chloride waters. The diagenetic facies E magnesium-rich brines are somewhat unusual and signal their diagenetic origins, while the facies G sodium chloride brines resulted from halite dissolution

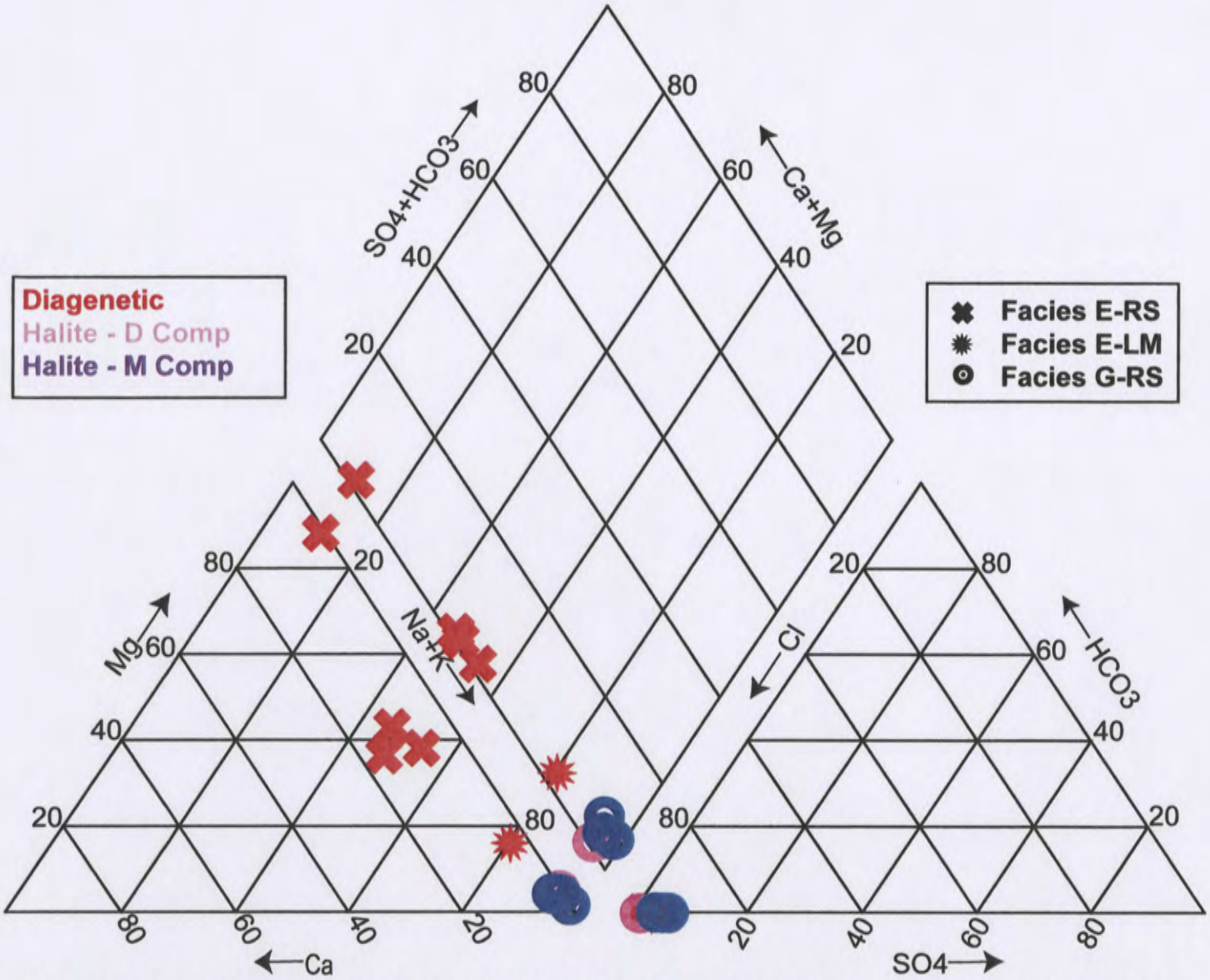


**Figure 30. Piper plot of the Los Medaños and Rustler-Salado contact waters symbol-coded to reflect their hydrochemical facies and color-coded to reflect their SNORM type.**

The areal distribution of hydrochemical facies for the Los Medaños and Rustler-Salado contact wells is displayed in Figure 31. The facies G wells all lie along the eastern margin of Nash Draw, while the facies E wells all lie further to the east. The location of the facies G wells correlates to the Salado dissolution margin and the M1-H1 margin, which explains why the waters of these wells have high alkali:alkaline cation ratios, and lower ionic strengths . The high alkali:alkaline ratio is due to the dissolution of halite, either Salado halite or halite present in the Los Medaños, by fresher water than is native to these units. Regardless of the halite source, it may be inferred that the hydraulics near these facies G wells is disturbed relative to the hydraulics near the facies E wells.

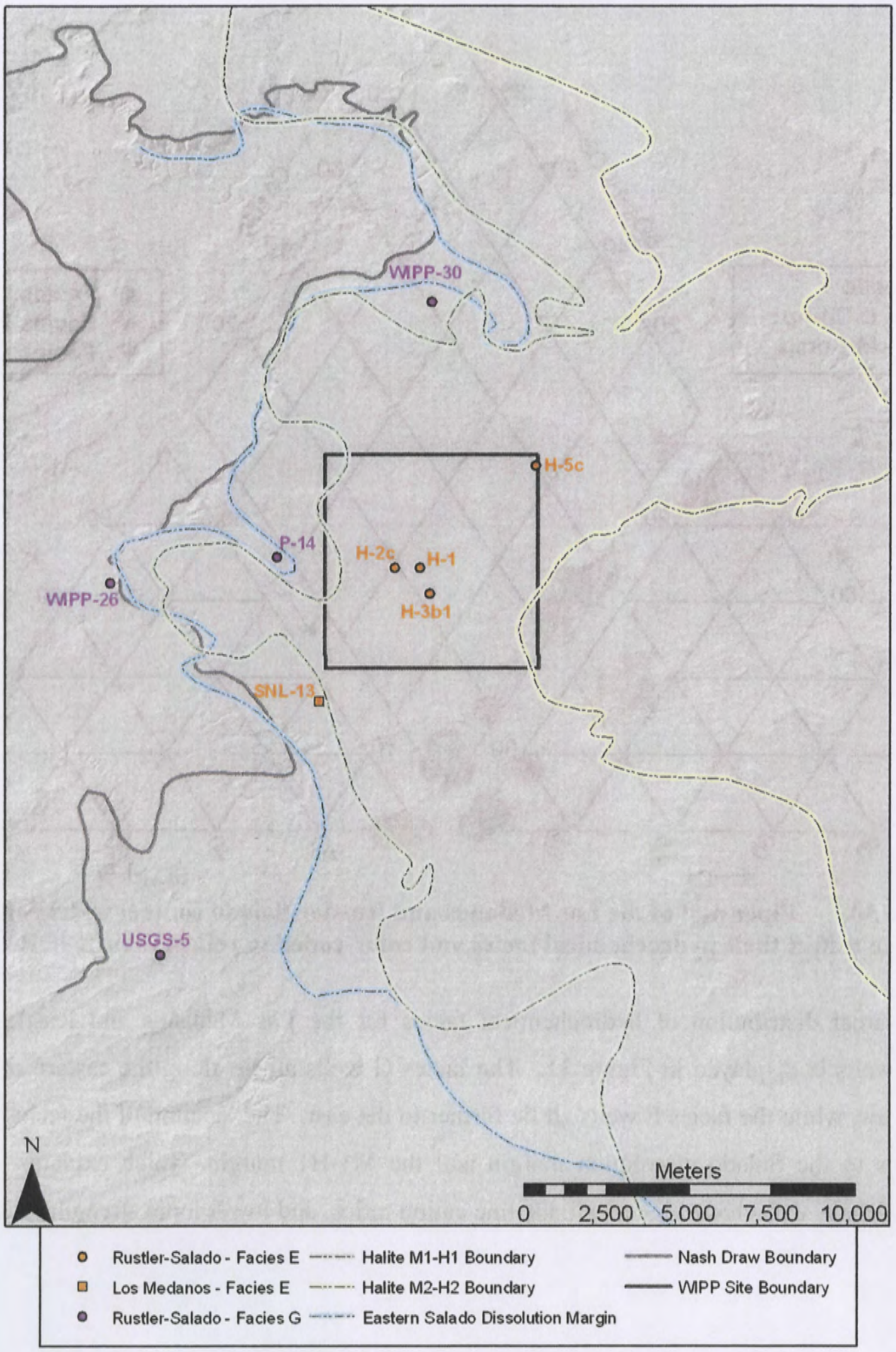


**Figure 31.** **Los Medaños and Rustler-Salado contact waters color coded on the basis of hydrochemical facies.**

The facies E wells all lie to the east of the Salado dissolution margin and the M1-H1 margin and their chemistry reflects conditions less perturbed than the facies G waters. The very high ionic strengths along with the low alkali:alkaline ratios of these waters reflects undisturbed hydraulic conditions.

### 3.4.3 Saturation Indices and Ionic Strength

Table 9 lists and Figures 32, 33, and 34 show the PHREEQCI-calculated saturation indices of calcite, carbon dioxide, gypsum, and halite for the Los Medaños and Rustler-Salado contact brines. Calcite is supersaturated in all but two of the brine samples (Figure 32), and no correlation between the calcite saturation and carbon dioxide is evident. Carbon dioxide likely degassed from the samples during sample collection, due to decreased surface pressure and compounded by the high salinity of the brines, which has the effect of increasing the apparent calcite saturation. Thus, under actual subsurface conditions, calcite and carbon dioxide saturation index values for the samples would likely be different than displayed in Figure 32.

**Table 9. Saturation indices for Los Medaños and Rustler-Salado contact waters.**

| Well | Geologic Unit | µ (molal) | Calcite SI | $CO_2$ (g) SI | Gypsum SI | Halite SI |
|---|---|---|---|---|---|---|
| WIPP-26 | Rustler-Salado | 4.2 | 1.44 | -2.70 | 0.091 | -0.65 |
| USGS-5 | Rustler-Salado | 4.8 | -0.83 | -3.21 | -1.60 | -0.40 |
| P-14 | Rustler-Salado | 8 | 1.28 | -2.44 | 0.31 | 0.36 |
| WIPP-30 | Rustler-Salado | 8.6 | 2.08 | -2.65 | 0.50 | 0.49 |
| SNL-13 | Los Medaños | 6.7 | 0.61 | -2.23 | 0.48 | -0.07 |
| H-2c | Rustler-Salado | 10 | 1.35 | -1.39 | 0.68 | 0.40 |
| H-3b1 | Rustler-Salado | 11 | 2.00 | -4.61 | 0.46 | 0.49 |
| H-1 | Rustler-Salado | 11.2 | 1.24 | -5.85 | 0.48 | 0.49 |
| H-5c | Rustler-Salado | 13.6 | -0.08 | -4.27 | 0.28 | 0.20 |

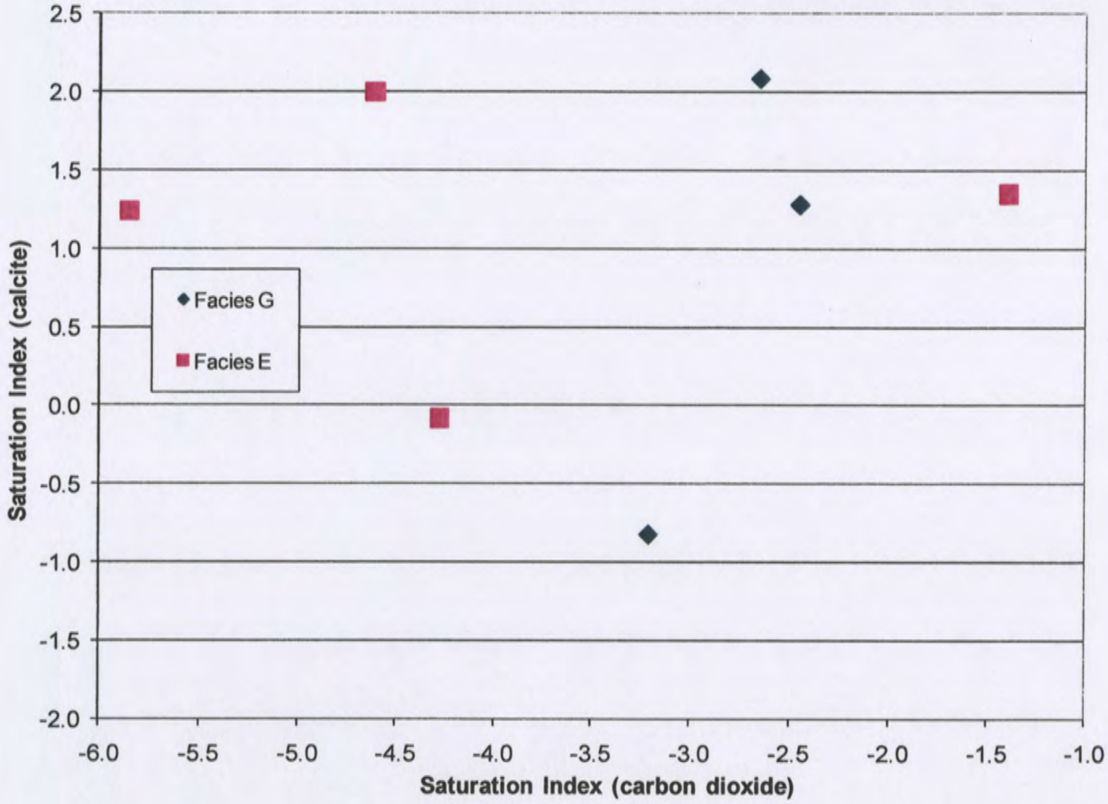


**Figure 32. Calcite versus carbon dioxide saturation indices for the Los Medaños and Rustler-Salado contact waters color-coded on the basis of hydrochemical facies.**

Figure 33 shows the saturation index for gypsum as a function of ionic strength. All of the samples with the exception of USGS-5 are supersaturated with respect to gypsum. Given the high ionic strength of the brines and the occurrence of anhydrite in both the Los Medaños and Rustler-Salado, it is not surprising that the waters are supersaturated with respect to gypsum.

The halite saturation index for each of the Los Medaños and Rustler-Salado brines is plotted in Figure 34 as a function of ionic strength, and six of the nine samples are supersaturated with respect to halite. The relationship between halite saturation and halite precipitation is highly dependent on the physical and chemical environment, so even though these brines are above halite saturation, this may be the condition required to coexist with the halite in the formation.

