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| Assessment of Geothermal Resource Potential at High-Priority Areas at UTTR |
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| Richard P. Smith, Ph.D., PG Robert P. Breckenridge, Ph.D. Thomas R. Wood, Ph.D. |
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EXECUTIVE Summary

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ACRONYMS

API American Petroleum Institute

Dugway Dugway Proving Grounds

GSLD Great Salt Lake Desert

HAFB Hill Air Force Base

PACES Pan American Center for Earth and Environmental Sciences

UGS Utah Geological Survey

USGS United States Geological Survey

UTTR Utah Testing and Training Range

UTTR-N Utah Testing and Training Range–North

UTTR-S Utah Testing and Training Range–South

Assessment of Geothermal Resource Potential at High-Priority Areas at UTTR

# INTRODUCTION

The purpose of this report is to summarize the current state of knowledge concerning potential high-temperature geothermal development on the lands controlled by Hill Air Force Base (HAFB) at the Utah Testing and Training Range (UTTR). This report is based on currently available published and publically available information and field data that was collected during 2011.

Much of the data gathered for this assessment of geothermal potential has been compiled as thematic layers, all at the same scale, so that diverse information can be compared and analyzed by means of map overlays. The material for the thematic layers was identified from literature searches and from published and unpublished maps.

During calendar year 2011, several tasks were accomplished to assess the geothermal resource potential for the UTTR:

* a comprehensive synthesis of existing and available information was compiled
* a preliminary report based on that synthesis was written
* additional investigations, including field activities, were conducted.

The following executive summary of the preliminary report is the starting point for this final report. In addition the figures in the preliminary report serve to illustrate the types of geologic and geophysical information compiled and synthesized in task #1, above. The additional investigations conducted after the preliminary report was issued are listed and described thoroughly in the sections following the preliminary report executive summary.

# REGIONAL SETTING

The UTTR lands are located within the Great Basin of the Basin and Range Province in northwestern Utah. Together, the Range and the Proving Grounds cover a large area of the Great Salt Lake Desert (GSLD). The UTTR is separated into two distinct areas, one north of Interstate 80 (UTTR-N) and one south of Interstate 80 (UTTR-S).

The GSLD is a structural basin (one of the larger basins within the Great Basin) which, like most basins of the province, has been filled with a thick sequence of Neogene, Quaternary, and Holocene sediments. Significant recent sediments covering the GSLD are fine muds and evaporite deposits associated with growth and desiccation of Lake Bonneville during Pliestocene glacial cycles.

The Great Basin Center for Geothermal Energy, located at the University of Nevada, Reno, has produced a map, which shows greater potential for the discovery of geothermal systems with warm colors and lesser potential with cool colors. The center’s assessment is that the greatest discovery potential lies in the western part of the Great Basin (i.e., western Nevada) and along the Wasatch front in the state of Utah. This is because the geothermal systems in the Great Basin are deep-circulation systems that depend on circulation of groundwater to great depths along fault zones for their existence. Fluids must be able to circulate to depths as great as 9 km to be heated to temperatures sufficient for primary electric generation. Therefore, faults must extend through the upper crust and maintain open flow conduits in the current stress environment. Deep circulation and heating of significant quantities of groundwater can occur only on faults that repeatedly rupture (i.e., active faults) in current stress conditions, which keeps permeability pathways open. Therefore, areas with a higher strain rate are more favorable than areas with lower strain rates. Active faults (i.e., Quaternary and Holocene in age) occur mostly along the eastern margin and in the western part of the Great Basin, thus providing for the higher potential assessed in those areas.

# EXECUTIVE SUMMARY OF THE PRELIMINARY REPORT

This preliminary report describes an in-depth investigation of relevant existing data that may be useful for evaluating the geothermal resource potential of the lands controlled by Hill Air Force Base (HAFB) at the Utah Testing and Training Range (UTTR) and the lands encompassed by the Dugway Proving Grounds (Dugway). Assembled data include published journal articles and maps, as well as extensive collections of geothermal, geologic, geophysical, and geochemical data available from numerous university and government websites. Several geothermal focus areas are identified for future detailed analyses. The review and interpretation of the data presented herein indicates that within the focus areas are prospects that have characteristics similar to other geothermal reservoirs in the Great Basin. Recommendations are provided regarding additional data required to design a well drilling program to more fully characterize the geothermal potential southeast of Wendover, UT, in the western portion of UTTR-S.

The UTTR/Dugway lands are located within the Great Basin of the Basin and Range Province in northwestern Utah, an area of North America known to have thin crust, warm upper mantle rocks, high heat flow, and numerous geothermal systems, which can host geothermal power plants. The UTTR/Dugway area is situated in the Great Salt Lake Desert (GSLD), a structural basin that has been filled with a thick sequence of sediments. This thick sequence of sediments, as well as the waxing and waning of ice age lakes and the more frequent filling and draining of playa lakes, has masked deep subsurface geologic features. Understanding the geothermal regime here is further complicated by the lack of data in the area due to restricted access of large parcels of lands for military reservations. Nevertheless, the limited data from deep wells and the projection of geologic trends into the UTTR/Dugway area indicate a strong possibility that geothermal systems exist here.

Four different geothermal exploration models for basin and range deep-circulation geothermal systems are described in this report. These models are sometimes called conceptual models and define the salient features of the geology, temperature regimes, and hydrogeology that must be present in order for a viable geothermal exploration target to exist. A geothermal system with commercial potential must have a combination of heat, water, and permeability. It is the coincident occurrence of multiple characteristics that contribute to the existence of a geothermal reservoir capable of electrical generation. The geothermal exploration models suggest that the location of the UTTR/Dugway lands within the Great Basin, near deep-seated faults, near regions of high extension rates, and over horst- and graben-bounding faults, makes it a prime exploration area for deep-circulation geothermal resources.

The four exploration models are discussed in relation to a number of characteristics relevant to the discovery of geothermal systems on UTTR/Dugway Lands. The characteristics considered include: (1) the location within the Great Basin; (2) the geologic structure of the basin beneath the GSLD; (3) thermal gradient and heat flow; (4) thickness of basin-fill sediments; (5) resurfacing of basin floor; (6) thermal springs; (7) cold springs; (8) Quaternary faults; (9) contemporary seismicity; (10) source of water for geothermal systems; (11) characteristics of rocks in adjacent and intra-basin mountain ranges; and (12) lack of exploration due to a military presence. Four areas of the UTTR are identified that hold the most promise for the discovery of a geothermal resource.

Focus Area 1 will be the first area considered for more detailed investigation during the summer and early fall of 2011. In addition to its favorable geologic and geophysical characteristics, Focus Area 1 is also in close proximity to existing power transmission lines, capable of handling power from a geothermal plant. Scientifically, this area is of interest for several reasons. First, the Blue Lakes Springs and other warm springs occur here and maintain a temperature of 84°F. Second, the Wendover Graben (as identified from existing gravity surveys of the area) probably extends to the southwest from the area east of Wendover into this focus area. The southeastern side of the Wendover Graben has not been mapped into the Blue Lakes area yet, but an extrapolation of the gravity gradient motivates collection of additional gravity data in the area this summer. A complex system of two or more graben intersecting beneath the desert in the area south and southeast of Wendover is thought to exist in Area 1. Such intersections of graben and faults of different trends commonly produce extensive zones of fractured rock, which serve as pathways for the deep circulation of geothermal waters and for the development of near-surface geothermal reservoirs. Third, temperature data from several nearby petroleum exploration and deep brine wells suggest very high thermal gradients exist in the area. And finally, the presence of several earthquake epicenters east of Wendover suggest that the graben-bounding faults are still active, which is a condition favorable for maintaining open pathways for circulation of geothermal waters in the fault zones. Taken as a whole, the existing data are indicative of the conditions necessary for the presence of a significant geothermal resource in Focus Area 1.

Our results indicate that the best use of exploration funds will focus on collecting data to better characterize the nature and extent of the Wendover Graben, searching for other evidence of geologic faulting, better characterization of the permeability of the deeper geologic formations, and collection of geochemistry data from wells and springs in the area to “finger print” waters for evidence of geothermal influences. These planned investigations for the summer and fall of 2011 include a high resolution gravity survey, geochemical sampling of springs and wells, temperature logging of deep wells (as available), evaluation of surface lineaments that might indicate deep structures, and a detailed analysis of available geophysical well logs for oil exploration wells. This data will be used for identifying drilling targets with high potential for a geothermal discovery in Focus Area 1.

It is noted that in the long-term, the other identified focus areas may be just as promising as Focus Area 1 and are worthy of more detailed exploration as well, and should not be neglected. Also, in large parts of UTTR-South and Dugway, so little geophysical and geologic data exist that subsurface interpretations are not possible. A long-term program of data collection in those areas may reveal other promising areas for geothermal exploration.

## UTTR Lands Focus Area

The available data for the GSLD provides rationale for selection of promising geothermal exploration areas on UTTR lands. It allows projection of favorable structures into the UTTR and comparison to analogous features in known geothermal systems. For this investigation, one area of the UTTR was selected and evaluated for its potential for discovery of a geothermal resource.

**Focus Area 1: The western portion of UTTR-S –** This area is of interest for several reasons. First, the Blue Lakes springs and other warm springs occur here. The Blue Lakes are fed by spring vents at the lake’s bottom, and although the water temperature entering from the vents at this spot is not known, the lakes maintain a temperature of 84°F (Blackett and Wakefield, 2002). Also, the Wendover Graben and its associated bounding faults probably extends to the southwest from the area east of Wendover into the focus area. In fact, the warm springs at and near the Blue Lakes area may be localized by the southeastern graben-bounding fault. The southeastern side of the Wendover Graben has not been mapped into the Blue Lakes area yet, but an extrapolation of the gravity gradient data collected in this was conducted during the summer of 2011 and are presented in this report.