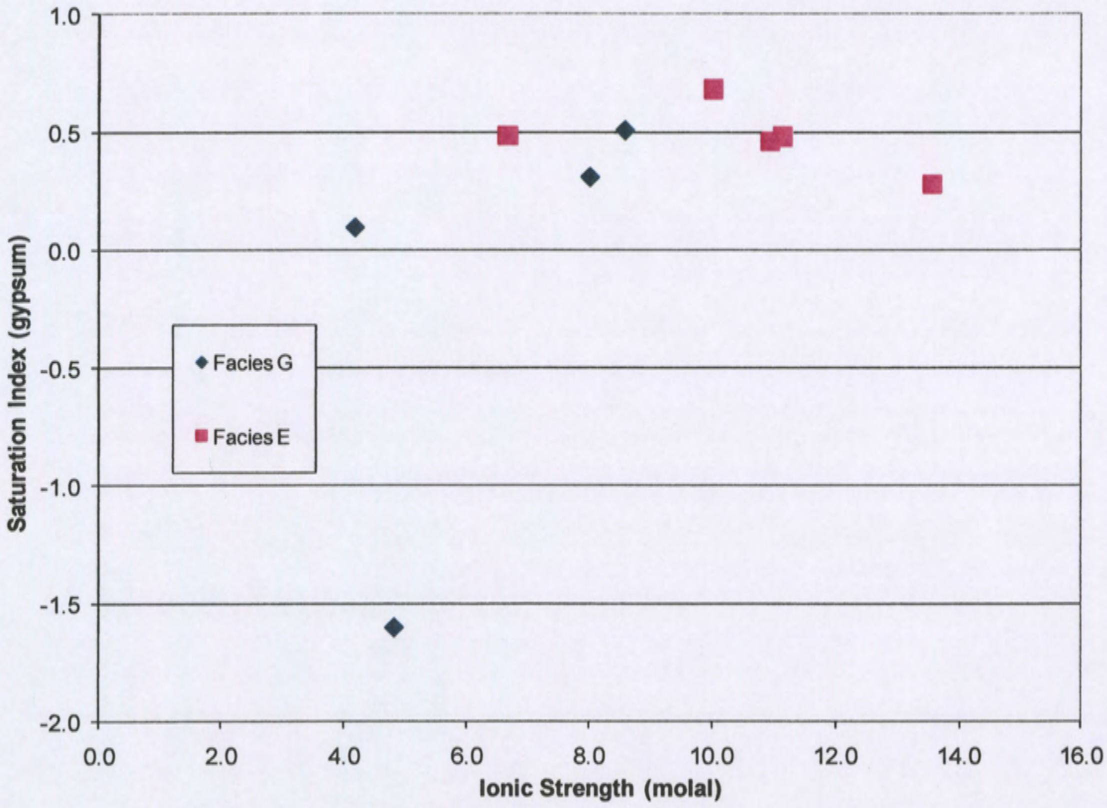


**Figure 33.** Gypsum saturation index versus ionic strength for the Los Medaños and Rustler-Salado contact waters color-coded on the basis of hydrochemical facies.

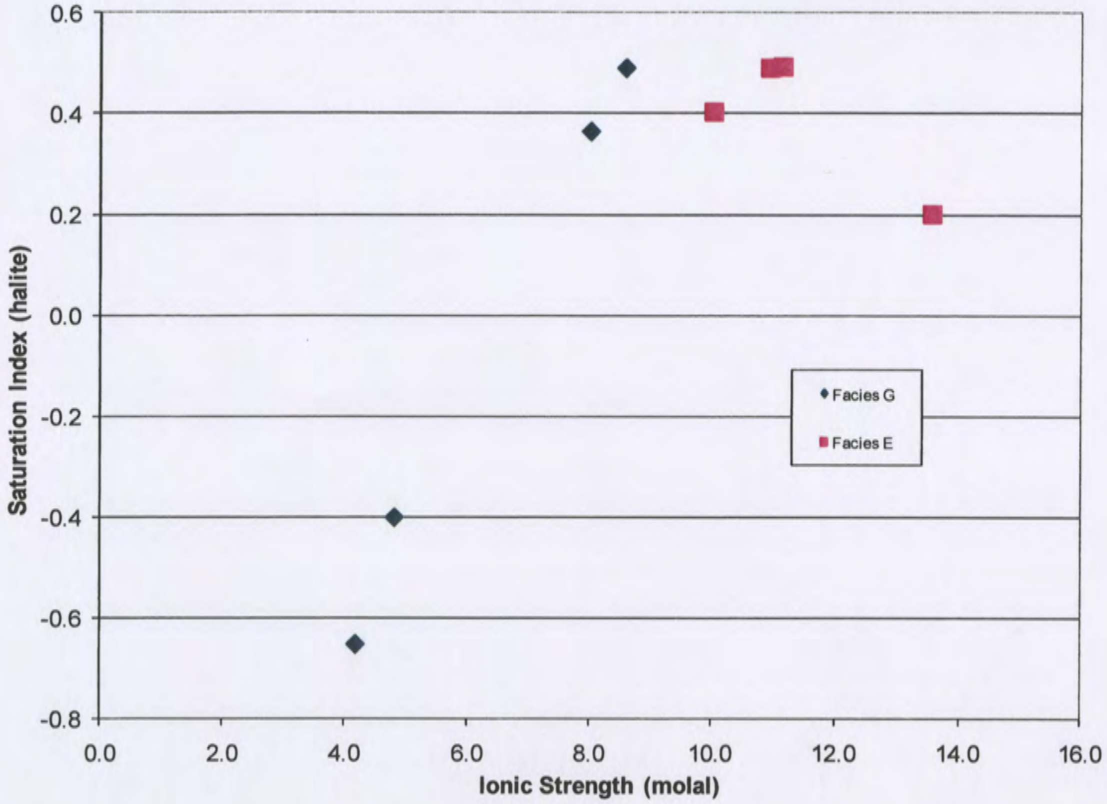


**Figure 34.** **Halite saturation index versus ionic strength for the Los Medaños and Rustler-Salado contact waters color-coded on the basis of hydrochemical facies.**

### 3.4.4 Chloride:Bromide Ratio

Bodine and Jones (1990) use the chloride to bromide weight ratio (Cl:Br) as a means of distinguishing primary sedimentary brines from those that are the product of the resolution of halite. Because bromide is more soluble than chloride, the Cl:Br ratio of evaporating seawater steadily decreases from around 300, the seawater value, to a low of approximately 50 as halite precipitates. Thus, primary brines have low Cl:Br values – less than that of seawater. Brines that are the product of halite resolution will have very high Cl:Br ratios, because bromide is not incorporated into halite crystals and only the chloride concentration rises as the halite is dissolved.

For the Los Medaños and Rustler-Salado contact waters, we have calculated the Cl:Br ratio when the data were available (Table 10). Unfortunately, we do not have bromide data for five of the nine samples. However, of the four for which there are bromide data, only the Cl:Br ratio of SNL-13 indicates that it may be a primary brine; the others are all the product of halite resolution. The wells USGS-5, WIPP-26, and WIPP-30 all have Cl:Br ratios greater than 300, which confirms them as halite resolution brines.

**Table 10. Chloride and bromide concentrations in Los Medaños and Rustler-Salado contact waters.**

| Well | Geologic Unit | Sample date | Cl (mg/L) | Br (mg/L) | Cl:Br |
|---|---|---|---|---|---|
| H-1 | Rustler-Salado | 2/23/1977 | 210000 | NA | NA |
| H-2c | Rustler-Salado | 2/23/1977 | 200000 | NA | NA |
| H-3b1 | Rustler-Salado | 2/23/1977 | 210000 | NA | NA |
| H-5c | Rustler-Salado | 5/16/1979 | 290000 | NA | NA |
| SNL-13 | Los Medaños | 4/26/2005 | 190000 | 1400 | 136 |
| USGS-5 | Rustler-Salado | 11/27/1961 | 156000 | 5.5 | 28364 |
| P-14 | Rustler-Salado | 2/24/1977 | 180000 | NA | NA |
| WIPP-26 | Rustler-Salado | 7/23/1980 | 108000 | 19 | 5684 |
| WIPP-30 | Rustler-Salado | 7/17/1980 | 192000 | 78 | 2462 |

NA: not available

From spreadsheet *Rus-Salado_final.xls*, sheet "Chloride-Bromide".

### 3.4.5 Salt Norm Types

The salt norm types for the Los Medaños and Rustler-Salado contact waters are shown on the Piper diagram in Figure 30. Figure 35 displays the detailed SNORM output for the Los Medaños and Rustler-Salado contact waters. The halite resolution waters are characterized by excess normative halite (92 to 95%) and low anhydrite (0 to 2%). The meteoric subgroup is distinguished by the presence of normative magnesite ($MgCO_3$), polyhalite ($K_2Ca_2Mg(SO_4)_4{\bullet}2H_2O$), bloedite ($Na_2Mg(SO_4)_2{\bullet}H_2O$), and kierserite ($MgSO_4{\bullet}H_2O$), phases which are present in the sulfatic weathering solution salt norm type, while the diagenetic subgroup of the halite resolution salt norm type contains tachyhydrite ($Mg_2CaCl_6{\bullet}12\ H_2O$), carnallite ($KMgCl_3{\bullet}6H_2O$), and bischofite ($MgCl_2{\bullet}6H_2O$), phases typical of diagenesis.

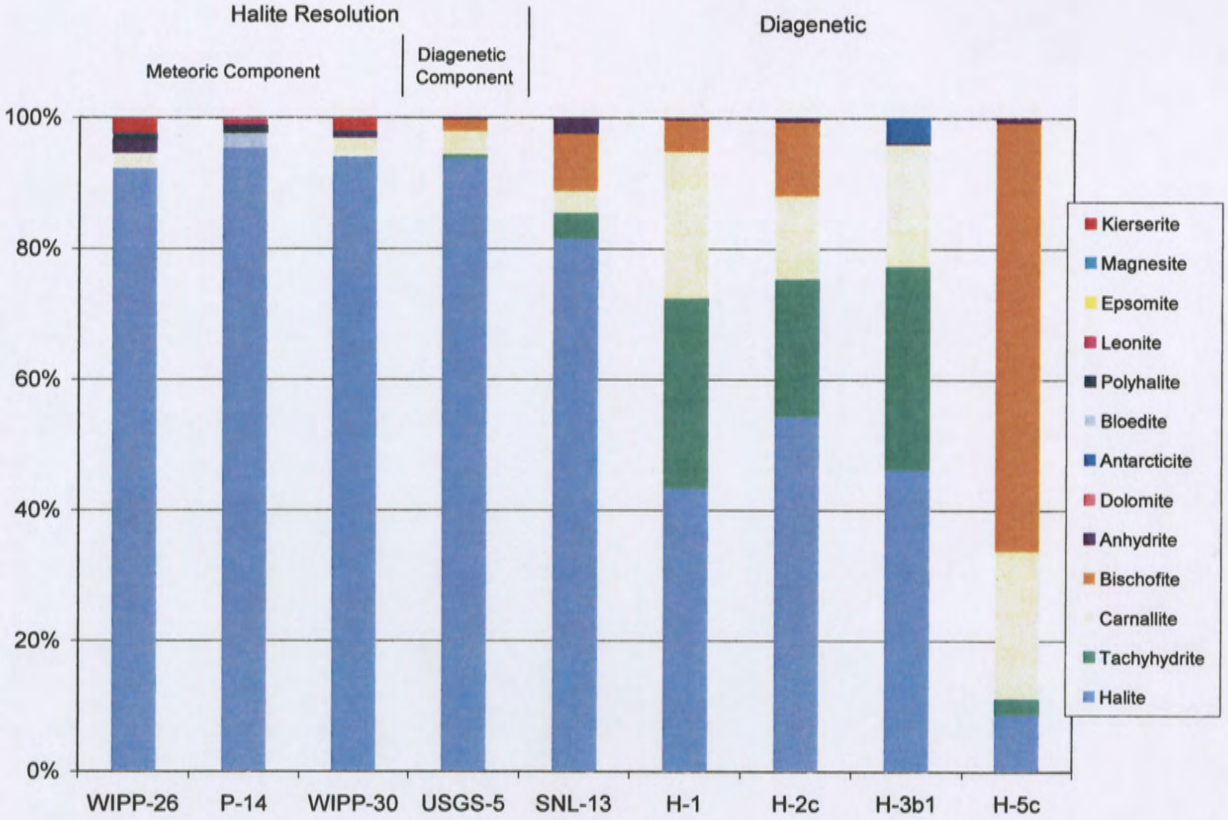


**Figure 35. Los Medaños and Rustler-Salado contact salt norms.**

The diagenetic wells have normative halite ranging from 9 to 81%, with four of the five wells at 9 to 54% and SNL-13 at 81% normative halite. The high normative halite of the Los Medaños sample from SNL-13 reflects its location close to the M1-H1 margin (Figure 36) where halite resolution brine from west of the margin is mixing with diagenetic brine from east of the margin. Anhydrite is below the excess level, and ranges from 0.2 to 2.4% for all of the wells. The diagenetic suite of minerals are present in significant fractions of each norm, with tachyhydrite

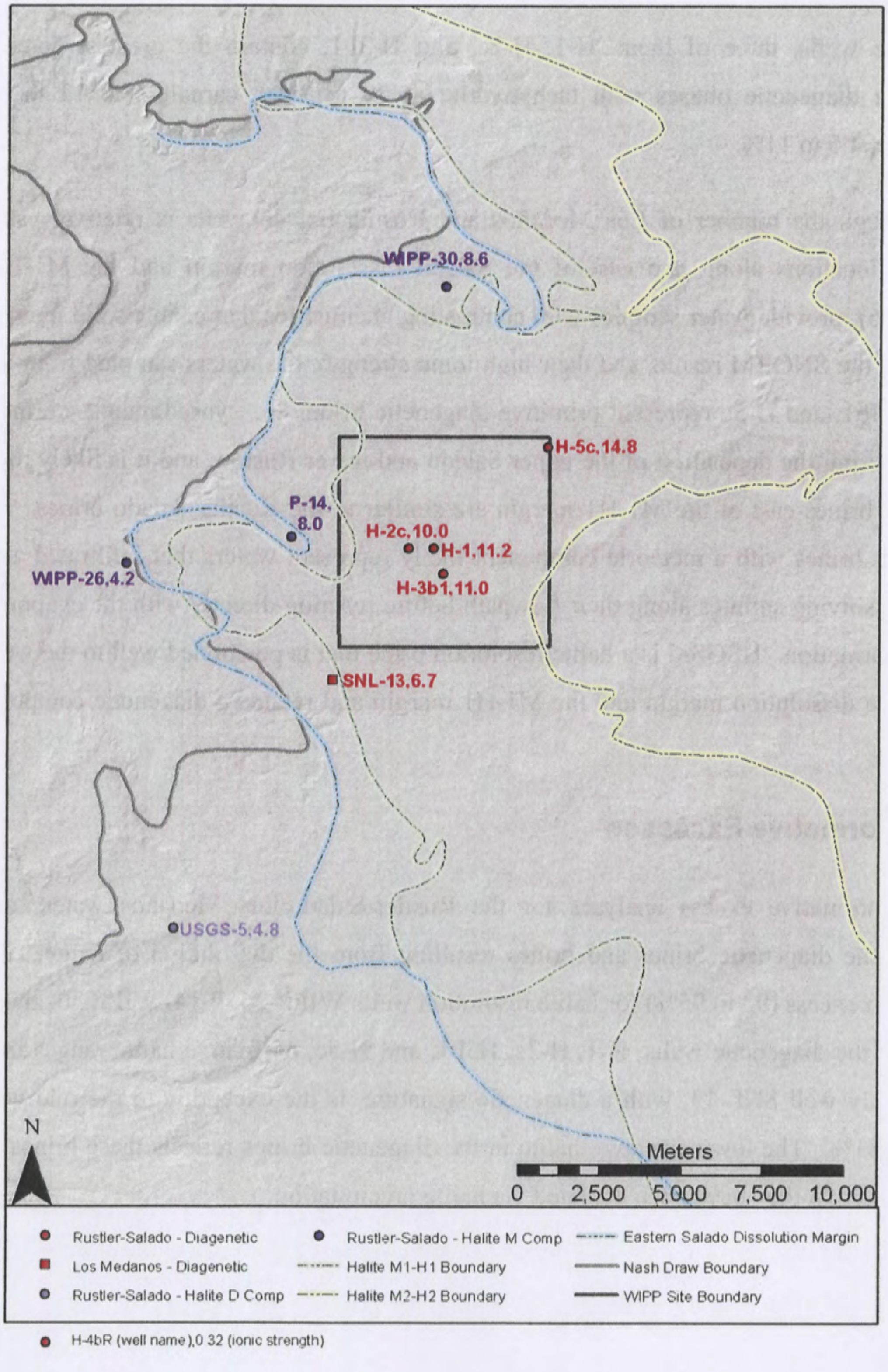


Figure 36. Los Medaños and Rustler-Salado contact waters color-coded on the basis of salt norm type.

(4 to 31%), carnallite (3 to 22%), bischofite (0 to 65%), and antarcticite (0 to 4%). Of the five diagenetic wells, three of them, H-1, H-2c, and H-3b1, contain the greatest percentages of normative diagenetic phases with tachyhydrite at 29 to 31%, carnallite at 13 to 22%, and bischofite at 5 to 11%.

Although the number of Los Medaños and Rustler-Salado wells is relatively small, their strategic locations along and east of the Salado dissolution margin and the M1-H1 margin (Figure 36), provide water samples with contrasting chemistries that enable solid interpretations. Based on the SNORM results and their high ionic strength, the waters sampled from wells H-1, H-2c, H-3b1, and H-5c represent primitive diagenetic brine, i.e., synsedimentary brine that was present during the deposition of the upper Salado and lower Rustler, and it is likely that the Los Medaños brines east of the M1-H1 margin are similar to the Rustler-Salado brines. The halite resolution brines with a meteoric component likely represent waters that infiltrated along Nash Draw, dissolving sulfates along their flowpath before reacting directly with the evaporites of the Salado Formation. USGS-5 is a halite resolution brine that is positioned well to the west of both the Salado dissolution margin and the M1-H1 margin and retains a diagenetic component to its salt norm.

### 3.4.6 Normative Excesses

The normative excess analyses for the Rustler-Salado/Los Medaños waters distinguish between the diagenetic brines and brines resulting from the dissolution of halite. Normative halite is in excess (92 to 95%) for halite resolution wells WIPP-26, P-14, WIPP-30, and USGS-5, while for the diagenetic wells, H-1, H-2c, H3b1, and H-5c, normative halite ranges from 9% to 54%. Only well SNL-13, with a diagenetic signature, is the exception to the rule with excess halite at 81%. The low normative halite in the diagenetic brines reflects these brines' primitive nature, and that they have been depleted via halite precipitation.

None of the Rustler-Salado/Los Medaños brines contain excess normative anhydrite, but the reasons for the lack of excess anhydrite differ depending on salt norm type. In the case of the halite resolution brines, the lack of excess normative anhydrite is a reflection of halite dissolution overwhelming the norms, while for the diagenetic brines, the minimal normative anhydrite is a reflection of the highly evolved and primitive nature of the brine where gypsum/anhydrite had precipitated from the original solution long ago. Here is an instance where two brines share a common characteristic, but one that was caused by different evolutionary paths.

Figure 37 shows the spatial distribution of the Los Medaños and Rustler-Salado contact brines color coded by normative excess. It is clear from the map that the position of the well relative to the M1-H1 margin and Salado dissolution front plays an important role in the mode of occurrence of wells with excess halite versus those with no excess halite. The well SNL-13 is an excellent example of a well that contains excess halite (81%) and yet retains a strong diagenetic salt norm signature. Examination of the location of SNL-13 on Figure 37 shows that it is located just slightly to the west of the M1-H1 mudstone/halite margin; therefore, its chemistry is being influenced by both the diagenetic brines from east of the margin and the halite resolution brines to the west of the margin. The low Cl:Br ratio of the SNL-13 brine may be the product of the relative fractions of resolution to diagenetic brine in the mixture, where diagenetic brine is dominant.

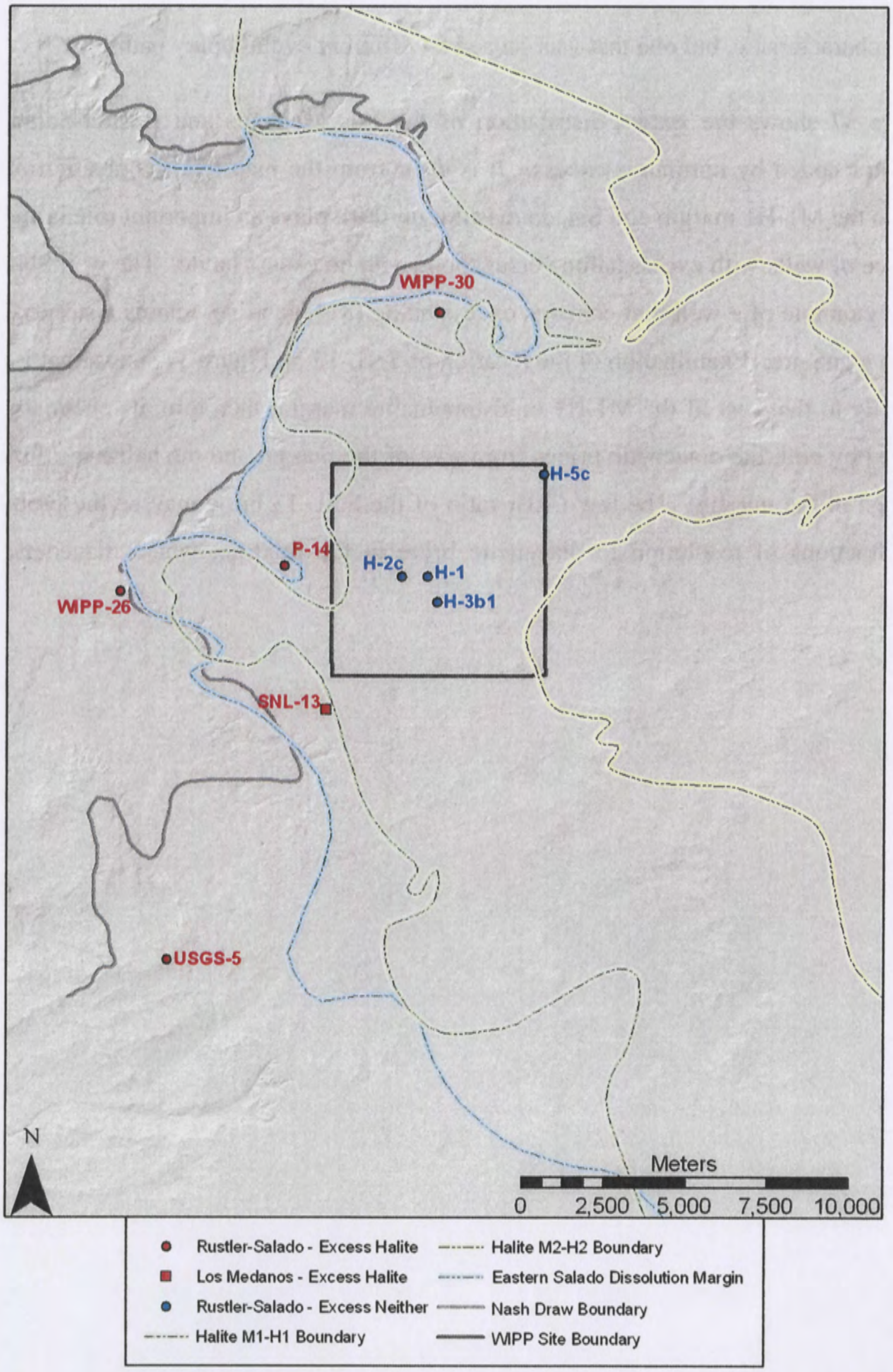


**Figure 37.** Los Medaños and Rustler-Salado contact waters color-coded on the basis of normative excess.

# 4. Relationships Among the Waters in the Formations Above the Salado at the WIPP Site

Study of the chemistry of the waters in the formations above the Salado Formation has shown that waters vary from shallow, dilute, carbonate recharge waters to halite-saturated sodium chloride brines. The evolution of these waters through the thick geologic section does not follow a linear pattern of progressive chemical change down a hydraulic gradient, but rather the chemistry results from a complex series of chemical interactions and complex hydraulic flow patterns that include both horizontal and vertical components.

Comparison of Figure 38 with Figure 8, the Piper plot of the Culebra data from Domski and Beauheim, (2008), shows the increased compositional variability in the current data set. Specifically, the Culebra anion data (Figure 8) all fall along the chloride-sulfate axis and the cation data form a series of compositions from nearly 100% sodium to 70% calcium, 30% magnesium. The current data set also shares both of these trends but has two additional trends, an anion trend of sulfate to carbonate, and a cation trend of sodium to magnesium. The carbonate anion trend reflects dilute meteoric waters of the Santa Rosa and Dewey Lake, while the sodium-magnesium trend reflects the diagenetic brines of the Los Medaños/Rustler-Salado. The current data set represents both less evolved and more evolved waters than the data set presented in Domski and Beauheim (2008).

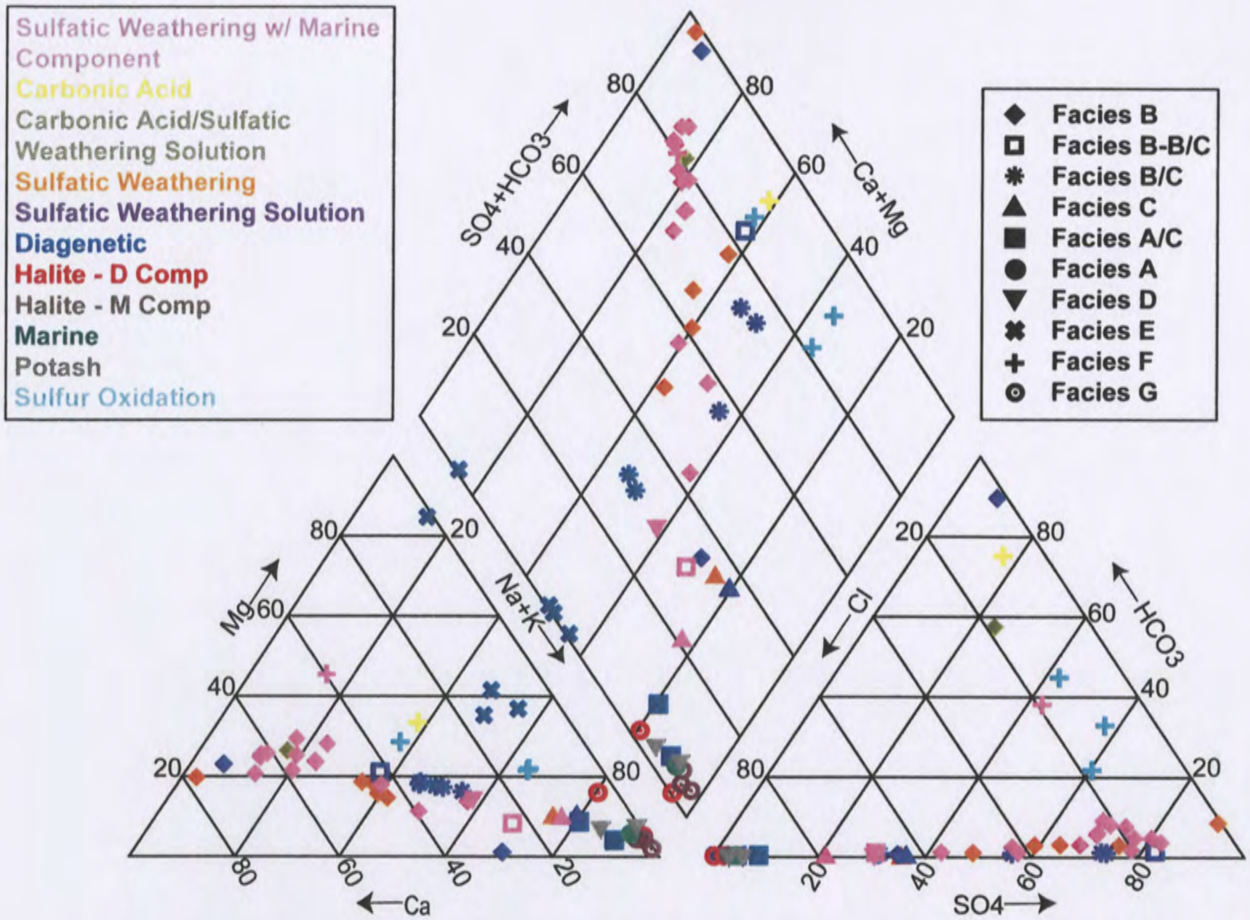


Figure 38. Piper plot of the all the waters in the formations above the Salado.