In addition, numerous springs in the area east and southeast of Wendover may also be localized by the graben-bounding faults. The oil wells southeast of Wendover and north of the focus area show that the thickness of sediment is about 3000 ft east of the graben and greater than 3000 ft within the graben. Gravity modeling indicates that the basin fill sediments in the deepest part of the graben is around 5000 ft (Cook et al, 1965). They also interpret a complex system of two or more graben intersecting beneath the desert in the area south and southeast of Wendover. Such intersections of graben and faults of different trends commonly produce extensive zones of fractured rock, which serve as pathways for the deep circulation of geothermal waters and for the development of near-surface geothermal reservoirs.

The presence of several earthquake epicenters east of Wendover suggest that the graben-bounding faults are still active, which is a condition necessary for maintaining open pathways for circulation of geothermal waters in the fault zones. In addition, several Quaternary faults mapped in the bedrock ranges northwest, north, and northeast of Wendover indicate contemporary tectonic activity in the area. Henrikson and Chapman (2002) show that heat flow calculated from an oil and gas well east of Wendover (specifically Alpha Minerals Federal #1) and north of Focus Area 1 is 120 mW/m2, which is among the highest heat flow values in Utah. Also, DB3, which is located about 5 miles southwest of Alpha Minerals Federal #1 has a measured temperature of about 88°C at a depth of about 500 meters (Turk, 1973; Whelan and Petersen, 1974), suggesting a geothermal gradient of 176°C/km (see Figure 1).

INSERT FIGURE 1

# ADDITIONAL INVESTIGATIONS CONDUCTED IN 2011

Because most of the land encompassed by Focus Area 1 is under military (UTTR) and industrial (Intrepid, Inc. potash operations) control, little geologic, geophysical, and geochemical information is available. In order to increase our understanding of the subsurface geology and temperature distribution in the area, a field campaign consisting of five different field investigations was conducted in 2011.

## Field Investigation 1: Detailed Gravity Survey

*Description.* A field campaign to acquire new gravity stations in and near Focus Area 1 was designed and performed. The gravity survey was designed to provide sufficient data to fill in the large area of few existing stations in the western part of UTTR-S, and to provide sufficient detail to evaluate the geometry of the southward extension of the Wendover graben into Focus Area 1. The survey consisted of 686 new gravity stations arranged in 17 east-west oriented lines. The lines are approximately 2km apart and in-line spacing between stations is 400m or 800m, depending on difficulty of access and time available for surveys (see Figures 2–4). In addition, the raw gravity data were converted to a complete Bouguer gravity anomaly (CBGA), and gridded to model basin depth and the magnitude of the horizontal gravity gradient. Also, 2D models were developed along several cross sections selected to provide details of the basement structure beneath the Focus Area. Details of data acquisition (field methods), data processing, and 2D and 3D modeling procedures are presented in Appendix A.

INSERT FIGURE 2

INSERT FIGURE 3

INSERT FIGURE 4

*Results.* The new gravity data are plotted as contours of the complete Bouguer gravity anomaly (CBGA) at each station, and as contours of the CBGA of each grid node in the gridded data (see a and c in Figure 5) to aid in interpretation of the subsurface structure. In each of the contoured maps, the areas of greatest horizontal gravity gradient (i.e., places where the gravity contours are closest together) are used to infer the positions of graben-bounding faults (see b and d in Figure 5). Although different in some details, the faults and overall shape of down-faulted basins (graben) inferred from contours of the station data (see Figure 5b) closely match those inferred from contours of the gridded data (see Figure 5d). The gravity data show that a deep northeast-trending graben extends through the Intrepid area just north of Focus Area 1 and through the northwestern part of Focus Area 1. Its deepest part occurs at its southern end, just west of the UTTR boundary and a little north of Blue Lakes springs. It defines the southern portion of the Wendover graben, first identified and modeled by Cook et al (1964) based on gravity data that mostly covered the area north of Wendover.

INSERT FIGURE 5

In addition to defining the southern part of the Wendover graben, a second deep basin is indicated just southwest of Wendover. It extends southeastwardly from the Goschute Mountains and intersects the Wendover graben near it deepest point, near the northwestern corner of Focus Area 1 (see b and d in Figure 5). Although the NW-trending graben is shorter and narrower than the Wendover graben, its zone of intersection with the Wendover graben is likely to consist of intersecting fault zones with enhanced permeability to geothermal fluids.

Some important details of the subsurface structure are revealed by modeling of the new gravity data. For example, a gridded version of the complete Bouguer gravity anomaly, with 1km grid cell size, is presented in Figure 6. Overlain on the gravity model are the contours of the gridded data at 5mgal contour interval. The gravity values range from around -170mgal (brightest yellow grid cells) to about -120mgal (deepest read grid cells). From this gridded model, a map of the areas of maximum horizontal gradient of the gravity values was developed (see Figure 7a). This map, also gridded at 1km grid cell size, simply shows the areas where the gravity values change most dramatically with horizontal distance (the lighter the color of the grid cell, the greater the change of the gravity values with horizontal distance). These areas of high gradient are associated with juxtaposition of rocks of differing density, and are most likely to represent faults in the subsurface. In Figure 7b, white lines are drawn on these areas of high gradient, and are used to infer the positions of graben-bounding faults in the subsurface (see b and d in Figure 4). In each case, they are areas where there is a steep contact between low-density sediments inside the graben and high-density basement rock outside the graben.

INSERT FIGURE 6

INSERT FIGURE 7

Additionally, the gravity data are used to model the depth to bedrock in the subsurface, i.e., the thickness of low-density sediments above the high-density bedrock of Paleozoic rocks (see Figure 8). This model covers a smaller area than that of Figures 6 and 7, and is gridded at a larger cell size (1.5km). The areas with greatest depth to bedrock (bright yellow to white cells) and the overall shape of the graben system is revealed by this model. The depth associated with each cell is strongly dependant on the density contrast assumed for the rocks present here; unconsolidated sediments of the basin-fill material verses solid limestones, dolomites, sandstones, quartzites, and shales of the basement. No density determinations are available for the materials, but a range of reasonable density contrasts can be estimated from analogous rocks in other areas where density data is available. For that range of contrasts, the depth to the deepest parts of the basin (bright yellow to white cells) can range from around 2km up to about 4km. Although the depth of each cell changes for different density contrast values in the reasonable range, the overall shape of the modeled graben structure does not.

INSERT FIGURE 8

## Field Investigation 2: Borehole Temperature Logging

*Description.* Several existing wells in the Intrepid area just north of Focus Area 1 were made available for temperature logging (see Appendix B for detailed report).

*Results.* Temperature increases across Intrepid area to the SE towards west end of UTTR South. This is shown both by temperatures reported by Turk 1973 and by recent temperature logs acquired by Blackett et al., 2011. (make 2 figures showing this temperature increase, one for the Turk data and one for the Blackett data). Temperature increase in this direction suggests circulation of geothermal fluids along the inferred boundary fault system of the Wendover graben in the NW part of UTTR-S.

Even at the modest gradients suggested by the temperature log of DBW-17 and corrected bottom-hole temperatures in Shell Salduro #1 and Alpha Federal #1 (33°C/km), temperature at 2km depth (interpreted depth of the Wendover graben) is close to 100°C (probably sufficient for binary power production). (make a figure showing these gradient estimations). If the average gradient of DBW-17 at 320–385m (70°C /km) is extrapolated to 2km depth the temperature is around 150°C. The gradients suggested by the 88°C temperature at about 500m in DBW-3 (170‑265°C/km) lead to temperatures of well over 200°C at 2km. These estimated gradients cannot be sustained to depth because they would lead to temperatures much higher than those in any known Great Basin deep circulation systems. Therefore, the gradients likely moderate or overturn with depth (decreasing temperature with depth after some maximum temperature is reached). If future drilling and temperature logging show that the gradients overturn, then the high temperatures encountered in DBW-17 and especially DBW-3 can be visualized as outflow from a geothermal system, probably lying to the south and east of DBW-3.

(make a figure showing overturning of temperature gradients with depth).

## Field Investigation 3: Lineament Study

*Description.* The study of linear features(lineaments) on images of the earth’s surface can sometimes help determine the location and character of deep seated geologic structures, for instance faults. Lineament analysis for Focus Area 1 was performed using a combination of high resolution NAIP (National Agricultural Imagery Program) imagery and GoogleEarth imagery. The NAIP imagery helped in the identification of linear vegetation anomalies and aligned springs that are generally related to faults. Field inspections were performed to validate mapped lineaments (see Appendix C for detailed description of EGI’s lineament study).

*Results.* A total of 22 lineaments were identified in the study (see Figure 4.3.1). As seen in the figure the lineaments trend primarily in a NE-SW direction in the center of the study area with NW-SE trending lineaments occurring more frequently near the perimeter of the study area. Most of the field evaluated lineaments were either not found or there was no significant tectonic influence associated with the feature. Of most interest for geothermal exploration are the lineaments numbered 3 to 6, shown in more detail in the central and northeast portion of figure 4.3.2 . These lineaments are in the vicinity of a warm water spring known as Mosquito Willey’s, and cross the outflow from the Blue Lakes springs that lie to the NNW of Mosquito Willey’s (Figure 4.3.2). In addition to the springs, further evidence of tectonic activity are the outcrops immediately to the west of the springs that consist of breciated limestones, secondary calcite and other materials that may have been derived from the footwall of a fault. The lineament also extends to the southwest into the low bedrock foothills where it defines a straight boundary between Neogene volcanics (rhyolite) and Paleozoic limestones. Limestones in outcrops directly west of the springs are brecciated (intensely broken into small, angular pieces by faulting), with fragments cemented together by hydrothermal or spring deposits of calcite. Such evidence of faulting suggests that these lineaments represent surface expressions of faults that provide permeable pathways for flow of warm waters from depth to feed the present spring systems. Taken as a whole this cluster of lineaments likely represent the surface expressions of both NE-SW and NW-SE trending faults from the intersecting grabens inferred from the new gravity data (See Section 4.1).