## 4.1 Vertical and Horizontal Variations in Concentration

Whether in an evaporating salt pan or a deep sedimentary basin, the concentration of a water sample is a direct measure of the degree of interaction that the water has had with the geologic environment. Likewise, groundwater concentration trends may provide qualitative information on flow directions. However, in complex geologic settings, such as the Culebra in the vicinity of the WIPP site, it may not always be possible to discern flow direction based on concentration trends because of low-conductivity, high-pressure regions containing high-salinity brines, i.e., the region east of the M2-H2 margin (Domski and Beauheim, 2008). This area functions as a source of solutes to the Culebra west of the margin; as such, the waters in this region do not obey the concept of increasing concentration as a function of distance along a flow path.

Figure 39 is a plot of ionic strength versus the east-west map position of the sampled well where the symbols are color coded by geology. Notice that the ordinate (y) axis is reversed such that ionic strength increases downward; the reason for doing so is to schematically represent the stratigraphy of the geologic section.

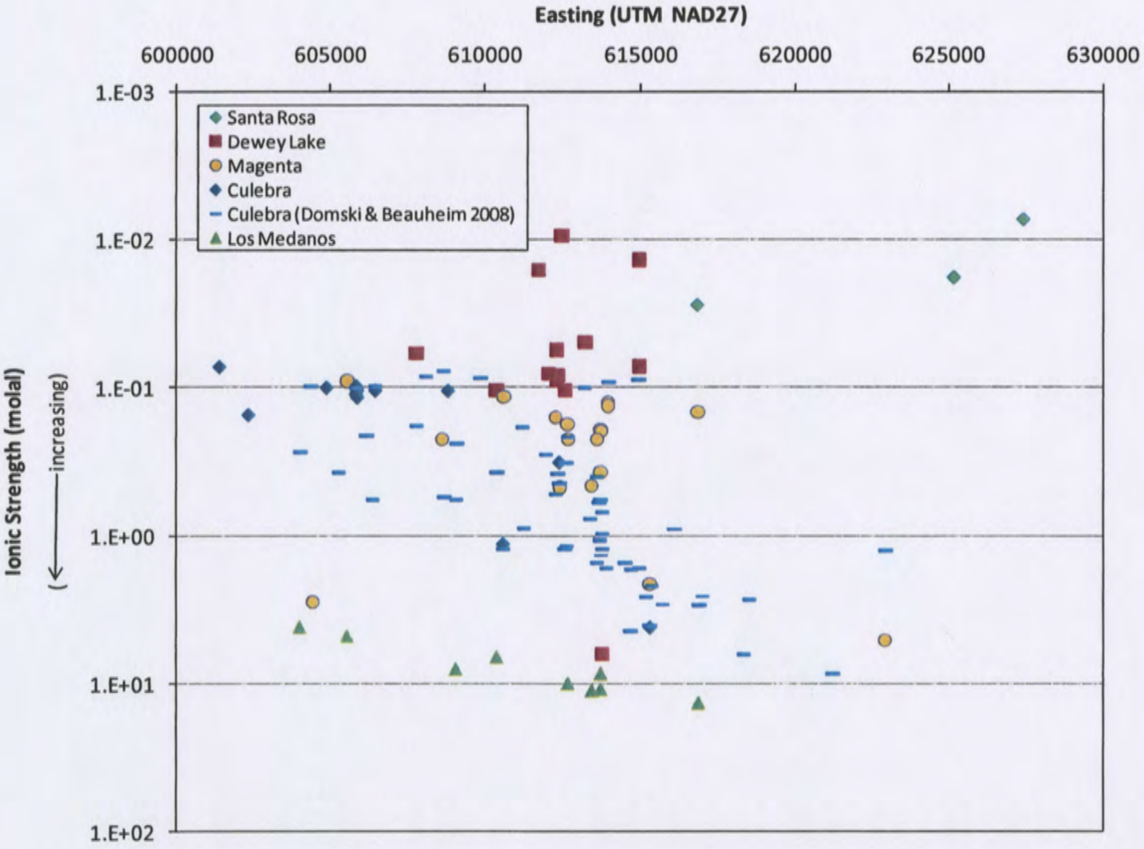


**Figure 39.** **Ionic strength versus easting coordinate for all the wells in the formations above the Salado.**

This figure provides some interesting points for discussion. The first and most striking feature is the range of ionic strength, which goes from less than 0.01 to greater than 10 molal, an increase of more than 3 orders of magnitude from the dilute waters of the Santa Rosa to the concentrated brines of the Rustler-Salado. This observation alone illustrates that the water chemistry undergoes radical changes over relatively short vertical distances, approximately 300 meters from the surface to the top of the Salado Formation. This increase in concentration is due largely to increases in sodium and chloride. Figure 40 is a bar chart of the average compositions for each of the geologic units showing the equivalent percentages of the major ions.

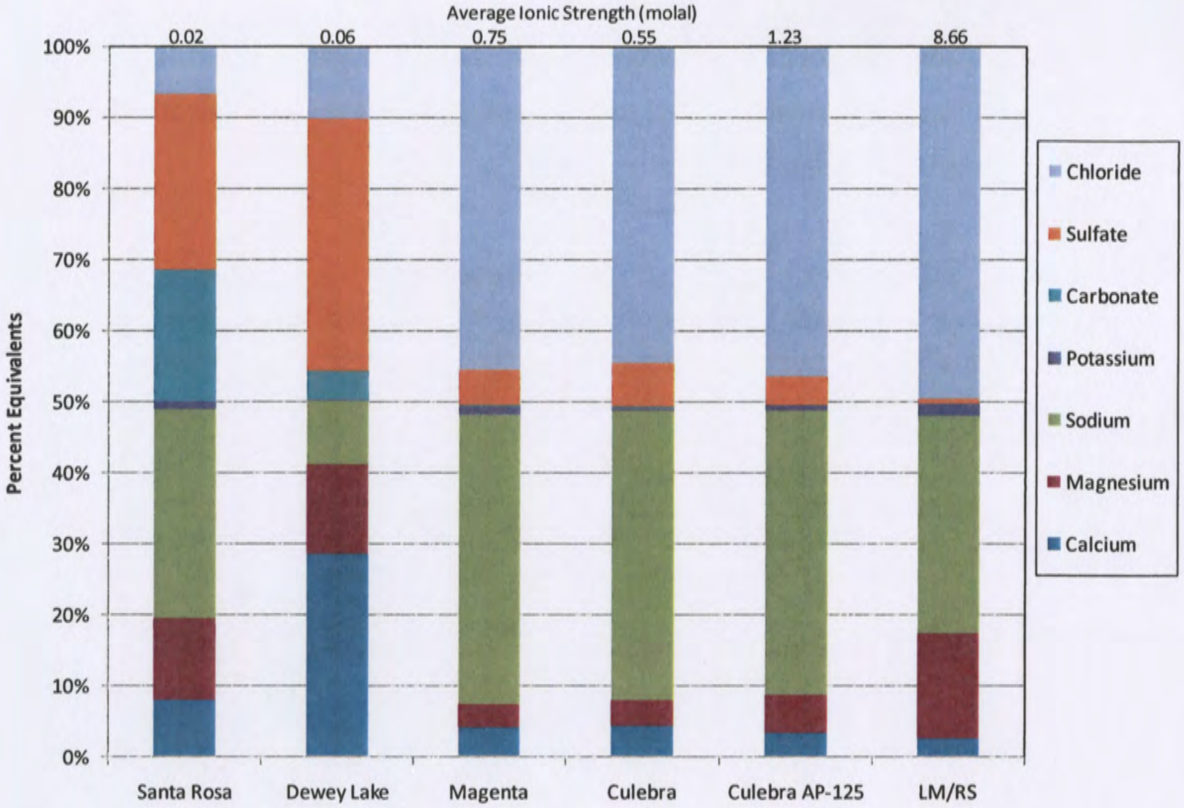


**Figure 40. Average water composition with average ionic strength values for the geologic units above the Salado.**

The average compositions plotted in Figure 40 and average ionic strength were calculated in Excel; the analyses for Dewey Lake SNL-1 and Magenta WIPP-27 were not used in the calculation of the average composition because they were contaminated with potash refinery water rather than representing naturally occurring waters. Figure 40 shows that the Santa Rosa water is sodium-carbonate-sulfate dominant, the Dewey Lake is calcium-sulfate dominant, and the Magenta, Culebra, and Los Medaños/Rustler-Salado waters are sodium-chloride dominant. The average compositions for the Magenta and Culebra are nearly identical, as shown in Figure 40. The Culebra analyses from AP-125 (Domski and Beauheim, 2008) have a much higher average ionic strength because they cover a much broader range of compositions.

The second interesting aspect of Figure 39 is the manner in which the concentration changes from west to east. For the waters of the Magenta, Culebra, and Rustler-Salado/Los Medaños, concentration tends to increase from west to east. This trend of increasing concentration has been previously correlated to proximity to the mudstone-halite margins both in the current report and in Domski and Beauheim (2008). The meandering north-to-south trends of the mudstone-halite margins account for variations and the imperfect nature of the increasing concentration trends.

The third interesting aspect of Figure 39 is the lack of increasing concentration trends for the wells of the Santa Rosa and Dewey Lake Formations. The reason for the absence of a trend in the data is that these formations may be receiving surface recharge that is reaching them uniformly over the study area. The flowpaths to the water table are short and do not allow for significant water-rock interaction, with the exception of calcite which is at saturation; the clastic phases are relatively insoluble.

The concentration trends observed in the formations below the Dewey Lake do not necessarily suggest that the direction of flow in each of these formations is west to east. It has been well established that east of the halite-mudstone margins, the transmissivity of the respective geologic units tends to decrease, and that flow in the Culebra tends to be oriented north to south. Figure 41 is the north-south counterpart to Figure 39, and shows no observable concentration trends in the north to south direction, which is contrary to a model of increasing ionic strength along flow lines.

From the perspective of the geologic/geomorphic environment, the chemistry of the waters in the formations above the Salado are easily explained. The Santa Rosa and upper Dewey Lake receive vertical recharge in a water table aquifer where the chemistry reflects weathering of siliciclastic grains via carbonic and weak sulfuric acid reactions. The lower Dewey Lake may be partially isolated from the upper Dewey Lake by confining interbeds, and the lower Dewey Lake water chemistry reflects dissolution of gypsum, which is commonly present. The source of water in the lower Dewey Lake is likely to be a combination of water leaking from the upper Dewey Lake and direct recharge along Nash Draw.

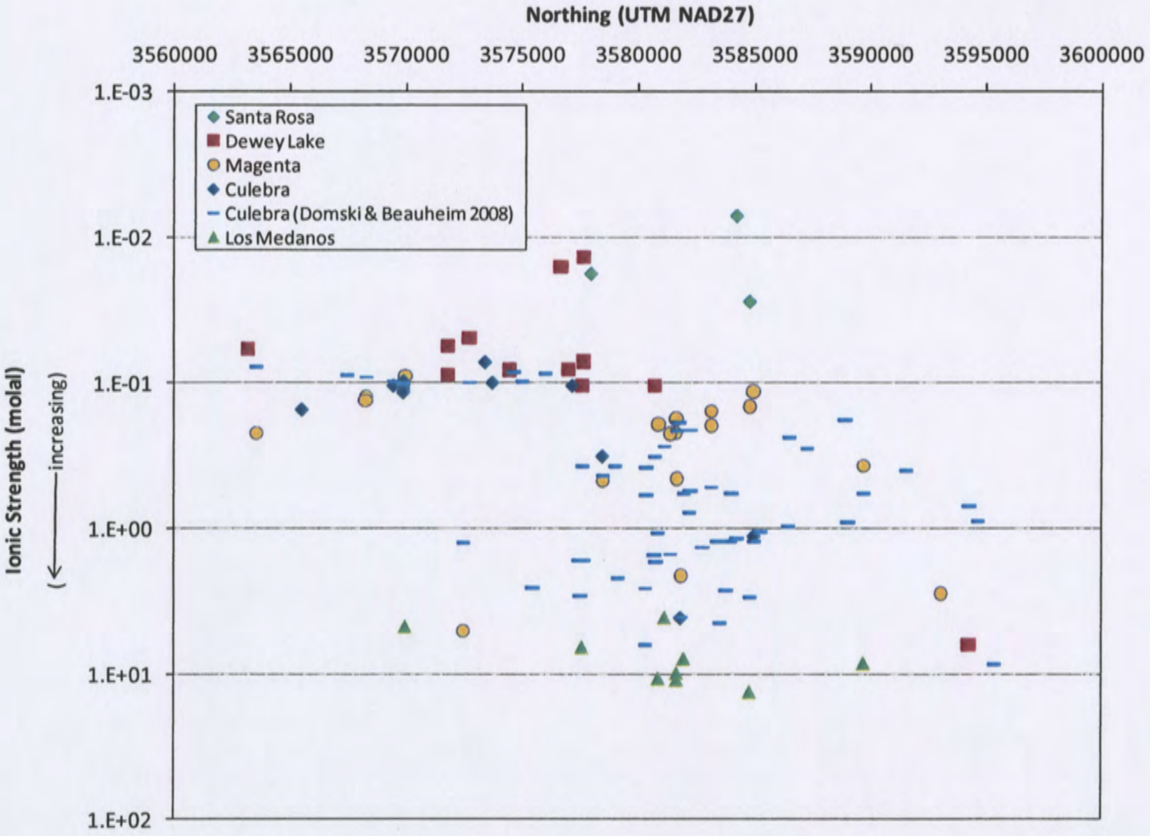


**Figure 41.** Ionic strength versus northing coordinate for all the wells in the formations above the Salado.

The Magenta and Culebra waters withdrawn along eastern Nash Draw share the common characteristics of being fresher and predominantly sulfate waters. The Culebra waters along the eastern margin of Nash Draw show higher variability of water types, but they all share the common characteristic of low ionic strength (Domski and Beauheim, 2008). Even the Rustler-Salado brines from Nash Draw show evidence of meteoric-derived solutes.

The increasing west-to-east concentration trends are caused by the combination of geomorphic, geologic, and hydrologic features of the system. Nash Draw on the west is the major geomorphic feature of the system, the mudstone-halite margins on the east represent the major geologic feature, and the transmissivity distribution and the direction of groundwater flow are the important hydrologic features.

Nash Draw is the major geomorphic feature in the study area that extends from the surface down to the Salado Formation, and has well-documented focal points for surface recharge (Powers, 2006). The Salado and all overlying formations are disturbed in Nash Draw and, as such, Nash Draw functions as a high-transmissivity hydraulic pathway where these formations are in a higher degree of hydraulic contact than in undisturbed areas.

Moving east from Nash Draw, the Salado and the units above the Salado are intact and dip off to the east where they are hydraulically confined. Holt et al. (2005) showed that as the Culebra dips and gets progressively deeper, i.e., as the overburden thickness increases, the transmissivity of the Culebra decreases. Given that the Magenta and the other formations are subject to the same down-dip increase in overburden as the Culebra, it may be speculated that their transmissivity may also decrease as a function of burial depth. At some distance from Nash Draw, the margins from mudstone to halite are crossed. It has been shown that east of the margins, the geology changes as halite occurs as pore- and fracture-filling cements in the Magenta, Culebra, and Los Medaños (Powers et al., 2006), the water chemistry (Domski and Beauheim, 2008, and this report) reflects synsedimentary connate brines, and the hydraulic properties of the formations change significantly. In the case of the Culebra, east of the M2-H2 margin, the transmissivity is very low (Bowman and Roberts, 2008), the pore pressures are very high, and the chemistry of the brines is that of primitive connate waters. Thus, east of the margin, the Culebra is isolated both hydraulically and chemically from the Culebra west of the margin. Domski and Beauheim (2008) demonstrated that along the M2-H2 margin, there is a zone where brine diffuses to the west, and the water chemistry on the west side of the margin reflects a mixture of waters from both sides of the margin. Thus, the down-dip transmissivity decrease acts to slow the transmission of water, solutes, and pressure, with the formation east of the mudstone-halite margin acting as the reservoir for these three elements.

The formations that are associated with mudstone-halite margins – the Rustler-Salado/Los Medaños, the Culebra, and the Magenta – all contain waters that have been influenced by the margins and by the waters existing east of the margins. The waters originating east of the mudstone-halite margins for the Rustler-Salado and Culebra are synsedimentary connate waters with a diagenetic salt norm signature and high ionic strength (Domski and Beauheim, 2008, and this report). While there are no Magenta samples available from east of the margins, the chemistry of wells close to the margins suggests that primitive connate waters exist in the Magenta east of the margins.

For the Magenta and Culebra, the region that lies between the mudstone-halite margins to the east, and Nash Draw on the west, is an area where the dilute waters entering from the west react and dissolve phases along their flowpath, and the concentrated brines from east of the mudstone-halite margins mix with the waters west of the margins; this is also the area where the WIPP site is located. The compositions of the waters from this region reflect these boundary conditions, where the compositions at the boundaries are end-member compositions, and compositions at intermediate locations can be explained via dissolution/precipitation reactions and mixing. Siegel et al. (1991b) and Domski and Beauheim (2008) demonstrated that a range of Culebra water compositions could be simulated with a partial-equilibrium model where halite dissolved irreversibly while maintaining gypsum and calcite or dolomite equilibrium, and trace amounts of polyhalite, carnallite, and/or leonite were added to the solution. Furthermore, Domski and Beauheim (2008) demonstrated that large-scale mixing of three end-member water types, sulfatic weathering solution, dilute diagenetic, and primitive diagenetic, could account for all of the other observed salt norm types observed in the Culebra.

## *4.2 Facies B Waters in the Dewey Lake, Magenta, and Culebra*

The Dewey Lake Formation and the Magenta and Culebra Members of the Rustler Formation all contain waters classified as facies B. The facies B waters are all relatively dilute (ionic strength ranges from 0.01 to 0.20 molal), show a normative excess of anhydrite, include a component of sulfatic weathering in their SNORM type, and are, for the most part, saturated with respect to gypsum, calcite, and dolomite. Thus, they represent waters that have not traveled a great distance from their recharge point, are young relative to the synsedimentary connate brines of some of the other facies, and have primarily interacted with calcite and sulfate-bearing minerals (gypsum and anhydrite) in the subsurface. Table 11 provides a summary of the facies B wells' classifications and chemistry.

Precipitation can infiltrate the Dewey Lake where it is exposed along the Livingston Ridge escarpment or by vertical seepage through surficial deposits where the Santa Rosa is absent. Water in the Dewey Lake may then migrate either down the stratigraphic dip to the east, or down the dip of the cement change discussed in Section 3.1.1, the orientation of which is not well defined. The facies B waters in the Dewey Lake, therefore, probably represent waters that have

**Table 11. Facies B wells of the Dewey Lake, Magenta, and Culebra.**

| Geology | Well | SNORM Excess | SNORM Type | μ (molal) | Calcite SI | Dolomite SI | Gypsum SI |
|---|---|---|---|---|---|---|---|
| Dewey Lake | Twin-Pasture | Anhydrite | Carbonic Acid - Sulfatic Weathering | 0.01 | 0.40 | 0.17 | -1.83 |
| Dewey Lake | Poker Trap | Anhydrite | Sulfatic Weathering | 0.06 | -0.14 | -0.47 | -0.16 |
| Dewey Lake | SNL-12 | Anhydrite | Sulfatic Weathering w/Marine component | 0.05 | -0.21 | -0.38 | -0.41 |
| Dewey Lake | Pocket | Anhydrite | Sulfatic Weathering w/Marine component | 0.06 | 0.58 | 1.09 | -0.28 |
| Dewey Lake | SNL-14 (93 m) | Anhydrite | Sulfatic Weathering w/Marine component | 0.07 | 0.57 | 1.20 | -0.24 |
| Dewey Lake | Ranch | Anhydrite | Sulfatic Weathering w/Marine component | 0.08 | 0.42 | 0.79 | -0.13 |
| Dewey Lake | Unger | Anhydrite | Sulfatic Weathering w/Marine component | 0.08 | -0.07 | -0.22 | -0.05 |
| Dewey Lake | Walker | Anhydrite | Sulfatic Weathering w/Marine component | 0.09 | 0.10 | 0.10 | -0.02 |
| Dewey Lake | WQSP-6A | Anhydrite | Sulfatic Weathering w/Marine component | 0.10 | 0.35 | 0.64 | 0.00 |
| Dewey Lake | SNL-13 | Anhydrite | Sulfatic Weathering w/Marine component | 0.11 | 0.63 | 1.13 | 0.06 |
| Magenta | H-8a | Anhydrite | Sulfatic Weathering | 0.22 | 0.19 | 0.25 | 0.03 |
| Magenta | USGS-5 | Anhydrite | Sulfatic Weathering w/Marine component | 0.09 | 0.49 | 0.79 | 0.03 |
| Culebra | South | Anhydrite | Sulfatic Weathering | 0.07 | 0.55 | 0.81 | -0.01 |
| Culebra | USGS-8 | Anhydrite | Sulfatic Weathering | 0.11 | 0.08 | -0.08 | -0.09 |
| Culebra | USGS-1 | Anhydrite | Sulfatic Weathering | 0.11 | 0.47 | 0.84 | -0.03 |
| Culebra | Windmill | Anhydrite | Sulfatic Weathering | 0.11 | -0.79 | 1.50 | -0.01 |
| Culebra | USGS-4 | Anhydrite | Sulfatic Weathering | 0.11 | 0.38 | 0.61 | -0.02 |
| Culebra | USGS-4 | Anhydrite | Sulfatic Weathering w/Marine component | 0.10 | -1.28 | -2.75 | -0.15 |
| Culebra | Indian | Anhydrite | Sulfatic Weathering w/Marine component | 0.10 | 0.72 | 1.40 | -0.01 |
| Culebra | USGS-8 | Anhydrite | Sulfatic Weathering w/Marine component | 0.12 | -0.09 | -0.26 | -0.03 |
| Culebra | Two-Mile | Anhydrite | Sulfatic Weathering w/Marine component | 0.16 | -0.81 | -1.65 | -0.07 |
| Culebra AP-125 | Poker Trap | Anhydrite | Sulfatic Weathering | 0.06 | -0.16 | -0.50 | -0.16 |
| Culebra AP-125 | H-8b | Anhydrite | Sulfatic Weathering | 0.08 | 0.67 | 1.36 | -0.06 |
| Culebra AP-125 | Engle | Anhydrite | Sulfatic Weathering | 0.09 | 0.25 | 0.44 | -0.02 |
| Culebra AP-125 | H-9b | Anhydrite | Sulfatic Weathering | 0.09 | -0.02 | -0.16 | 0.04 |
| Culebra AP-125 | USGS-1 | Anhydrite | Sulfatic Weathering | 0.10 | 0.15 | 0.14 | -0.03 |
| Culebra AP-125 | H-7b1 | Anhydrite | Sulfatic Weathering w/Marine component | 0.09 | 0.33 | 0.57 | -0.05 |
| Culebra AP-125 | SNL-17A | Anhydrite | Sulfatic Weathering w/Marine component | 0.09 | 0.37 | 0.66 | -0.01 |
| Culebra AP-125 | Mobley | Anhydrite | Sulfatic Weathering w/Marine component | 0.10 | 0.08 | 0.04 | 0.02 |
| Culebra AP-125 | SNL-12 | Anhydrite | Sulfatic Weathering w/Marine component | 0.10 | 0.67 | 1.16 | -0.03 |
| Culebra AP-125 | USGS-4 | Anhydrite | Sulfatic Weathering w/Marine component | 0.10 | -0.88 | -1.89 | -0.10 |

entered the unit either directly or by seepage through relatively thin overlying units. Figures 11 and 12 show clear trends of increased ionic strength and calcite and gypsum saturation from the shallower facies F waters to the Dewey Lake facies B waters. Given that the upper Dewey Lake is primarily cemented with calcite, and gypsum cements increase with depth, these are exactly the trends one would expect as water seeps deeper into the system.

Continued downward movement of the Dewey Lake facies B water would probably not, however, lead to the occurrence of facies B water in the Magenta or Culebra. This would require that the facies B water cease to react with the geologic environment after it leaves the lower Dewey Lake, which is unlikely because the water would have to pass through multiple thick anhydrite and mudstone units, all with very low hydraulic conductivity, along its path to the Magenta and Culebra, and rock-water interaction along the way would be expected to change the initial facies B composition. In the vicinity of Dewey Lake facies B wells WQSP-6A, SNL-13, SNL-14, and Ranch, for example, the Magenta and Culebra wells do not themselves contain facies B waters. Thus, most of the facies B Magenta and Culebra waters must have a different origin. The USGS-5 location is somewhat unique, in that the Forty-niner is apparently absent and the Magenta is directly overlain by the Dewey Lake (Cooper, 1962).

The spatial distribution of the facies B Magenta and Culebra waters provides insights into its origins. Figure 42 shows the locations of all the facies B wells, distinguished by geologic unit, as well as the locations of the surface drainage basins mapped by Powers (2006) in the southeastern arm of Nash Draw. The precipitation falling in these basins that does not undergo evapotranspiration drains to karstic openings in Forty-niner gypsum above the Magenta, the Magenta itself, or Tamarisk gypsum above the Culebra. With the exception of a few Dewey Lake wells, all of the wells with facies B signatures are located either within the area of these basins or to the south and southeast – the direction of groundwater flow in the Culebra. Thus, the occurrence of facies B water in the Culebra and Magenta appears to be correlated to the location of drainage basins providing recharge to Rustler gypsum units. Once it has entered a Rustler gypsum unit, water has a relatively short pathway from the Forty-niner down into the Magenta, or from the Tamarisk down into the Culebra, and can derive its sulfatic signature along the way. This signature is then carried downgradient, where the Culebra and Magenta have apparently been flushed of high-salinity fluids over the years.

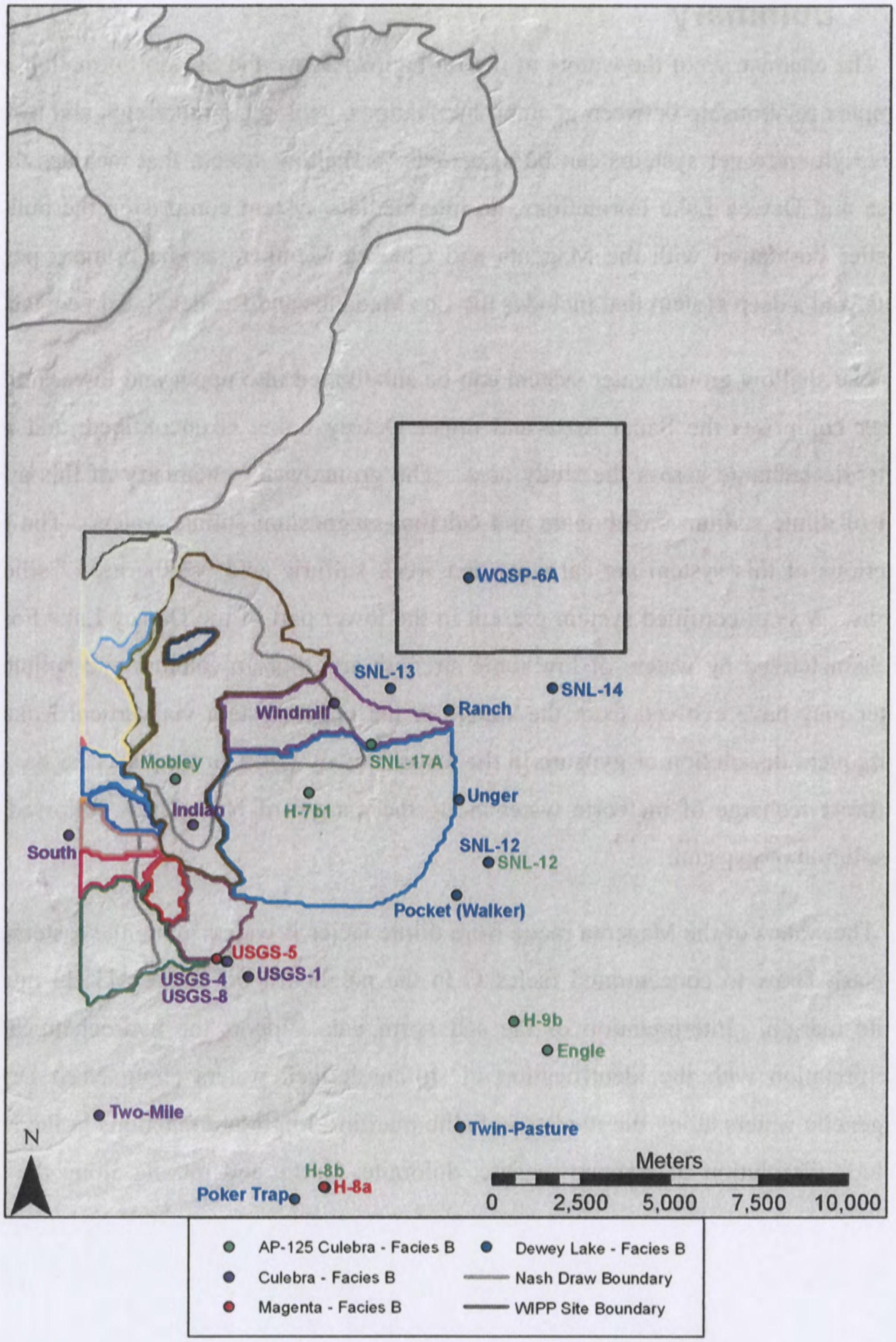


**Figure 42.** Map of the occurrence of facies B waters for the units above the Salado showing closed drainage basins in southeastern Nash Draw.