Insert Figure 4.3.1 Numbered fault lineaments on hill shaded map, which displays topographic lows as white and highs as black.

Insert Figure 4.3.2. NAIP image overlain with lineaments 3-6 and 14 in the Mosquito Willey’s and Blue Lake area south of Wendover, Utah

## Field Investigation 4: Analysis of Borehole Geophysical Logs of Existing Wells

*Description.* See Appendix D for a detailed description of procedures and for summary logs of wells studied.

*Results.* Estimation of matrix properties of Paleozoic and Cenozoic rocks in selected wells near Focus Area 1 reveals low porosities and permeabilities, similar to that of similar rocks throughout the Great Basin. Therefore, as with other deep-circulation geothermal systems in the Great Basin, discovery of zones of enhanced fracture permeability will be necessary for development of potential geothermal systems in Focus Area 1. Correlation of Cenozoic rock units in two wells just north and north-east of Focus Area 1, using a distinctive volcanic unit as a marker, shows that….

## Field Investigation 5: Sampling and Analysis of Surface Waters and Springs

*Description.*  Thermal waters discharge at several locations in and adjacent to the West Desert of Utah. Analysis of thermal waters can lead to an understanding of the thermal history of the water and give an indication of the deep reservoir conditions. The principle of chemical geothermometry is based on temperature dependent chemical equilibrium between the water and minerals in the geothermal reservoir and it is assumed that thermal water preserves its chemical composition during its ascent from the reservoir to the surface. Geothermometry is a commonly employed geothermal exploration technique; however, the assumption of the preservation of water chemistry may not always hold resulting in some uncertainty in the calculated results.

Geothermometry has been performed on nine water samples for the UTTR Study; four from the Blue Lake area and five from wells located on the southeast flank of the Silver Island Mountains (Fig. 4.5.1, 4.5.2 and 4.5.3). See Appendix E for detailed description of water chemistry study and the field and laboratory procedures.

*Results.* The results of the chemical analyses are presented in Table 4.5.1. The samples were analyzed for major, minor a several trace elements using standard chemical techniques by Thermochem Inc. The analytical results are included in Appendix E. All of the waters are NaCl in composition with minor HCO3 and SO4. Waters from the Blue Lake area display significantly lower salinities than those from the Intrepid Potash Inc. wells although the measured temperatures of the waters are similar (Table 4.5.1). Total dissolved solids contents of the Blue Lake waters range from approximately 5000-5500 mg/L whereas those from the Intrepid Potash Inc. wells range from 8000-12500 mg/L. Figures 4.5.4 and 4.5.5 show the relationship between Na and Cl and it suggests that the well waters from wells IW6, IW7, IW13, and IW10 could represent mixtures of water from IW12 and Blue Lake waters. The very high Cl contents of the Intrepid Potash Inc. well waters suggests that IW12 water has interacted with salt deposits present in the Bonneville Salt Flats of the west desert. Because of the potential interactions with salt deposits, and their effects on the compositions of the waters, the following discussion is focused on waters from the Blue Lake area, which are more likely to reflect interactions with the sedimentary and volcanic rocks below the salt deposits.

A significant feature of the Blue Lake waters is their relatively high Ca and Mg contents and Ca/Mg ratios near 3. High contents of these cations are typical of carbonate reservoirs. Langmuir (1971) suggested that Ca/Mg ratios >3.0 indicate interactions with limestones. Ratios between 1.5 and 3.0 can indicate the presence of dolomite beds with a dominantly limestone reservoir whereas ratios <1.5 implies interactions with reservoirs consisting mainly of dolomite. Based on the Ca/Mg ratios of the Blue Lake waters we suggest that the reservoir rocks consist primarily of limestone with interbedded dolomite beneath the cover of Tertiary and Quarternary sediments and volcanic rocks.

Figure 4.5.5 shows the K-Na-Mg relationships for the Blue Lake area waters. These waters plot near the base of the region of partial equilibration. Giggenbach (1991) suggested that both silica and K/Mg geothermometers (Giggenbach, 1991) could be applied to samples plotting in this portion of the diagram, although with caution. Temperatures calculated based on the K/Mg geothermometer yield values of 108-111oC. The chalcedony geothermometer, the most appropriate silica geothermometer for low temperature waters, in contrast yields temperatures of 40 to 48oC. Although it cannot be demonstrated that mixing with low silica waters has occurred, the low measured temperatures of these waters and the significantly higher temperatures encountered the Intrepid Deep Brine Well DB-3 (Turk, 1973) suggests that dilution is a likely explanation for the low calculated values.

The anhydrite geothermometer is based on equilibria between the fluid and anhydrite. It is calculated from the Ca and SO4 contents of the thermal fluids and assumes the presence of anhydrite in the reservoir. Although the presence of anhydrite was not noted on the well logs of nearby wells, gypsum was observed. Anhydrite is a common mineral in carbonate terrains and is likely to be present. Temperatures calculated from the anhydrite geothermometer range from 138-140oC.

# INTERPRETATION OF NEW DATA AND CONCEPTUAL MODEL

Summarize the important new conclusions from the additional investigations, show that big advances have been made with minimal expense, and develop a conceptual model of the subsurface in and near Focus Area 1. The conceptual model should be presented both in text and in a figure or series of figures. Dick and Tom to develop this section using input from the field investigations and assessment of well logs. This will identify how the geology can or may support the presence of a geothermal resource and will be the basis for the recommendations section that will follow, length about 6-10 pages. Rick and Joe will review this section.

# RECOMMENDATIONS FOR EXPLORATORY DRILLING

Based on the conceptual model, recommend places for drilling of exploratory wells and the depths necessary to fully test the model, and either support or question the existence of favorable temperatures and permeability. Provide some recommendations to Hill that they can use to either move forward or retire the idea of developing a geothermal resource on the UTTR. Include in the assessment some discussion about infrastructure and logistical concerns relative to possible drilling locations. Dick, Bob and Tom will produce this section and provide to Rick, Joe and Erik to review.

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Figure Captions

Figure 1. NEED CAPTION.

Figure 2. Existing gravity stations from the PACES database at the University of Texas, El Paso. Note the sparsity of stations within the western portion of UTTR-S, including all of Focus Area 1. This lack of gravity data precludes robust interpretation of the structure of the southward extension of the Wendover graben into and near Focus Area 1, and is corrected by the collection of new gravity data in 2011.

Figure 3. Prioritization of areas for collection of new gravity data in 2011. Based on best interpretations of existing gravity, on locations and orientations of lineaments (green dashed lines), and on location of thermal springs and lakes, the area was prioritized so that the most probable areas underlain by the Wendover graben were well covered.

Figure 4. Map showing the location and spacing of new gravity stations measured in 2011. Gaps in the pattern of new stations in the Intrepid area, just north of Focus Area 1, are due to large evaporation ponds that limit access. Also note that no new data was collected in the northern portion of the Priority 3 Area because of restricted access to this area of the UTTR-S.

Figure 5. Map showing contoured values (Inverse Distance Weighted) of the complete Bouguer gravity anomaly (CBGA) based on new data from stations shown in Figure 4. Contour lines are color coded with cool colors representing low values and warm colors representing high values. Two different contour maps are shown. Figure 5a is a contour map of the CBGA values recorded at each of the 686 new gravity stations. Figure 5c is a contour map of the CBGA values calculated at each of the approximately 2800 grid nodes in an equivalent-source model with a 1km grid size. Figures 5b and 5d show faults (white lines) interpreted from the contour maps in 5a and 5c, respectively. Label Goschute Mtns on maps. Add I-80 to maps.

Figure 6. Gridded model of the complete Bouguer gravity anomaly (CBGA), shown with contours of the gridded gravity data at 5mgal contour interval. Grid size is 1km, and CBGA ranges from -170mgal (bright yellow cells) to -120mgal (deep red cells).

Figure 7. Horizontal gravity gradient maps.

Figure 8. Depth to bedrock model.

Appendix A  
  
Western UTTR Gravity Surveys & Processing

Paul Gettings

Introduction

To help determine the subsurface structure, and hence favorable exploration targets, the Utah Geological Survey (UGS) acquired new gravity data in Priority Areas 1, 2, and the southern part of Priority Area 3; the northern part of Priority Area 3 was closed due to security concerns. Some gravity measurements and gravity modeling, primarily Cook et al., 1964, have been performed in this area but generally, the gravity coverage is sparse. New gravity stations for this investigation are located in areas of historically poor coverage. Locations were selected to leverage the existing data coverage and maximize the extent of the gravity mapping. Figure A-1 shows the study area with existing and new gravity stations; note that seven existing stations (collected during previous investigations) were reoccupied during this survey to determine offsets between the 1970s-era data and the new gravity stations.

INSERT FIGURE A-1

A total of 686 new stations provided coverage at 800 and 400 m in-line spacing (E-W), and ~2 km cross-line spacing (N-S). Most stations were accessed using All Terrain Vehicles (ATVs); however, some areas were inaccessible due to ground conditions, such as active evaporation ponds or deep mud. Trimble survey-grade dual-frequency receivers were used for positioning each station during the gravity readings.

Exploration gravity data, such as acquired in the UGS survey, reflects the density and depth of the subsurface materials between land surface and the center of the Earth. However, because deep structure has small amplitude and large wavelengths, it is possible to focus the interpreted gravity signal on the near-surface structure by removing a large-scale anomaly signal. Note that the gravity data presented here is quoted in mGal, which are equivalent to 10-5 m/s2; the average Earth gravity field is 980,000 mGal.

Based on assembled portions of geologic maps of the region around the study area, the basement is interpreted to be a mix of Paleozoic sedimentary rocks, mostly quartzite and limestone. There are few exposures of bedrock in the study area, and only at the extreme edges, so actual basement lithology can only be inferred. The sedimentary cover is lacustrine, but maps show only undifferentiated alluvium. Cross sections were assembled from a number of neighboring maps, due to the lack of exposures in the study area and the large scale of maps covering the site. A detailed geologic map of the area immediately west of the study area (Leppy Peak Quadrangle) was particularly useful. Cross sections were also assembled from the Gold Hill and Pilot Peak quadrangles for comparison. Due to the lack of basement exposures in the study area, rock densities have therefore been assumed based on averages for the various rock types.

Data Acquisition & Processing

Gravity data were acquired using two Scintrex CG-5 gravimeters. Station occupations consisted of six-minute time series of 30-second averages. Time series were corrected for Earth tides using the harmonic formulation from Tamura (1987). Time series are converted to a single gravity reading using a weighted average, after dropping the first three minutes to remove transport effects. Instrument drift is removed using linear interpolation between repeated occupations of local and remote base stations. The drift function, acquisition, and processing techniques are described in detail in Gettings et al (2008).

Position data were acquired using Trimble dual-frequency survey-grade receivers. Some positions were suitable for post-processing, but errors within the Trimble device software prevent post-processing of all locations. Stations without post-processed positions used the six‑minute averages in the field. Post-processed positions are good to 0.1 m or better; the six‑minute averages are accurate to 1 m or better horizontal? And vertical? resolution. Error bounds have been assumed using a constant position error of 1 m for all stations; 1 m elevation error translates to 0.309 mGal. It should be noted that existing gravity stations have position and elevation errors of at best 1 m, so the new stations compare favorably with the old.

Gravity readings at field stations were compared to the absolute gravity value at the University of Utah base station at the President’s Circle benchmark. Absolute gravity at the base station was last measured in 1996, but drift in the gravity value at the base station due to hydrologic changes will be on the order of 0.1 mGal or less, and is ignored.

Observed gravity values at the new stations were compared with existing data at the seven existing stations (new stations within 10 m of old stations). The average offset of 1.975 mGal between the old gravity stations and the new gravity stations has been removed from the new stations, so all stations can be used in a single, consistent map.

For interpretation, the observed gravity values are converted to a complete Bouguer gravity anomaly (CBGA). Theoretical gravity due to the rotating ellipsoid (latitudinal and shape-of-the-Earth effects), elevation effects (free-air correction), and terrain effects have been removed. See Hinze (2005) for a discussion of the modern reference equations for theoretical gravity and the various corrections. The free-air correction assumed a typical gradient of -0.3086 mGal/m. Bouguer slab, curvature, and terrain corrections have been computed using an assumed density of 2400 kg/m3. Terrain corrections for near-station topography computed using half cones and half slopes, based on sketches of near-station topography drawn during acquisition. Most stations did not need any near-zone corrections. Terrain corrections were computed to a radius of 166.7 km using a global code based on 468 m spherical diamonds and SRTM digital elevations (Gettings, 2012). Testing with various Bouguer reduction densities between 2200 and 2800 kg/m3 showed a minimum correlation of CBGA with elevation at 2400 kg/m3.

All stations are used in an equivalent-source method to create a regular N-S/E-W grid (Cordell, 1992). Grid interval is set to 1 km, for the range 225–270 km easting, 4460–4520 km northing. Figure A-2 shows the gridded observed anomaly map (upper left panel) and its horizontal gradients (remaining three panels). This upper left panel, showing the observed anomaly, has the average anomaly (-142.68 mGal) subtracted to allow interpretation to focus on the shallow structure. The average anomaly reflects the broad, deep structure of the crust in Utah and Nevada, which is not of interest in this project. The upper right panel shows the magnitude of the horizontal gradient. High gradient values indicate areas of rapid change, which are associated with faults and other sharp structural boundaries. The individual easting (g\_x) and northing (g\_y) gradient maps highlight changes in the E-W and N-S directions.

INSERT FIGURE A-2

Discussion & Modeling of Basin Structure

The prominent gravity lows and highs in the central western portion of the anomaly map indicate a buried basin, with higher bedrock to the east. The large area of high gravity to the east of the basin has poor station coverage, and thus should not be interpreted to mean there is not a basin to the east of the deepest gravity low. Station coverage clearly shows that there is a bedrock high bordering the east edge of the buried basin, but that high could be a ridge and not a plateau as suggested by the interpolation of data in an area with poor coverage. Due to security limitations, stations were not allowed in the northern part of Priority Area 3, and thus it is not possible to determine the structure in that eastern area.

Based on the assumed basement geology, basement density is set to 2800 kg/m3. The lacustrine sediment cover is assigned an average constant density of 2000 kg/m3; this accounts for less dense material at the surface and more dense sediments in the deep basins.

As a first pass of modeling the buried structure, the observed gravity anomalies at stations are gridded at a 1500 m interval (using the same technique as for Figure A-2), and a Newton’s Method inversion for a two-layer system is performed. An initial model of 1000 m depth-to-basement across the whole space and a maximum model depth of 3000 m is used. Iterations update individual columns with a new depth-to-basement, constrained to a minimum of zero. Sediments are assumed to have a constant density of 2000 kg/m3, while the basement is assigned a density of 2800 kg/m3 (suitable for a mixture of limestone, quartzite, dolomite, etc.). Iterations are continued until the RMS difference (model-observed) increases, the difference change drops below 10-4 mGal, or 100 iterations is reached. For the 1500 m grid, eight iterations achieve an RMS difference of 0.473 mGal with differences between observed and modeled anomaly bounded between -2 to +5 mGal.

Figure A-3 shows the observed gridded data (with stations), the modeled gravity effect, the difference between what was modeled and what was observed, and the best-fit depth model. Note that the depth is computed relative to the elevation of each grid cell.

INSERT FIGURE A-3

Depths range from 1001–2150 m in the deep basin. The depth range depends on the assumed density contrasts—for example, using a basement density of 2700 kg/m3 and a sediment density of 2000 kg/m3 results in a depth range of 973–1866 m and final RMS difference of 0.303 mGal; likewise, using a basement density of 2800 kg/m3 and a sediment density of 2100 kg/m3 results in a depth range of 995–2850 m and a final RMS difference of 0.994 mGal. As expected, the shape of the depth model does not depend on the chosen densities. The 5 mGal residual at the deepest basin block indicates that the modeled depth is at a minimum.

The spatial pattern of the depth model is consistent with a deep basin system bounded by NE‑SW trending faults; the largest and deepest basin is between 4490 and 4495 km northing, and is ~5 x 7 km in the north and east extent. Additional shallower basin-like geometries exist to the NE and NW of the deepest basin. The basement highs to the north and SE of the deep basin are sufficiently sharp to likely be caused by large offsets of fault(s).

Two-dimensional gravity models were built from the 1 km gridded data, as shown in Figure A-2. Figure A-4 provides the modeled lines overlain on the gridded CBGA values and on the gridded elevations. Note that the lines show significant gravity variations, but little elevation change. Figures A-5 and A-6 show the 2-D models. Note that the models assume constant densities of 2000 and 2800 kg/m3 (-0.4 g/cc, +0.4 g/cc) as with the 3-D modeling. Lines across the gravity lows can be modeled as 2–3 km deep basins shallowing to 1 km on the west and east sides. As with most models, small changes in geometry can be made while maintaining the goodness of fit between the calculated and observed data. In particular, note that the sharp points of the models can be replaced with a broader, shallower boundary. In Profile E, the sharp changes between 7 and 13 km must be related to near-surface geology; such rapid changes cannot be caused by interfaces at depths of 2+ km due to the diffusive nature of gravity. Without better geologic maps, magnetic data, tighter gravity coverage, or other additional geophysics, it is not possible to identify what is causing the anomalously low (or high) gravity values between 7 and 13 km along profile E.

INSERT FIGURE A-4

INSERT FIGURE A-5

INSERT FIGURE A-6

The long NW-SE profile, as shown in Figure A-6, warrants additional discussion. Note that the stepped, tilted gravity points between 10 and 25 km. The geometry of the profile model is consistent with either tilted graben blocks or small horst blocks at the bottom of the basin. Maximum sediment depths are up to 4.5 km below the surface. This is consistent with the 3-D modeling results—the 3-D model has a depth of 2.2 km at the same location, but the model is 5 mGal too positive at the same point.

All models are consistent with a typical sediment thickness of about 1 km in the gravity highs, dropping to 2–4.5 km in the gravity lows.

The structure could be caused by tilted graben blocks in the deepest gravity low;

Using the smaller 1500 m grid model and the 2-D lines as a basis, a qualitative interpretation of the larger, finer gravity grid of Figure 2 is straight-forward. The deep gravity low in the center is the deep basin, bounded by faults running NE-SW. An additional basin is due south of the deep basin, but that basin appears to be bounded by a nearly E-W fault. Unfortunately, without additional station coverage in Priority Area 3, it is difficult to interpret what the basement high at the edge of the two basin systems looks like, and thus how to interpret the geologic structure.

Acknowledgements

Hobie Willis and Adam Hiscock of the Utah Geological Survey conducted most of the field work. Marie Green at the University of Utah built the 2-D models.