# 5. Summary

The chemistries of the waters of the formations above the Salado Formation reflect a complex relationship between geomorphic features, geology, mineralogy, and hydrology. Three groundwater systems can be discerned: a shallow system that includes the Santa Rosa and Dewey Lake Formations, an intermediate system comprising the bulk of the Rustler Formation with the Magenta and Culebra Members as the primary permeable units, and a deep system that includes the Los Medaños and Rustler-Salado contact.

The shallow groundwater system can be subdivided into upper and lower units. The upper comprises the Santa Rosa and upper Dewey Lake, is unconfined, and receives meteoric recharge across the study area. The groundwater chemistry of this system is that of dilute sodium bicarbonate and calcium-magnesium sulfate waters. The primary reactions of this system are carbonic and weak sulfuric acid weathering of siliciclastic grains. A semi-confined system present in the lower part of the Dewey Lake Formation is characterized by waters of low ionic strength and high in calcium and sulfate. This water may have evolved from the waters in the upper system via vertical leakage and subsequent dissolution of gypsum in the lower Dewey Lake, or they may be the product of direct recharge of meteoric water along the margin of Nash Draw followed by the dissolution of gypsum.

The waters of the Magenta range from dilute facies B waters along the eastern margin of Nash Draw to concentrated facies G in the neighborhood of the M3-H3 mudstone-halite margin. Interpretation of the salt norm data support the hydrochemical facies interpretation with the identification of sulfate-derived waters along Nash Draw and diagenetic waters along the mudstone-halite margin. Important reactions in the Magenta include dissolution of gypsum, calcite, dolomite, halite, and mixing along the M3-H3 margin.

The Culebra data set presented in this report supplements the data discussed by Domski and Beauheim (2008), and provides an opportunity to compare historical analyses with current analyses for several wells. With the exception of one well location, the H-4 hydropad, no changes were observed between the old and new analyses.

Comparing the analysis of the H-4bR sample to the analysis of the older H-4b sample discussed in Domski and Beauheim (2008), the classifications were unchanged, but the ionic strength had decreased; future analyses may reveal if this is a trend or an anomaly. As was documented in Domski and Beauheim (2008), the Culebra waters range from dilute sulfate-dominant waters along Nash Draw to synsedimentary connate brines east of the M2-H2 margin. Like the Magenta, the primary reactions for the Culebra include dissolution reactions of calcite, dolomite, gypsum, and halite. Mixing of dilute waters with brines along the M2-H2 margin is an important process in the evolution of the waters of the Culebra.

Facies B waters occur in the upper and intermediate groundwater systems where meteoric water has relatively easy access to the subsurface. Facies B water in the Dewey Lake is probably derived from precipitation that has infiltrated the Dewey Lake where it is exposed along the Livingston Ridge escarpment or by vertical seepage through surficial deposits where the Santa Rosa is absent, and has then dissolved calcite and gypsum naturally present. Facies B waters in the Magenta and Culebra probably entered the subsurface through karstic openings in Rustler gypsum in the southeastern arm of Nash Draw and then seeped downward into the dolomite members of the Rustler.

The water chemistries observed in the Magenta are very similar to those found in the Culebra, probably because of the similarity of the mineralogy and geology of the two dolomite units. The depositional environment of both the Magenta and Culebra was a low-energy lagoon environment where carbonate deposition was terminated by desiccation of the basin with subsequent sulfate deposition. Thus, the Culebra and Magenta are micritic dolomites sandwiched in a sequence of sulfates and mudstones that transition to halite. This similarity and the post-depositional evolution of the Delaware Basin combined to create a hydrogeologic system that resulted in waters of the Magenta and Culebra having similar chemistries.

The deep groundwater system includes the Los Medaños and Rustler-Salado contact zone. The brines from these units are either halite resolution brines in Nash Draw where Salado halite dissolution has occurred, or synsedimentary connate brines east of the

Salado dissolution margin. The halite resolution brines are a reflection of dissolution of the Salado halite and retain signatures of their precursors, either sulfate-type meteoric waters or connate brine. The synsedimentary connate brines are very highly concentrated, magnesium rich, and supersaturated with respect to halite. These brines are highly evolved and reflect multiple episodes of sulfate and halite deposition during the deposition of the Los Medaños.

Rather than reflecting simple evolution of water chemistry down flow paths from recharge areas to discharge areas, the Rustler waters discussed in this report result from the interplay of waters present at the time of deposition of these formations, especially east of the mudstone-halite margins, waters that have recharged these formations west of the margins in Nash Draw, soluble minerals in the subsurface, and the distribution of transmissivity in the various units, which exerts a strong control on the rates and direction of groundwater flow. Outside of Nash Draw, the Rustler water chemistries largely reflect strata-bound processes, with little to no vertical, interstratal influences.

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## Appendix A – Information Pertinent to Magenta Samples

| Well | Sample Date | Sample Collection Reference | Analysis Reference | Drilling History | Sampling Conditions |
|---|---|---|---|---|---|
| H-1 | 6/4/1976 | Mercer & Orr (1979) (testing only--no reference to sampling) | Bodine & Jones (1990) | Hole drilled with air and air-mist beginning 5/20/1976, then conditioned with drilling fluid and logged. | Apparently collected during straddle-packer testing of the Magenta in the open hole--probable drilling fluid contamination |
| H-1 | 5/10/1977 | Mercer & Orr (1979) | Mercer & Orr (1979) | Drilled with air and air mist, filled with brine mud and logged 6/8/76, cased and cemented from 797 ft on 6/9/76. Perfed 562-590 ft on 4/5/77. | Bailed 804 gal on 4/6/77. Bailed 612 gal on 5/10/77—potential for some fluid/mud intrusion prior to casing and later cement contamination—no other units open to well |
| H-2a | 2/22/1977 | Mercer & Orr (1979) | Mercer & Orr (1979) | Cored with air mist 2/19/77, rest of hole cased off | Bailed fluid that had collected since hole was cored 3 days before—only potential contamination from air mist—no other units open to well. Possible oil in hole? |
| H-3(b1) | 5/10/1977 | Mercer & Orr (1979) | Mercer & Orr (1979) | Drilled with air mist, then filled with brine mud after reaming for logging, then cased (8/12/76) and cemented from 804 ft. Perfed and bailed Magenta 4/6-7/77, with bridge plug set beneath. | "Magenta" water levels during the period leading up to sampling were representative of Culebra, not Magenta, leading to conclusion that bridge plug was leaking --> Magenta sample cannot be considered reliable |

| Well | Sample Date | Sample Collection Reference | Analysis Reference | Drilling History | Sampling Conditions |
|---|---|---|---|---|---|
| H-3(b1) | 7/1/1985, 9/16/1986, 9/2/1987, 3/16/1989, 8/28/1990,5/21/1991 | Uhland & Randall (1986); Uhland et al. (1987); Randall et al. (1988); WEC (1991; 1992) | Uhland & Randall (1986); Uhland et al. (1987); Randall et al. (1988); WEC (1991; 1992) | unknown | 6 rounds of WQSP sampling |
| H-4a | 12/14/1978 | Mercer et al. (1981) | Mercer et al. (1981); Mercer (1983); Bodine & Jones (1990) | Cored with air foam, flushed with brine, then blew out, all on 5/22/1978 | Bailed 164 gal 12/1/78, used ~31 gal in slug-injection test 12/2/78, ~31 gal in slug-injection test 12/4/78, then bailed 167 gal 12/4/78. No info on actual sampling. |
| H-4c | 11/4/1986, 10/5/1987, 7/19/1988, 4/21/1989,10/2/1990, 10/9/1991 | Uhland et al. (1987); Randall et al. (1988); Lyon (1989); WEC (1991; 1992) | Uhland et al. (1987); Randall et al. (1988); Lyon (1989); WEC (1991; 1992) | Unknown | 6 rounds of WQSP sampling |
| H-5a | 12/14/1978 | Dennehy & Mercer (1982) | Dennehy & Mercer (1982); Mercer (1983); Bodine & Jones (1990) | Cored with brine 6/19-20/78, then blew out 6/20/78. | Bailed 383 gal 12/9/78, used ~58 gal in slug-injection test 12/11/78. No info on actual sampling. |

| Well | Sample Date | Sample Collection Reference | Analysis Reference | Drilling History | Sampling Conditions |
|---|---|---|---|---|---|
| H-5c | 10/24/1986,<br>3/3/1988,<br>8/18/1988,<br>9/14/1989,<br>5/16/1990,<br>7/17/1991 | Uhland et al. (1987); Lyon (1989); WEC (1991; 1992) | Uhland et al. (1987); Lyon (1989); WEC (1991; 1992) | Unknown | 6 rounds of WQSP sampling |
| H-6a | 12/20/1978 | Dennehy (1982) | Dennehy (1982); Mercer (1983); Bodine & Jones (1990) | Cored with freshwater 7/10/78, then flushed with brine and blew out 7/11/78 | Bailed 259 gal, then used ~49 gal for slug-injection test. Sampled after bailing an additional 124 gal. |
| H-6c | 10/1/1986,<br>11/4/1987,<br>7/26/1988,<br>8/4/1989,<br>3/15/1990,<br>5/2/1991 | Uhland et al. (1987); Randall et al. (1988); Lyon (1989); WEC (1991; 1992) | Uhland et al. (1987); Randall et al. (1988); Lyon (1989); WEC (1991; 1992) | Unknown | 6 rounds of WQSP sampling |
| H-8a | 2/12/1980 | ?? | Mercer (1983); Bodine & Jones (1990) | Drilled with fluid (brine?), then blew out 9/18/79 | No info about actual sampling, but in previous days had bailed 60 gal then run slug-injection test using similar amount of water (Richey, 1986)--possibly minor contamination with drilling brine not blown out of hole or fluid used to set packer for slug test |

| Well | Sample Date | Sample Collection Reference | Analysis Reference | Drilling History | Sampling Conditions |
|---|---|---|---|---|---|
| H-9a | 2/5/1980 | ?? | Mercer (1983); Bodine & Jones (1990; has date wrong as 1982) | Cored with air mist, then reamed (with brine?). Blew out 9/5/79. | No info about actual sampling, but had bailed 245 gal on 2/2/80, then ran slug-injection test 2/4/80 using 46+ gal (Richey, 1986)--possibly minor contamination with fluid used to set packer for slug test |
| H-10a | 3/21/1980 | Richey (1986) | Mercer (1983); Bodine & Jones (1990) | Cored with air mist, then reamed (with brine?) 8/26/79. Blew out 8/26/79. | Bailed 310 gal 2/20/80, used 122 gal for slug-injection test 2/22/80, 69 gal for slug-injection test 2/23/80, then bailed 240 gal and sampled on 3/21/80. Potential for contamination with water used to set PIP used for slug test. |
| WIPP-25 | 9/4/1980 | Richey (1987) | Mercer (1983); Bodine & Jones (1990) | Hole drilled and reamed with salt-based mud 8/28-9/11/78, cemented casing 9/12/78. Perforated 300-330 ft 9/3/80. | Sampled after bailing 280 gal, then 580 gal. First 280 gal left in casing before perforating? |
| WIPP-25 | 9/17/1980 | Lambert & Robinson (1984) | Bodine & Jones (1990); Robinson (1997) | Hole drilled and reamed with salt-based mud 8/28-9/11/78, cemented casing 9/12/78. Perforated 300-330 ft 9/3/80. | Sampled after pumping ~51,000 gal--later testing raises questions about Magenta's ability to produce this much water--possibly Culebra? |

| Well | Sample Date | Sample Collection Reference | Analysis Reference | Drilling History | Sampling Conditions |
|---|---|---|---|---|---|
| WIPP-27 | 7/24/1980 | Richey (1987) | Mercer (1983); Bodine & Jones (1990) | Hole drilled and reamed with salt-based mud 9/12-22/78, cemented casing 10/9/78. Perforated 175-195 ft 9/19/80. | Sample misidentified--sample was taken from Rustler-Salado interval from 426-460 ft on this date--Magenta interval had not yet been perforated. Mercer (1983) analysis with this label appears to correspond to Bodine & Jones (1990) R/S sample with this date. Bodine & Jones (1990) analysis with this label is a complete mystery. |
| WIPP-27 | 9/20/1980 | Richey (1987) | Mercer (1983); Robinson (1997; has date wrong as 9/4/80) | Hole drilled and reamed with salt-based mud 9/12-22/78, cemented casing 10/9/78. Perforated 175-195 ft 9/19/80. | Sampled after bailing 870 gal after perforating; BDR suggests entire Rustler is single hydrostratigraphic unit |
| WIPP-27 | 9/25/1980 | Lambert & Robinson (1984) | Bodine & Jones (1990); Robinson (1997) | Hole drilled and reamed with salt-based mud 9/12-22/78, cemented casing 10/9/78. Perforated 175-195 ft 9/19/80. | Sampled after pumping ~14660 gal; BDR suggests entire Rustler is single hydrostratigraphic unit |

| Well | Sample Date | Sample Collection Reference | Analysis Reference | Drilling History | Sampling Conditions |
|---|---|---|---|---|---|
| WIPP-30 | 9/24/1980 | Richey (1987) | Mercer (1983); Bodine & Jones (1990); Robinson (1997; has date wrong as 9/20/80) | Hole drilled and reamed with salt-based mud 9/8-29/78, cemented casing 10/2/78. Perforated 510-540 ft 9/13/80. | Sampled after bailing 430 gal, then 11 gal. First 430 gal probably left in casing before perforating. Final 11 gal bailed probably contaminated to some extent with perf water. Robinson (1997) questions representativeness of sample. |
| USGS-5 | 11/15/1961 | Cooper (1962) | Bodine & Jones (1990) | Drilled with cable tool rig. | Sample bailed when hole depth was 418 ft (Magenta is 400-417 ft). Forty-niner is absent. |