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Figure Captions

Figure A-1. Study area with existing and new gravity stations. Basemap is aerial photography of the Intrepid Potash and UTTR areas. Priority areas are outlined in green. Coordinate crosses are 0.25 degrees apart. A total of 686 new stations were added in Priority Areas 1 through 3.

Figure A-2. Gridded complete Bouguer anomaly values, with horizontal gradients. Bouguer anomaly computed assuming 2400 kg/m3 density. Grid computed at 1 km interval from all stations (shown as blue triangles), using an equivalent source technique (Cordell, 1992). Upper right panel shows the magnitude of the gradient; the bottom two panels are gradients in east and north directions.

Figure A-3. 3-D depth-to-basement modeling. Upper left panel is observed with CBGA and gridded at 1.5 km spacing from all stations. Upper right panel is the calculated gravity anomaly from the 3-D model. Lower left panel is misfit (residual) between calculated and observed grids, in mGal. Lower right panel is the depth model in meters below surface.

Figure A-4. Profile locations on gridded gravity anomaly and elevations. Left side shows profile locations on CBGA, in mGal. Right panel shows profiles on gridded elevations, in m.

Figure A-5. Gravity models for profiles A, B, D, and E. Models computed assuming a -0.4 and 0.4 g/cc density contrasts for sediment and basement (2000 and 2800 kg/m3). See text for discussion of model features.

Figure A-6. Gravity model for long NW-SE profile. Bodies assumed to have 2000–2800 kg/m3 constant densities.

Appendix B  
  
Borehole Temperature Logging

Robert Blackett, Mark Gwynn, and Andrew Rupke

Utah Geological Survey

November 2011

Abstract

Based on data gathered from six deep brine wells within a study area located southeast of Wendover, Utah and adjacent west of the southern tract of the Utah Test and Training Range (UTTR), subsurface temperatures are elevated and suggest that hydrothermal fluids circulate to relatively shallow depths, possibly along faults marginal to the Wendover graben. Based upon an 88°C (190°F) temperature at 499 m (1637 ft) depth reported by Turk (1973) in well DBW-3, and down-hole temperature data from other deep brine wells owned by Intrepid Potash, subsurface temperatures appear to increase southeastward toward the west side of the southern tract of the UTTR. The highest temperature recorded in wells measured as part of this study was a bottom‑hole temperature of 43.9°C (111°F) measured at 410 m (1345 ft) depth in well DBW-17. The temperature profile from the interval 320–385 m (1050–1263 ft) of the bottom part of this well yields an approximate thermal gradient of 70°C/km (3.9°F/100 ft).

Introduction

This report supports efforts by the Idaho National Laboratory and the U.S. Department of Defense to investigate the geothermal resource potential of the Utah Test and Training Range (UTTR) located in Tooele and Box Elder Counties of northwestern Utah. On 22 and 23 June 2011, geologists from the Utah Geological Survey (UGS) measured down-hole temperatures in six inactive brine production wells at a facility near Wendover, Utah operated by Intrepid Potash, Inc. Intrepid produces brine from a number of both shallow and deep brine wells for potash and other salt extraction. Turk (1973) presents data on 13 “deep brine wells” drilled to depths ranging from 326–631 m (1070–2070 ft). The highest temperature recorded was 88°C (190°F), measured in the (bailed) drilling mud of one well designated as “DBW-3” at a depth of 499 m (1637 ft). The brine produced from these deep wells contains 120,000–130,000 mg/L total dissolved solids.

Hydrothermal systems indicated by thermal springs and wells are scattered throughout this large, sparsely populated region of Utah. The region extends westward from the Cedar Mountains in central Tooele County across the Bonneville Salt Flats to the Nevada-Utah state line, and then southward into Snake and Tule Valleys of Juab and Millard Counties. Mundorff (1970) included information on thermal springs and general geology for the Great Salt Lake Desert and western Utah as part of his report on major thermal springs in the state. Turk (1973) noted abnormally high geothermal gradients in brackish water wells, several deep brine wells, and two warm springs in the Bonneville Salt Flats area. Blue Lake and Salt Spring, located in western Tooele County near the Utah-Nevada border, are small lakes fed by thermal springs. Blue Lake maintains a fairly constant temperature at about 29°C (84°F), although during a water-sampling exercise in September 2011, we measured temperatures of about 28°C (82°F). Whelan and Petersen (1974) focused a brief report on the geothermal potential of the Bonneville Salt Flats, referencing the work of Turk. Goode (1978) also reported on thermal springs in this region as part of an overall study of thermal waters in Utah.

Whelan and Petersen (1974) discuss the relationship of the location and depths of the deep brine wells with respect to the Wendover Graben (see Figure B-1). As suggested by Cook and others (1964), this graben trends southwest-northeast parallel to the Silver Island Range to the north. The graben is more than 56 km (35 mi) long and at least 16 km (10 mi) in maximum width. Beneath the salt crust, the graben is filled with lacustrine sediments underlain by fluvial sediments. At about 366 m (1200 ft), the deep brine wells described by Turk (1973) penetrated “hard rock” or “conglomerate” that Whelan and Petersen (1974) suggest may be volcanic breccia corresponding to volcanic rocks in the Silver Island Range.

INSERT FIGURE B-1

Temperature Profiles

Russ Draper of Intrepid Potash’s Wendover, Utah facility provided UGS geologists with access to six of Intrepid’s unused deep-brine wells. Temperature profiles (see Figure B-2) were recorded by UGS personnel (R. Blackett, M. Gwynn, and A. Rupke) using a high-precision thermistor probe and temperature logging equipment. The equipment consists of a thermistor probe linked to four-conductor cable on a reel in connection with a volt-ohm meter. Probe resistance is read from the volt-ohm meter, manually recorded and converted to temperature using a probe-specific polynomial determined by the manufacturer (Natural Progression Instruments, Olympia, Washington). Instrument characteristics and periodic calibrations result in a temperature measurement precision of 0.01°C (0.02°F). Temperatures were recorded at 5-m (16-ft) intervals in the six deep brine wells with a total of 1130 m (3706 ft) of borehole length recorded. Bottom-hole temperatures ranged from 15 to 44°C (59 to 111°F) in boreholes ranging from 85 to 410 m (279 to 1345 ft) depth (see Table B-1). All wells were completed with surface casing of approximately 43 cm (17-in) diameter with a production casing of about 18.4 cm (7.25‑in) diameter. Shallow temperatures recorded above the static water levels (in air) depict negative thermal gradients downward to the static water level in all wells. Below the static water level (in most cases) temperature-depth profiles reverse becoming positive.

INSERT FIGURE B-2

Table B-1. Summary of Intrepid Potash’s “deep brine wells” near Wendover, Utah. Temperature profiles were measured in June 2011.

| **Name** | **Latitude** | **Longitude** | **Location** | **Datum** | **Elev. (m)** | **Date** | **Depth (m)** | **Bht (°C)** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 1-2 Harvest | 40.7237 | -113.9797 | (C-01-19)23cbc | NAD83 | 1286.0 | 6/22/2011 | 90.0 | 15.0 |
| DBW8 | 40.6834 | -113.9955 | (C-02-19)03bcd | NAD83 | 1285.0 | 6/23/2011 | 240.0 | 24.2 |
| DBW14A | 40.6770 | -113.9791 | (C-02-19)02ccc | NAD83 | 1285.0 | 6/22/2011 | 200.0 | 21.6 |
| DBW17 | 40.6569 | -113.9654 | (C-02-19)14adb | NAD83 | 1285.0 | 6/22/2011 | 410.0 | 43.9 |
| DBW22 | 40.6907 | -113.9914 | (C-01-19)34cdd | NAD83 | 1285.0 | 6/23/2011 | 105.0 | 16.4 |
| DBW23 | 40.7040 | -113.9861 | (C-01-19)34aba | NAD83 | 1285.0 | 6/23/2011 | 85.0 | 15.2 |

The following paragraphs summarize the temperature logging within Intrepid’s deep brine wells. The locations of the wells are shown on Figure B-1. Russ Draper (Intrepid) reported that he thought that all of the wells were originally completed to about 400 m (1300 ft). However, since the wells had not been used in a number of years, we found that only DBW-17 was open to the original total depth of about 410 m (1345 ft).

*1-2 Harvest:* A blockage was encountered in this well at 90 m (295 ft) depth, stopping the temperature probe. The bottom-hole temperature (BHT) recorded was 15.0°C (59°F). The temperature profile is nearly isothermal to probe depth. A driller’s log was not available for this well. Static water level was 11.7 m (38.4 ft) depth.

*DBW-8:* Temperatures in this well were measured to 240 m (787 ft) where a blockage was encountered. The bottom-hole temperature (BHT) was 24.2°C (75.5°F). The thermal gradient between 100–200 m (328–656 ft) is about 57°C/km (3.13°F/100 ft). Turk (1973) shows a driller’s log for DBW-8 extending to 343 m (1126 ft) depth, encountering alternating layers of clay and gypsum to a depth of about 283 m (930 ft). At this depth, the drillers encountered mainly “gravel” and “conglomerate.” Static water level was at a depth of 14.3 m (46.9 ft).

*DBW-14A:* Temperatures were measured in this well to a depth of 200 m (656 ft) where the probe became stuck. The profile reveals a conductive gradient from about 50 m (164 ft) to about 200 m (656 ft) depth where a temperature of 21.6°C (70.8°F) was measured. A driller’s log was not available for this well. Static water level was 7.25 m (23.8 ft) depth.

*DBW-17:* Temperatures were measured in DBW-17 to 410 m (1345 ft), where the BHT was 43.9°C (111°F). A drillers log was not available for this well, however, DBW-17 is near DBW-1, which was completed in 1943 (Turk, 1973) to a depth of 366 m (1200 ft). DBW-1 reportedly encountered mostly clay, gypsum, and sand to 356 m (1168 ft), apparently entering black volcanic rock at that depth. The temperature profile from the interval 320–385 m (1050–1263 ft) of the bottom part of the well yields an approximate thermal gradient of 70°C/km (3.9°F/100 ft). Static water level was 26.5 m (86.9 ft) depth. Changes in thermal gradients above the valley-fill/bedrock contact (about 350 m) may be due to higher thermal-conductivity layers of salt interbedded with lower thermal-conductivity layers of clay and silt.

*DBW-22:* A blockage was encountered in this well at about 105 m (345 ft) depth where a BHT of 16.4°C (61.6°F) was measured. The temperature profile to that depth was nearly isothermal. Static water level was 15.5 m (50.9 ft) depth.

*DBW-23:* A blockage was encountered in this well at about 85 m (279 ft) depth where a BHT of 15.2°C (59.4°F) was measured. The temperature profile to that depth was nearly isothermal. Static water level was 8.1 m (26.6 ft) depth.

Whelan and Petersen (1974) describe the lithologies penetrated in Shell Oil Salduro #1 exploratory well drilled in 1956 (see Figure B-1). The well was drilled to 900 m (2950 ft) penetrating typical lacustrine clay, gypsum, and limestone to about 410 m (1350 ft). From this point the well continued through “conglomerate” to 490 m (1610 ft), followed by a sequence of “volcanic breccia” with alternating beds of clay/tuff. The well then entered basalt at about 835 m (2740 ft). “Microgabbro” was described at 863 m (2830 ft) and the well was bottomed in dark igneous rock described as “olivine augite diabase”. Records from the Utah Division of Oil, Gas, and Mining (DOGM) indicate an uncorrected maximum recorded temperature (or BHT) of 56°C (133°F) for the Salduro #1 well and 68°C (154°F) for the Alpha Gov’t #1 well. Corrected BHTs of 61°C (142°F) at 899 m (2950 ft) and 73°C (163°F) at 1302 m (4720 ft) were computed for the Salduro #1 and Alpha Gov’t #1 wells, respectively (M. Gwynn, written communication, November 2011). See the plotted values on Figure B-2. Note that these corrected BHTs are rough estimates by adding 5°C/km (0.27°F/100 ft) to the uncorrected value, considering typical conditions. No information about bottom-hole mud circulation times (time when the temperature measurement was recorded versus time when circulation stopped) was available on the log headers. We estimate the uncertainty associated with these corrected temperatures at ± 5°C.

Summary

Based on temperature profiles from six deep brine wells located on Intrepid Potash’s property near Wendover, Utah, subsurface temperatures appear elevated and suggest that hydrothermal fluids circulate to relatively shallow depths, possibly along faults marginal to the Wendover graben. A down-hole temperature of 88°C (190°F) at 499 m (1637 ft) was reported by Turk (1973) in well DBW-3, located less than 5 km (3 mi) west of the southern tract of the UTTR. Down-hole temperature data from other deep brine wells owned by Intrepid Potash also suggest that temperatures appear to increase southeastward toward the west side of the southern tract of the UTTR. The highest temperature recorded in wells measured as part of this study was a bottom-hole temperature of 43.9°C (111°F) measured at 410 m (1345 ft) depth in well DBW‑17. The temperature profile from the interval 320–385 m (1050–1263 ft) of the bottom part of the well yields an approximate thermal gradient of 70°C/km (3.9°F/100 ft).

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Figure Captions

Figure B-1. Map showing locations of deep brine wells and other wells at Intrepid Potash, Inc. Wendover, Utah operations.

Figure B-2. Temperature-depth profiles of some of Intrepid Potash, Inc. deep brine wells near Wendover, Utah. Profiles measured by UGS personnel on 22 and 23 June 2011. Reported BHT value for DBW-3 (Turk, 1974), and corrected BHT values for the Shell Oil Salduro #1 and the Alpha Gov’t #1 oil/gas exploratory wells are shown for reference.

Appendix C  
  
Lineament Study

Clay Grant Jones, Richard Smith, Beth Murphy, and Greg Nash

Introduction

Fault/lineament mapping on Hill Air Force Base Bombing-Range was done using high resolution NAIP (National Agricultural Imagery Program) imagery as a mapping base. Mapping was done using ESRI ArcGIS 10.0 producing an output shapefile (see Figure C-1). The NAIP imagery helped in the identification of linear vegetation anomalies and aligned springs that are generally related to faults.

INSERT FIGURE C-1

ArcGIS Explorer was used to visualize the imagery in 3-D (Figure C-2). This helped facilitate the identification of geomorphic features that are related to faults such as rotated blocks and faceting along range-fronts.

INSERT FIGURE C-2

Field work was conducted on October 25 and 26, 2011, to validate faults and lineaments mapped from imagery. When discussing particular fault lineaments reference will be made to the numbers shown in Figure C-3.

INSERT FIGURE C-3

Lineaments 1 and 2

Expressions of lineaments 1 & 2 were not observed. The area was traversed multiple times in zig-zag pattern via truck in an attempt to locate any linear features. The area was covered by light colored mud and randomly interspersed vegetation, and cut by several shallow dry washes with meandering to braded channels in a direction parallel to sub- parallel with the lineaments in Figure 3. These channels may represent the surface expression of a concealed fault or faults. However, the physical evidence is weak.

Lineaments 3 to 6

Lineaments 3, 4, 5 and 6 are in the vicinity of a spring known as Mosquito Willey’s. Spring fed pools were found at 2 locations. The northern spring (see Figures C-4 and C-7) was warm to the touch. The southern spring was found to be at roughly ambient temperature (day time high on Oct 25 ~50°F). Outcrops immediately to the west of these two springs consisted of brecciated limestone cemented by secondary calcite (see Figure C-5), with minor hematite staining. The outcrop is draped by a calcite cemented conglomerate (see Figure C-6), which consists of poorly-sorted and angular limestone clasts up to several feet in diameter, many of which are also brecciated. This may have been a deposit derived from the footwall of a normal fault scarp cemented by calcite precipitating from spring waters discharging into paleo Lake Bonneville. Near where the springs emanate there are thin (a couple of feet thick) white, botryoidal calcite deposits (see Figure C-7). These springs and the outcrop are located roughly between the southern termination of lineament #3 and the northern extension of #5.

INSERT FIGURE C-4

INSERT FIGURE C-5

INSERT FIGURE C-6

INSERT FIGURE C-7

No expression of lineament #3 could be seen from the top of the outcrop west of Mosquito Willey’s. Several sandy mounds that appeared to trend to the N-to-NE in roughly the same direction as mapped lineament #3 are present, but these are likely to be lakeshore or aeolian deposits (see Figure C-8).

INSERT FIGURE C-8

No surface expression was found of lineament #4, which is mapped as bisecting a NW-SE trending topographic feature, on the SE edge of which is Mosquito Willey’s (see Figure C-9). The lineament runs perpendicular to this feature, but offset was observed in the outcrop.

INSERT FIGURE C-9

A limestone outcrop was investigated in the vicinity of lineament #5, south of Mosquito Willey’s. Here limestone beds with brown chert nodules dip nearly 90°. Outcrops near Mosquito Willey’s (between the southern termination of lineament #3 and the northern extension of #5, as above) had nearly horizontal bedding. This outcrop is extensively brecciated, but less so at than Mosquito Willey’s. Several shear zones (see Figure C-10) were observed as well as botryoidal calcite deposits (see Figure C-11).

INSERT FIGURE C-10

INSERT FIGURE C-11

Lineament #6 followed the base of a NW-to-SE trending fin of limestone (see Figures C-12 and C-13). Areas of intense brecciation were observed in the limestone (see Figures C-14 and C‑15). Botryoidal calcite deposits, most likely consisting of Lake Bonneville tufa, were seen filling fractures and coating the entire outcrop from base to top (see Figures C-16 and C-17). To the NE of the limestone fin there was a break in slope that could potentially be due to faulting; alternatively it could be an eroded paleo lake terrace (see Figure C-13).

INSERT FIGURE C-12

INSERT FIGURE C-13

INSERT FIGURE C-14

INSERT FIGURE C-15

INSERT FIGURE C-16

INSERT FIGURE C-17

Lineament 7

Lineament #7 trends SW-to-NE. Near the lineaments NE end it crosses in front of a mesa with a large planar face (see Figure C-18), which appears to be roughly parallel with the lineament. The lineament was crossed twice on a dirt road which stayed within several hundred meters of the mapped lineament for about two kilometers. No linear break in slope was observed. The area is covered by lake deposits. There was a vegetation change which roughly followed the same trend. The vegetation change was marked by grass on the NW to brush on the SE (see Figure C-19).

INSERT FIGURE C-18

INSERT FIGURE C-19

Lineament 8

Lineament #8 crosses a saddle between two topographic highs (see Figure C-20). A paleo lake shore can be correlated from one side to the other, indicating that there hasn’t been any offset in the recent past (see Figure C-21). In addition, it appears that a thick band of limestone can be correlated across the saddle, consistent with the conclusion that there is no offset across the lineament.

INSERT FIGURE C-20

INSERT FIGURE C-21

Lineaments 9 and 10

Lineament #9 follows the northern and eastern edges of a topographic feature called Rocky Point (see Figure C-22). Lineament #10 cuts through a saddle roughly perpendicular to lineament #9 (see Figure C-23). There is no offset of the lake shore terrace between the topographic highs to either side of the saddle, and a thicker band of limestone outcrops above the terrace on both sides suggesting that there has been little to no movement. Limestone outcrops on the lower reaches of rocky point were extensively brecciated (see Figure C-24) and sheared. Botryoidal calcite deposits were observed filling fractures as well as deposited on the exterior of the limestone outcrops. Minor calcite cemented conglomerate deposits composed of locally derived limestone clasts were also observed (see Figure C-25).