## Appendix B – Information Pertinent to Rustler-Salado Samples

| Well | Sample Date | Sample Collection Reference | Analysis Reference | R-S Contact Depth (ft bgs) | Open interval (ft bgs) | Drilling History | Sampling Conditions |
|---|---|---|---|---|---|---|---|
| H-1 | 2/23/77 | Mercer & Orr (1979) | Mercer & Orr (1979) | 824 | 803-827 (perfed) | Drilled with air mist 5/29/76, open to Culebra fluid, then filled with "drilling fluid" 5/30/76 for logging. Open-hole testing 5/31-6/5, reamed 6/5-7, filled with brine mud and logged 6/8, cased and cemented from 797 ft on 6/9. Drilled plug to 831 ft on 1/22/77, bailed dry and perfed on 1/22/77 | Bailed fluid (25 gal) that had collected since hole was bailed "dry" 33 days before—potential for Culebra intrusion prior to casing and later cement contamination—no other units open to well |
| H-2c | 2/23/77 | Mercer & Orr (1979) | Mercer & Orr (1979) | 764 | 743-795 (open hole) | Cored with air mist 2/4-5/77, rest of hole cased off | Bailed fluid (14 gal) that had collected since hole was cored 18 days before—only potential contamination from air mist—no other units open to well |

| Well | Sample Date | Sample Collection Reference | Analysis Reference | R-S Contact Depth (ft bgs) | Open interval (ft bgs) | Drilling History | Sampling Conditions |
|---|---|---|---|---|---|---|---|
| H-3(b1) | 2/23/77 | Mercer & Orr (1979) | Mercer & Orr (1979) | 821 | 813-837 (perfed) | Drilled with air mist 8/2/76, open to Culebra fluid, then filled with brine mud 8/11/76 after reaming for logging, then cased (8/12/76) and cemented from 804 ft. Drilled plug to 864 ft on 1/20/77, bailed dry 1/21/77, perfed 1/22/77 | Bailed fluid (37 gal) that had collected since hole was bailed "dry" 32 days before—potential for Culebra intrusion prior to casing and later cement contamination—no other units open to well |
| H-4c | 3/16/79 | Mercer et al. (1981) | Bodine & Jones (1990) | 626 | 610-661 (open hole) | Drilled with air foam, flushed with brine, then blew out 5/8/78 | Sampled immediately after slug-injection test with brine—sample can only be injection brine |
| H-5c | 5/16/79 | Dennehy & Mercer (1982) | Bodine & Jones (1990) | 1041 | 1025-1076 (open hole) | Drilled with brine, then blew out 6/3/78; surface water entered well 10/3-11/7/78, bailed dry 12/15/78 | Sampled by bailing after ~40 ft of water level recovery from surface water bailing |
| H-6c | 4/9/79 | Dennehy (1982) | Bodine & Jones (1990) | 721 | 700-741 (open hole) | Drilled with brine, then blew out 6/26/78 | Sampled immediately after slug-injection test with brine—sample can only be injection brine |

| Well | Sample Date | Sample Collection Reference | Analysis Reference | R-S Contact Depth (ft bgs) | Open interval (ft bgs) | Drilling History | Sampling Conditions |
|---|---|---|---|---|---|---|---|
| H-7c | 3/20/80 | Richey (1986) | Bodine & Jones (1990) | 380? | 357-420 (open hole) | Drilled with air mist, then blew out 9/13/79. Severe bridging/lost circulation problems in Oct-Nov 79—casing filled up to 312 ft, cleaned out with brine. Also in Nov 80. | Sampled after bailing ~2190 gallons—good chance contamination remained from Oct-Nov 79 events. |
| H-8c | 9/6/80 | Richey (1986) | Bodine & Jones (1990) | 733 | 735-808 (open hole) | Drilled with brine(?), then blew out 8/6/79 | Sample from 10 gal bailed (interval is all Salado) |
| H-9c | 5/20/80 | ?? | Bodine & Jones (1990) | 791 | 785-816 (open hole) | Drilled with brine(?), then blew out 8/14/79. Replaced casing to 343 ft in Sept 79, using lots of brine. Blew dry 9/24/79. | ?? No info in records |
| H-10c | 5/19/80 | ?? | Bodine & Jones (1990) | 1501 | 1483-1538 (open hole) | Drilled with brine(?), then blew out 8/20/79 | ?? No info in records |

| Well | Sample Date | Sample Collection Reference | Analysis Reference | R-S Contact Depth (ft bgs) | Open interval (ft bgs) | Drilling History | Sampling Conditions |
|---|---|---|---|---|---|---|---|
| P-14 | 2/24/77 | Mercer & Orr (1979) | Mercer & Orr (1979) | 687 | 676-700 (perfed) | Drilled with air mist and soap, hole filled with mud gel, casing set and cemented to 775 ft all on 9/29/76. Casing bailed dry then perfed on 1/21/77. | Bailed fluid (250 gal) that had collected since hole was perfed 34 days before—potential for Culebra and mud intrusion prior to casing—no other units open to well |
| P-14 | 2/4/80 | ?? | Bodine & Jones (1990) | 687 | 676-700 (perfed) | Drilled with air mist and soap, hole filled with mud gel, casing set and cemented to 775 ft all on 9/29/76. Casing bailed dry then perfed on 1/21/77. | ?? No info in records |
| P-15 | 4/3/79 | ?? | Mercer (1983) | 542 | 532-560 (perfed) | Drilled with air mist and soap, hole filled with mud gel, casing set and cemented to 635 ft 10/6-9/76. Casing bailed dry then perfed on 1/21/77—82 gal of inflow in next 72 days. | Lambert & Harvey (1987) consider unreliable; Bodine & Jones (1990) concur |

| Well | Sample Date | Sample Collection Reference | Analysis Reference | R-S Contact Depth (ft bgs) | Open interval (ft bgs) | Drilling History | Sampling Conditions |
|---|---|---|---|---|---|---|---|
| P-17 | 5/11/79 | ?? | Mercer (1983) | 715 | 702-726 (perfed) | Drilled with soap and water, then loaded with mud gel before setting and cementing casing to 751 ft 10/19-20/76. Drilled to 1660 ft then plugged back to 716 ft 10/21-26/76. Drilled and washed to 731 ft 10/28/76. Bailed hole dry and then perforated on 1/20/77—71 gal of inflow in next 73 days | ?? No info in records |
| P-18 | 5/11/79 | ?? | Mercer (1983) | 1088 | 1076-1100 (perfed) | Drilled with salt water gel 10/27/76. Cemented casing to 1138 ft 10/28/76. Bailed hole dry and then perforated on 1/21/77—34 gal of inflow in next 73 days | ?? No info in records. Lambert & Harvey (1987) consider unreliable; Bodine & Jones (1990) retain |

| Well | Sample Date | Sample Collection Reference | Analysis Reference | R-S Contact Depth (ft bgs) | Open interval (ft bgs) | Drilling History | Sampling Conditions |
|---|---|---|---|---|---|---|---|
| P-18 | 5/20/80 | ?? | Bodine & Jones (1990) | 1088 | 1076-1100 (perfed) | Drilled with salt water gel 10/27/76. Cemented casing to 1138 ft 10/28/76. Bailed hole dry and then perforated on 1/21/77—34 gal of inflow in next 73 days | ?? No info in records |
| SNL-13 | 4/24/05 | Powers & Richardson (2008) | Powers & Richardson (2008) | >480 | 412-480 (open hole; Los Medaños) | Drilled Los Medaños with air and foam 4/23-24/05 | Borehole was open from 192-480 ft at the time of sampling, but the interval from 468-480 ft was the major producer. Sample collected from drilling rolloff containing brine blown from hole. |
| WIPP-25 | 3/19/80 | Richey (1987) | Bodine & Jones (1990) | 565 | 579-608 (perfed) | Drilled with salt-based mud 9/6-11/78, cemented casing 9/12/78. Perforated 579-608 ft 3/13/80. | Sampled after bailing 680, then 280 gallons. First 680 gal left in casing before perforating? (interval is all Salado) |
| WIPP-25 | 7/17/80 | Lambert & Robinson (1984) | Robinson (1997) | 565 | 579-608 (perfed) | Drilled with salt-based mud 9/6-11/78, cemented casing 9/12/78. Perforated 579-608 ft 3/13/80. | Pumped 27 hr @ 1.1 gpm (interval is all Salado) |

| **Well** | **Sample Date** | **Sample Collection Reference** | **Analysis Reference** | **R-S Contact Depth (ft bgs)** | **Open interval (ft bgs)** | **Drilling History** | **Sampling Conditions** |
|---|---|---|---|---|---|---|---|
| WIPP-26 | 3/18/80 | Richey (1987) | Bodine & Jones (1990) | 309 | 228-329 (perfed) | Drilled with salt-based mud 9/1-6/78, cemented casing 9/8&11/78. Perforated 228-329 ft 3/11/80. | Sampled after bailing 340, then 230 gal. First 340 gal left in casing before perforating? |
| WIPP-26 | 7/23/80 | Lambert & Robinson (1984) | Robinson (1997) | 309 | 228-329 (perfed) | Drilled with salt-based mud 9/1-6/78, cemented casing 9/8&11/78. Perforated 228-329 ft 3/11/80. | Pumped 19 hr @ 0.92 gpm, 36 hr @ 0.42 gpm (Total ~1956 gal) (Culebra not yet perforated) |
| WIPP-27 | 5/21/80 | ?? | Bodine & Jones (1990) | 416 | 426-460, 480-510 (perfed) | Drilled with salt-based mud 9/16-22/78, cemented casing 9/22/78. Perforated 480-510 ft 3/14/80, and 426-460 ft 3/17/80. | ?? No info in records (interval is all Salado) |
| WIPP-27 | 7/24/80 | Richey (1987) | Bodine & Jones (1990) | 416 | 426-460, 480-510 (perfed) | Drilled with salt-based mud 9/16-22/78, cemented casing 9/22/78. Perforated 480-510 ft 3/14/80, and 426-460 ft 3/17/80. | Sampled after bailing ~410 gal from upper perfs only. Source of water uncertain. (interval is all Salado) |

| Well | Sample Date | Sample Collection Reference | Analysis Reference | R-S Contact Depth (ft bgs) | Open interval (ft bgs) | Drilling History | Sampling Conditions |
|---|---|---|---|---|---|---|---|
| WIPP-28 | 3/20/80 | Richey (1987) | Bodine & Jones (1990) | 531 | 549-589 (perfed) | Drilled with salt-based mud 8/19-26/78, cemented casing 8/28/78. Perforated 549-589 ft 3/15/80. | Sampled after bailing 450, then 450 gal. First 450 gal left in casing before perforating? (interval is all Salado) |
| WIPP-28 | 7/31/80 | Lambert & Robinson (1984) | Robinson (1997) | 531 | 549-589 (perfed) | Drilled with salt-based mud 8/19-26/78, cemented casing 8/28/78. Perforated 549-589 ft 3/15/80. | Pumped ~22 hr @ ~3.1 gpm (interval is all Salado) |
| WIPP-29 | 3/18/80 | Richey (1987)? | Bodine & Jones (1990) | 143 | 216-250 (perfed) | Drilled with salt-based mud 10/4-9/78, cemented casing 10/10/78. Perforated 216-250 ft 3/10/80. | Sampled after bailing ~440 gal on 3/10/80, not 3/18/80? Mostly water left in casing before perforating? (interval is all Salado) |
| WIPP-29 | 7/24/80 | Lambert & Robinson (1984) | Robinson (1997) | 143 | 216-250 (perfed) | Drilled with salt-based mud 10/4-9/78, cemented casing 10/10/78. Perforated 216-250 ft 3/10/80. | Pumped 46 hr @ 1.5 gpm (interval is all Salado) |

| **Well** | **Sample Date** | **Sample Collection Reference** | **Analysis Reference** | **R-S Contact Depth (ft bgs)** | **Open interval (ft bgs)** | **Drilling History** | **Sampling Conditions** |
|---|---|---|---|---|---|---|---|
| WIPP-30 | 3/19/80 | Richey (1987) | Bodine & Jones (1990) | 749 | 731-753 (perfed) | Drilled with salt-based mud 9/20-29/78, cemented casing 10/2/78. Perforated 731-753 ft 3/12/80. | Sampled after bailing 280, then 230 gal. First 280 gal left in casing before perforating? |
| WIPP-30 | 7/17/80 | Lambert & Robinson (1984) | Robinson (1997) | 749 | 731-753 (perfed) | Drilled with salt-based mud 9/20-29/78, cemented casing 10/2/78. Perforated 731-753 ft 3/12/80. | Pumped 45 hr @ 0.22 gpm (Total ~594 gal) (Culebra not yet perforated) |
| USGS-5 | 11/27/61 | Cooper (1962) | Bodine & Jones (1990) | 662 (residuum)<br>686 (salt) | 661-693 (slots) in casing set in 660-696 open hole | Drilled with cable tool rig. | Sample bailed. Hole cased to 660 ft. Uncertain if slotted casing (uncemented) had been installed at time of bailing. |

# Appendix C – Computer Files

File Storage: These files will be stored in CMS (LIBAP147_FILES in class AP147)

File Key:
Table C1 contains the file information for the Santa Rosa and Dewey Lake, Section 3.1,

Table C1: File names and purpose from the Section 3.1 directory and application labeled subdirectories.

| Subdirectory | File(s) Names | Purpose |
|---|---|---|
| PHRQC | Dewey_Lake.pqi | PHREEQCI input file |
| | Dewey_Lake.pqo | PHREEQCI output file |
| | Dewey_Lake1.xls | PHREEQCI generated output |
| SNORM | DL_QA | SNORM input file |
| | DL_QA.out | SNORM output file |
| | DL_QA.ss | SNORM simple salt file |
| XLS | DeweyLake_SantaRosa_Final.xls | Processed output for plotting and table generation |

Table C2 contains the file information for the Magenta, Section 3.2.

Table C2: File names and purpose from the Section 3.2 directory and application labeled subdirectory.

| Subdirectory | File(s) Names | Purpose |
|---|---|---|
| PHRQC | Magenta.pqi | PHREEQCI input file |
| | Magenta.pqo | PHREEQCI output file |
| | Magenta.xls | PHREEQCI generated output |
| SNORM | mag_QA3 | SNORM input file |
| | mag_QA3.out | SNORM output file |
| | mag_QA3.ss | SNORM simple salt file |
| XLS | Magenta_Final.xls | Processed output for plotting and table generation |

Table C3 contains the file information for the Culebra, Section 3.3.