INSERT FIGURE C-22

INSERT FIGURE C-23

INSERT FIGURE C-24

INSERT FIGURE C-25

Lineament 11

Lineament #11 cut across some low foothills (see Figure C-26). No linear trending topographic feature was observed, and the outcrops examined near the mapped lineament showed little to no evidence of tectonic influence (see Figure C-27). However, this fault is present in the U.S.G.S. Quaternary fault database and labeled as “Unnamed fault zone in Ferber Hills.”

INSERT FIGURE C-26

INSERT FIGURE C-27

Lineament 12

No expression of lineament #12 was observed in a bicycle traverse of the area from west to east and back again. Lineament #13was not checked. The area was fairly densely vegetated but also very flat (see Figure C-28). A vegetation anomaly (vegetation on one side but not the other) is seen on the NAIP imagery along the northern part of lineament #12. Changes in drainage direction are also present along these lineaments, although not consistently.

INSERT FIGURE C-28

Lineaments 13-22 Not Examined

These areas were not examined due to time (#19–#22), vehicle (#14) and access (#15–#18) constraints.

Figure Captions

Figure C-1. NAIP image overlain with faults/lineaments in the Blue Lake area south of Wendover, Utah.

Figure C-2. 3-D rendering of the Blue Lake area from ArcGIS Explorer.

Figure C-3. Map of study area. Hill shaded digital elevation model displays topographic lows as white and highs as black. US Air Force property is cross-hatched in blue. Major roads, I-80 and Nevada State Road 93 are displayed as black lines. The location of the towns of Wendover, Utah and Nevada are marked with a red circle. Fault lineaments are shown as red lines, with corresponding red numbers. See text for a discussion of the lineaments.

Figure C-4. Northern warm spring fed pool at Mosquito Willey’s. Vegetation in the upper left portion of the picture shows the path taken by the waters emanating from the southern spring.

Figure C-5. Extensively brecciated limestone cut by a dense network of calcite veins near the warm spring at Mosquito Willey's.

Figure C-6. Calcite cemented conglomerate composed of locally derived limestone clasts deposited on a brecciated limestone outcrop cut by calcite veins. This outcrop is located to the photographers left in Figure C-2.

Figure C-7. White botryoidal calcite deposit adjacent to the northern warm spring at Mosquito Willey’s.

Figure C-8. Looking to the N from the vicinity of lineament #3. The terrain is relatively flat although a few low sandy hills are present. Springs feeding Blue Lake discharge at the break in slope indicated by the white arrow.

Figure C-9. Looking S-to-SW from the vicinity of lineament #3 toward the NW-to-SE trending outcrop. The springs of Mosquiot Willy’s emanate from the SE end of the outcrop. from the SE portion of which emanate the springs of Mosquito Willey’s. Lineament #4 runs roughly perpendicular to this outcrop. No offset was observed.

Figure C-10. Shear zone in a limestone outcrop in the vicinity of lineament #6.

Figure C-11. White botryoidal calcite deposit at the base of a limestone outcrop in the vicinity of lineament #6. The limestone contains dark brown chert nodules.

Figure C-12. Lineament #6 follows the base of this NW-SE trending limestone fin.

Figure C-13. Looking SE along lineament #6 as it follows the base of this NW-SE trending limestone fin. Note the breaks in slope.

Figure C-14. Extensively brecciated limestone in the vicinity of lineament #6. The outcrop is approximately 2 m in height.

Figure C-15. Brecciated limestone cemented by calcite.

Figure C-16. Botryoidal calcite deposits filling a fracture in a limestone outcrop.

Figure C-17. Light colored botryoidal calcite deposits coating the entire height of the limestone fin. The outcrop is roughly 10 m tall.

Figure C-18. Looking north toward a steep trapezoidal planar slope face that is roughly parallel to lineament #7. Lineament #7 crosses the picture between the spot the photo was taken and the distant slope. No topographic feature was observed.

Figure C-19. Change in vegetation that roughly parallels lineament #7. Looking to the SE from near the bottom of the planar slope face shown at the far right of figure C-16.

Figure C-20. Looking to the SW where lineament 8 crosses through the saddle (white arrow).

Figure C-21. Looking to the N at a lake shore terrace that can be seen running from the west (left) to east (right) across the image (yellow arrow). Lineament #7 runs in from of the planar face shown in figure C-16 (at the far right). Lineament #8 cuts through the saddle shown by the white arrow. There is no offset between the lake terraces.

Figure C-22. Northern edge of ‘Rocky Point’ associated with lineament #9. The lineament follows this feature around to the east (left).

Figure C-23. Lineament #10 cuts through the saddle perpendicular to lineament #9 which runs along the base. A lake terrace can be correlated from one side to the other demonstrating that there hasn’t been any offset since the lake level was last at this height. A thick band of limestone is also found just above the lake terrace on both sides of the saddle.

Figure C-24. Brecciated limestone cut by calcite veins, with a small piece of light colored botryoidal calcite on the exterior of this outcrop near lineament #9.

Figure C-25. Calcite-cemented conglomerate found in outcrop near lineament #9.

Figure C-26. Looking SW at where lineament #14 was mapped crossing in front of the foothills running from the NW (right) to the SE (left).

Figure C-27. Outcrop in the vicinity of lineament #14, which showed little evidence of tectonism.

Figure C-28. Vicinity of lineament 12 which was flat and densely vegetated.

Appendix D  
  
Analysis of Borehole  
Geophysical Logs of Existing Wells

Dan Brinton, John McLennan and Richard Smith

Abstract

Borehole geophysical well logs, various descriptive logs (e.g., sample description logs, mud logs, core descriptions, and formation tops) and well files were obtained from the area near Focus Area 1. The data were used to estimate porosity, water saturation and matrix permeability of the subsurface. The results of the analyses indicate that porosity in the shallow Cenozoic rocks show average porosities between 16 and 35%. Permeabilities in the Cenozoic rocks are typically greater than 100 mD, with the highest values exceeding 10 D. Calculated permeabilities greater than 1 D are not considered reliable but suggest that permeabilities throughout the Cenozoic section are high. Porosity and permeability in the Paleozoic rocks vary with depth. In the Paleozoic section above 3500 ft, porosities range up to 15% with permeabilities ranging up to 70 mD. Below 3500 ft, porosities are typically less than 10% and permeabilities less than 10 mD.

Data Acquisition and Selection

Seven oil and gas wells were identified within approximately 30 miles of the center of Focus Area 1 and were evaluated as part of this study. Table D-1 lists the seven wells with their API numbers and common names. Figure D-1 shows the locations of the seven oil and gas wells in relation to Focus Area 1, which is outlined in red. Further information, including Township/Range/Section location description, latitude and longitude coordinates and logs available for the various wells are tabulated in Attachment D-1.

Table D-1. List of seven oil and gas wells within approximately 30 miles of Focus Area 1..

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **API No.** | **State** | **County** | **Operator** | **Well Name** |
| 27-007-05001 | Nevada | Elko | Western Osage Oil, Inc. | Government No. 1 |
| 27-007-05002 | Nevada | Elko | Last Frontier Oil Co. | Government No. 1 |
| 27-007-05012 | Nevada | Elko | Gulf Oil Corp. of California | Owl Hill Federal No. 1 |
| 27-007-05207 | Nevada | Elko | Shell Oil Co. | Goshute Unit No. 1 |
| 27-033-05007 | Nevada | White Pine | Gulf Refining Co. | Dennison-Federal No. 1 |
| 43-045-11076 | Utah | Tooele | Swepi/Western Division | Salduro No. 1 |
| 43-045-30001 | Utah | Tooele | Alpha Minerals | Alpha Govt. No. 1 |

INSERT FIGURE D-1

The GeoGraphix DiscoveryTM suite of programs was used for the management and interpretation of well log data. The GeoGraphix WellBaseTM database was populated with the header information of the seven wells. Borehole geophysical logs were acquired from the Utah Division of Oil, Gas and Mining (2011) and the Nevada Bureau of Mines and Geology (Hess, 2011) in TIF image format. The logs were then digitized using NeuraLog. The digitized logs were exported in log ASCII standard (LAS) format and imported into GeoGraphix PRIZMTM, the well log analysis tool in the GeoGraphix DiscoveryTM suite. Mudlogs, sample descriptions, formation tops, etc. were also imported into GeoGraphix.

Well Data Sets

Well 43-045-30001 is located approximately 2.4 miles south of Interstate 80 and 14.7 miles east of the Utah/Nevada state line in Section 34 of Township 1 south, Range 17 west, Salt Lake Base and Meridian. Ground elevation is 4222 ft. The well was drilled by Alpha Minerals, Inc. between December 23, 1975 and January 12, 1976 to a total depth of 4260 ft. Borehole geophysical logs were generated. Prints of these logs and a sample description log were obtained from the Utah DOGM.

The well file indicates that the shallow portion of well 43-045-30001 penetrates lake sediments and alluvial conglomerate rocks believed to be of Quaternary age at its shallowest depths followed by Tertiary volcanic rocks at 500 ft and Tertiary shale at 1128 ft. Based on the sample description and geophysical logs, the well appears to penetrate Paleozoic rocks near 3000 ft. The sample description log indicates a transition from mostly shale with some interbedded limestone in the shallow portion of the well to dolomite and limestone below 3000 ft. Additionally, the caliper log shows that the borehole is severely out of gauge between 1900 and 2750 ft; below 2800 ft, the caliper log shows only thin intervals where the borehole is out of gauge. Density and acoustic logs show a significant change from low density, high porosity rocks to high density, low porosity rocks at approximately 2970 ft. The well file contains documents that place the top of the Paleozoic rocks at either 2970 or 2980 ft. Bottom hole temperatures from the well log headers range from 148 to 153 °F.