Table C3: File names and purpose from the Section 3.3 directory and application labeled subdirectory.

| Subdirectory | File(s) Names | Purpose |
|---|---|---|
| PHRQC | Old Culebra Data.pqi | PHREEQCI input file |
| | Old Culebra Data.pqo | PHREEQCI output file |

| Subdirectory | File(s) Names | Purpose |
|---|---|---|
|  | Old Culebra1.xls | PHREEQCI generated output |
|  | Old Culebra2.xls | PHREEQCI generated output |
| SNORM | Cul_QA | SNORM input file |
|  | Cul_QA.out | SNORM output file |
|  | Cul_QA.ss | SNORM simple salt file |
| XLS | Old Culebra_Final.xls | Processed output for plotting and table generation |

Table C4 contains the file information for the Los Medanos, Section 3.4.

Table C4: File names and purpose from the Section 3.4 directory and application labeled subdirectory.

| Subdirectory | File(s) Names | Purpose |
|---|---|---|
| PHRQC | Rus-Sal.pqi | PHREEQCI input file |
|  | Rus-Sal.pqo | PHREEQCI output file |
|  | Rus-Sal.xls | PHREEQCI generated output |
| SNORM | Rus-Sal | SNORM input file |
|  | Rus-Sal.out | SNORM output file |
|  | Rus-Sal.ss | SNORM simple salt file |
| XLS | Rus-Salado_Final.xls | Processed output for plotting and table generation |

Table C5 contains the file information for Section 4.1.

Table C5: File names and purpose from the Section 4.1 directory and application labeled subdirectory.

| Subdirectory | File(s) Names | Purpose |
|---|---|---|
| Section 4.1 | Average_Comps.xlsx | Processed output for plotting figures 39, 40, & 41. |

## AP-147 Hydrochemical Data

**Dewey Lake**

| *Description* | *Date* | *pH* | *Density* | *Ca* | *Mg* | *Na* | *K* | *Cl* | *S(6)* | *Alkalinity as CaCO3* | *Data Reference* | *Notes* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BARN | 7/13/1989 | 7.12 | 1.0008 | 74 | 37 | 93 | 2.5 | 48 | 210 | 280 | DOE/WIPP 91-025 | |
| Clifton Well | 10/28/1987 | 6.72 | 1.002 | 35 | 34 | 190 | 3.9 | 45 | 330 | 240 | DOE/WIPP 92-007 | |
| Comanche Well | 10/26/1987 | 7.45 | | 31 | 22 | 45 | 5.1 | 15 | 40 | 230 | DOE/WIPP 88-006, DOE/WIPP 92-007 | |
| H-5c grab | 5/24/1978 | 7 | | 56 | 51 | 280 | 25 | 120 | 530 | 240 | USGS 83-4016 | 7.0 used when no pH available |
| RANCH | 6/20/1990 | 7.2 | | 550 | 150 | 220 | 0 | 340 | 1400 | 230 | DOE/WIPP 92-007 | |
| SNL-1 | 3/25/2004 | 6.82 | 1.21 | 540 | 4500 | 91000 | 21000 | 190000 | 15000 | 290 | Hall Rpt 403227, BDR DOE/WIPP 04-3301 | |
| SNL-12 | 6/26/2003 | 7 | 1 | 303 | 100 | 109 | 5.44 | 215 | 942 | 133 | SNL Rpt 6/22/04 | 7.0 used when no pH available |
| SNL-13 | 4/12/2005 | 8.02 | 1 | 680 | 150 | 270 | 5.7 | 440 | 2200 | 58 | Hall Rpt 504146, BDR DOE/WIPP 05-3319 | |
| SNL-14 | 5/3/2005 | 7.98 | 1.0255 | 74 | 51 | 29 | 6.1 | 54 | 160 | 180 | Hall Rpt 505083, BDR DOE/WIPP 05-3320 | |
| SNL-14 | 5/5/2005 | 7.68 | 1.0025 | 430 | 150 | 240 | 4.9 | 350 | 1300 | 140 | Hall Rpt 505083, BDR DOE/WIPP 05-3320 | |
| Twin-pasture | 9/28/1989 | 7.41 | 1.0016 | 79 | 24 | 9 | 2.5 | 40 | 50 | 220 | DOE/WIPP 91-025 | |
| Unger | 1/26/1984 | 7 | | 530 | 130 | 120 | 3.2 | 260 | 1800 | 130 | SAND 86-0917, Tbl 133 | 7.0 used when no pH available |
| Walker | 7/31/1962 | 7.1 | | 613 | 145 | 140 | 3.6 | 325 | 1790 | 134 | SAND 88-0196, Tbl 4.7 | |
| Pocket | 11/2/1983 | 7.7 | 1 | 380 | 96 | 95 | 2.4 | 210 | 1100 | 140 | SAND 86-0917. Tbl 130 | |
| WQSP-6A | 6/10/1998 | 7.47 | 1 | 649 | 173 | 335 | 4.49 | 644 | 1950 | 103 | DOE/WIPP 99-2225, Tbl 7.8, separate analysis sheet | |
| Poker Trap | 12/19/1987 | 7.09 | 1.001 | 420 | 82 | 43 | 3.2 | 24 | 1400 | 100 | DOE/WIPP 88-006, pg A-54 | |

**Magenta**

| *Description* | *Date* | *pH* | *Density* | *Ca* | *Mg* | *Na* | *K* | *Cl* | *S(6)* | *Alkalinity as CaCO3* | *Data Reference* | *Notes* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C-2737 | 1/30/2007 | 7.34 | 1.0112 | 910 | 290 | 2200 | 26 | 4100 | 2400 | 38 | Hall Rpt 702003, SN, Magenta 7 | |
| H-1 | 5/10/1977 | 7.2 | | 1000 | 460 | 6200 | 840 | 10000 | 3600 | 93 | USGS WRI 79-98 | |
| H-10a | 3/21/1980 | 7.1 | 1.175 | 2500 | 2600 | 93000 | 510 | 160000 | 2700 | | USGS WRIR 83-4016 | |
| H-15 | 3/19/2008 | 7.79 | 1.0741 | 2500 | 880 | 39000 | 180 | 65000 | 4100 | 39 | Hall Rpt 803246, SN Magenta 8 | |
| H-18 | 4/17/2009 | 7.47 | 1.0081 | 600 | 200 | 1300 | 18 | 1700 | 2900 | 44 | Hall Rpt 904340, SN Magenta 9 | |
| H-2a | 2/22/1977 | 8.6 | | 820 | 170 | 2700 | 81 | 4100 | 2400 | 74 | USGS WRI 79-98, Tbl 2 | |
| H-3b1 | 3/16/1989 | 6.96 | 1.0085 | 1000 | 300 | 1450 | 34 | 3300 | 2000 | 43 | DOE/WIPP 91-025 | Ref records 14500 for Na, but historical knowledge dictates it should be 1450 mg/L, known order of magnitude issue with report |
| H-3b1 | 7/30/2009 | 7.8 | 1.009 | 890 | 280 | 1500 | 29 | 3900 | 2300 | 33 | Hall Rpt 907569, SN Magenta 10 | |
| H-4c | 10/9/1991 | 8.28 | 1.018 | 734 | 456 | 6480 | 65 | 8812 | 6740 | 120 | DOE/WIPP 92-007, App A | |
| H-5c | 5/16/1990 | 8.33 | | 560 | 180 | 1000 | 36 | 870 | 3300 | 46 | DOE/WIPP 92-007 | |
| H-9a | 2/5/1980 | 8.5 | 1.003 | 550 | 170 | 800 | 28 | 750 | 2700 | 42.7 | USGS WRIR 83-4016, Tbl 2 | |
| H-9c | 5/22/2002 | 8.2 | 1.005 | 558 | 178 | 930 | 34.8 | 1110 | 2620 | | SNL Rpt ERMS 523030, SN Magenta 2 | |
| USGS-5 | 11/15/1961 | 7.6 | | 648 | 122 | 150 | 8.3 | 250 | 1940 | 103 | SAND 88-0196, Tbl 4.6 | |
| WIPP-27 | 9/25/1980 | 6.3 | 1.09 | 3660 | 2100 | 43200 | 8090 | 85200 | 3410 | 210 | SAND 88-0196, Tbl 4.6 | |
| WIPP-30 | 9/24/1980 | 8.2 | 1.012 | 731 | 203 | 5930 | 119 | 7980 | 3660 | | Bodine and Jones (1990), Tbl 10 | |
| WIPP-18 | 3/18/2010 | 7.15 | 1.01 | 550 | 210 | 2000 | 19 | 2400 | 3600 | 23 | Hall Rpt 1003482, SN Magenta 11 | |
| H-6c | 3/15/1990 | 7.45 | | 570 | 170 | 570 | 20 | 390 | 2600 | 51 | DOE/WIPP 92-007 | |
| H-6c | 4/27/2010 | 7.74 | 1.007 | 560 | 140 | 780 | 60 | 890 | 2800 | 0 | Hall Rpt 1004666, SN, Magenta 11 | |
| H-8a | 2/12/1980 | 7.8 | 1.004 | 845 | 15 | 2300 | 75 | 3520 | 2490 | 34 | Bodine and Jones (1990), Tbl 10 | |
| H-8a | 4/20/2010 | 7.73 | 1.01 | 650 | 140 | 2500 | 47 | 3400 | 3700 | 50 | Hall Rpt 1004462, SN Magenta 11 | |
| H-2b1 | 2/8/2011 | 8.96 | 1.0086 | 760 | 210 | 1500 | 33 | 2300 | 2800 | 27 | Hall Rpt 1102238, SN WSWT 14 | |
| H-4c | 3/1/2011 | 9.14 | 1.0207 | 660 | 420 | 6800 | 82 | 8500 | 6800 | 63 | Hall Rpt 1103085, SN WSWT 14 | |
| H-9c | 4/18/2011 | 8.64 | 1.0064 | 590 | 130 | 890 | 28 | 1000 | 2800 | 21 | Hall Rpt 1104715, SN WSWT 14 | |

**Old Culebra**

| *Description* | *Date* | *pH* | *Density* | *Ca* | *Mg* | *Na* | *K* | *Cl* | *S(6)* | *Alkalinity as CaCO3* | *Data Reference* | *Notes* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Indian | 1/22/63 | 7.6 | | 624 | 169 | 315 | 8.6 | 533 | 1950 | 193 | SAND 88-0196 Bodine, Jones, Lambert Tbl 4.5 | |
| Two-Mile | 8/8/62 | 6.7 | | 630 | 177 | 1410 | 25 | 2200 | 2200 | 66 | SAND 88-0196 Bodine, Jones, Lambert Tbl 4.5 | |
| Windmill | 9/14/61 | 8 | | 564 | 139 | 525 | 23 | 515 | 2290 | 108 | Bodine and Jones (1990), pg 247 | |
| South | 8/8/62 | 7.4 | | 589 | 90 | 24 | 4.8 | 18 | 1660 | 196 | SAND 88-0196 Bodine, Jones, Lambert Tbl 4.5 | |
| USGS-1 | 8/18/1960 | 7.6 | | 608 | 146 | 520 | 11 | 770 | 1960 | 114 | SAND 88-0196 Bodine, Jones, Lambert Tbl 4.5 | |
| USGS-4 | 12/5/1961 | 7.5 | | 644 | 134 | 640 | 16 | 948 | 1950 | 114 | SAND 88-0196 Bodine, Jones, Lambert Tbl 4.5 | |
| USGS-8 | 1/27/1963 | 7.1 | | 624 | 155 | 630 | 27 | 1190 | 2050 | 108 | SAND 88-0196 Bodine, Jones, Lambert Tbl 4.5 | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| USGS-4 | 7/30/2008 | 6.36 | 1 | 600 | 120 | 650 | 15 | 1100 | 1400 | 31 | Hall Rpt 807447 | |
| USGS-8 | 7/30/2008 | 7.75 | | 570 | 97 | 810 | 16 | 1000 | 1800 | 35 | Hall Rpt 807446 | |
| H-4bR | 8/13/2009 | 7.76 | 1.014 | 660 | 280 | 3800 | 130 | 6100 | 4500 | 54 | Hall Rpt 908237, SN, WSWT 13 | |
| H-6bR | 12/10/2008 | 7.73 | 1.041 | 2000 | 950 | 17000 | 350 | 32000 | 4000 | 77 | Hall Rpt 812250, SN WSWT 12 | |
| H-15R | 1/22/2009 | 7.53 | 1.13 | 1800 | 2100 | 66000 | 1200 | 110000 | 6400 | 63 | Hall Rpt 901317, SN WSWT 13 | |

**Rustler-Salado**

| *Description* | *Date* | *pH* | *Density* | *Ca* | *Mg* | *Na* | *K* | *Cl* | *S(6)* | *Alkalinity as CaCO3* | *Data Reference* | *Notes* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H-1 | 2/23/1977 | 7.9 | | 13000 | 30000 | 56000 | 17000 | 210000 | 520 | 675 | USGS WRIR 83-4016, Tbl 2 | |
| H-2C | 2/23/1977 | 5.9 | | 9200 | 25000 | 66000 | 9100 | 200000 | 1300 | 199 | USGS WRIR 83-4016, Tbl 2 | |
| H-3B1 | 2/23/1977 | 7.6 | | 18000 | 25000 | 59000 | 14000 | 210000 | 370 | 467 | USGS WRIR 83-4016, Tbl 2 | |
| H-5C | 5/16/1979 | 6 | 1.193 | 2100 | 82000 | 14000 | 21000 | 290000 | 2000 | 219.6 | USGS WRIR 83-4016, Tbl 2, WRI 82-19, Tbl 3 | CaCO3 value calculated from HCO3 value in report |
| P-14 | 2/24/1977 | 7.2 | | 570 | 1200 | 120000 | 1300 | 180000 | 10000 | 222 | SAND 88-0196 Bodine, Jones, Lambert Tbl 4.3 | |
| SNL-13 | 4/26/2005 | 6.55 | 1.19 | 3700 | 10000 | 95000 | 2300 | 190000 | 5300 | 76 | Hall Rpt 504272, BDR DOE/WIPP 05-3319 | |
| USGS-5 | 11/27/1961 | 7 | 1.2 | 424 | 2710 | 94700 | 2090 | 156000 | 540 | 18 | Bodine and Jones (1990), Tbl 7 | |
| WIPP-26 | 7/23/1980 | 7.7 | | 1410 | 1660 | 68600 | 1200 | 108000 | 7480 | 270 | SAND 88-0196 Bodine, Jones, Lambert Tbl 4.3 | |
| WIPP-30 | 7/17/1980 | 7.5 | | 955 | 2770 | 120600 | 2180 | 192000 | 7390 | 620 | SAND 88-0196 Bodine, Jones, Lambert Tbl 4.3 | |

NOTE: There was no value of pH for H-5c given in Bodine and Jones (1990), pH was set to 6 because the code failed to converge at pH=7, PSD.