Well 43-045-11076 is located approximately 7.0 miles west southwest of well 43-045-30001, 3.8 miles south of Interstate 80 and 7.8 miles east of the Utah/Nevada state line in Section 4 of Township 2 south, Range 18 west, Salt Lake Base and Meridian. Ground elevation at the site is 4216 ft. The well was drilled by Shell Oil beginning June 30, 1956 and reached a total depth of 2950 ft on July 9, 1956. Borehole geophysical logs were run and the well was then plugged and abandoned on July 11, 1956. The well log headers list the bottom hole temperature to be 132 °F.

Wells 43-045-30001 and 43-045-11076 are on opposite sides of an interpreted normal fault, with well 43-045-11076 located on what would be the down-thrown side (Smith, 2011). An interval between 1450 and 1950 ft depth in well 43-045-11076, characterized by elevated gamma ray log values appears to be correlative with an interval between 500 and 1150 ft depth in well 43-045-30001, characterized by similarly elevated gamma ray log values.

Wells 27-007-05001 and 27-007-05002 are located within approximately one-half mile of one another, about 13.6 miles south southwest of Wendover, Nevada in Sections 14 and 23, respectively, of Township 31 north, Range 69 east, Mt. Diablo Base and Meridian. The wells were drilled in the early to mid 1950s and information on their completions is scarce. The exact depth of well 27-007-05001 is not known but is thought to be about 785 ft, likely reaching to near the top of the Paleozoic rocks. Well 27-007-05002 was drilled to a total depth of 1327 ft and is said to have intersected Permian rocks at 590 ft followed by Pennsylvanian rocks at 1000 ft. A sample description log of this well is available; however no geophysical logs were run in either well.

Well 27-007-05012 was spudded on August 5, 1963 and is located approximately 30.4 miles south south-west of Wendover, Nevada in Section 18, Township 28 north, Range 70 east, Mt. Diablo Base and Meridian. Ground elevation is approximately 5600 ft. Drilling was completed on August 31, 1963 after reaching a total depth of 1546 ft. A limited number of borehole logs were run to 1100 ft and no sample description logs or formation tops are available. Well log headers indicate that the temperature at 1100 ft depth is 86 °F. The caliper log shows that the borehole was frequently out of gauge below about 700 ft. The Nevada Oil and Gas Database indicates that the Mississippian Scotty Wash formation was penetrated at 562 ft.

Well 27-033-05007 is located about 43.4 miles south of Wendover, Nevada in Section 20, Township 26 north, Range 70 east, Mt. Diablo Base and Meridian. Ground level at the site is 5504 ft. Drilling by Gulf Refining Company began on October 24, 1953 and concluded on March 1, 1954 after having reached a total depth of 4498 ft. Borehole geophysical logs were run and a formation top record is available covering the entire depth of the well. Bottom hole temperature from the well log headers is listed as 120 °F. According to the formation top record, the Permian Gerster-Phosphoria formation was penetrated at 2215 ft.

Well 27-007-05207 lies 22.2 miles to the west south-west of Wendover, Nevada in Section 19, Township 32 north, Range 67 east, Mt. Diablo Base and Meridian. Ground elevation is approximately 5600 ft. Drilling commenced on January 30, 1976 and continued to a total depth of 5569 ft before the well was abandoned on February 27, 1976. The well file contains a sample description log and a borehole log suite that is extensive in comparison with the other wells discussed. The Nevada Oil and Gas Well Database indicates that the well penetrated Permian rocks at 5280 ft. The well log headers indicate that the bottom hole temperature is 140 °F.

While well 27-007-05207 is somewhat closer to the center of Focus Area 1 than well 27-033-05007, it is located in Goshute Valley on the west side of the Toano Range (Focus Area 1 and other wells discussed are on the east side of the Toano Range). The geology of Goshute Valley is considered distinct from that of the area surrounding Focus Area 1 and the decision was therefore made to exclude well 27-007-05207 from further analysis and discussion.

Table D-2 contains the ground elevation, depth of the top of the Paleozoic rocks, well total depth and bottom hole temperatures for the seven wells just discussed. Bottom hole temperatures are affected by the drilling process as formation rock is cooled by circulating drilling fluid. These temperatures can be corrected for the affects of cooling during the drilling process but no such corrections were attempted in the present study.

Table D-2. Ground elevations, tops of the Paleozoic rocks, total depth and bottom hole temperatures recorded in oil and gas wells near Focus Area 1.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Well** | **Ground Elevation (ft)** | **Top of Paleozoic**  **(ft)** | **Total Depth**  **(ft)** | **Bottom Hole Temp.**  **(°F)** |
| 27-007-05001 | ? | ? | 785 | ? |
| 27-007-05002 | ? | 590 (Permian) | 1327 | ? |
| 27-007-05012 | 5600 | 562 (Mississippian) | 1546 | 86 (@ 1100 ft) |
| 27-007-05207 | 5600 | 5280 (Permian) | 5569 | 140 (@ 5434 ft) |
| 27-033-05007 | 5504 | 2215 (Permian) | 4498 | 120 |
| 43-045-11076 | 4216 | N/A | 2950 | 132 |
| 43-045-30001 | 4222 | 2970 | 4260 | 148-153 |

Analysis of Well 43-045-30001

Methodology

Well logs from well 43-045-30001 were analyzed to estimate the porosity, water saturation and permeability of potential reservoir rocks in the area surrounding Focus Area 1.

Porosity

Matrix density and sonic wave travel time values were selected for individual intervals based on the lithologies identified in the sample description log of well 43-045-30001. Porosities (density porosity and sonic porosity) of the well were calculated according to the porosity equations given in Table D-3. In the Cenozoic section, non-carbonate rocks were assigned the matrix density of sandstone. The only exceptions were intervals characterized as volcanic rocks and shales. All rock intervals described as volcanic were assigned a matrix density between that of andesite and basalt. In intervals characterized in the sample description log as shales, rock matrix properties of intervals immediately above were used in the porosity equations. Porosity equation rock matrix parameters (matrix density, *ρma*, and acoustic wave travel time, *Δtma*) are listed in Table D-4.

Table D-3. Porosity equations used in estimating sonic and density porosity (Asquith, 1983).

|  |  |  |
| --- | --- | --- |
| Porosity Type | Equation | Eq. No. |
|
| Density |  | (1) |
| Sonic |  | (2) |
| * Fluid properties: ρfld = 1.00 g/cc; Δtfld = 189 μs/ft * ρB is the bulk density read from the density log. * Δt is the acoustic wave travel time read from the acoustic log. | | |

Table 4. Rock matrix parameters used in porosity equations.

|  |  |  |  |
| --- | --- | --- | --- |
| Age | Lithology | Density, ρma  (g/cc) | Acoustic Wave Travel Time, Δtma  (μs/ft) |
| Cenozoic | Conglomerate | 2.65 |  |
| Claystone | 2.65 |  |
| Chert | 2.65 |  |
| Dolomite | 2.876 | 43.5 |
| Limestone | 2.71 | 47.6 |
| Mudstone | 2.65 |  |
| Sandstone | 2.65 | 53.5 |
| Siltstone | 2.65 |  |
| Volcanic | 2.8 |  |
| Paleozoic | Dolomite | 2.876 | 43.5 |
| Gypsum | 2.317 | 52.4 |
| Limestone | 2.793 | 47.6 |
| Sandstone | 2.65 | 53.5 |

Shale Volume

The presence of shale can result in the sonic and density logs predicting porosities that are artificially high. Modified porosity equations that account for the shale volume can be used to give more realistic estimations of porosity if the shale volume is known.

Shale volume is typically estimated from 1) the gamma ray log; 2) the spontaneous potential (SP) log; and, 3) the neutron-density porosity log. It is common for shale volume to be estimated using each of the three methods and the minimum of the three taken as the actual shale volume for any given depth (Hilchie, 1982). No neutron log was available for well 43-045-30001; thus the shale volume was calculated from the gamma ray and SP logs.

In order to calculate the shale volume based on the gamma ray log, the gamma ray index is first calculated. The gamma ray index, IGR, (Equation 3) is the gamma ray value normalized by the difference between the gamma ray values of shale and clean intervals (Schlumberger, 1974):

|  |  |  |
| --- | --- | --- |
|  |  | (3) |

where GRmax is the gamma ray value in a shale bed and GRmin is the gamma ray value in a shale-free interval and GRlog is the reported gamma ray value at a particular depth. GRmax was taken as the average gamma ray value in the interval from 3144 to 3146 ft; GRmin was taken as the average in the interval from 3852 to 3864 ft.

The gamma ray index can itself be taken as the shale volume; however, Equation 4 (Dresser Atlas, 1979) provides improved accuracy by accounting for rock age and consolidation.

|  |  |  |
| --- | --- | --- |
|  | C1 = 0.33; C2 = 2 for older, consolidated rocks  C1 = 0.083; C2 = 3.7 for Tertiary, unconsolidated rocks | (4) |

The shale volume from the SP is calculated according to Equation 5 (Asquith, 1983):

|  |  |  |
| --- | --- | --- |
|  |  | (5) |

The static spontaneous potential (SSP) is the SP value read from the SP log in a thick, shale-free formation and represents the largest divergence of the SP log curve from the shale baseline. The pseudostatic spontaneous potential (PSP) is the SP of a shaly formation. For the current calculations, SSP was identified as the average SP value from 3862 to 3866 ft. That SSP value was used in shale volume calculations throughout the well.

SP curves tend to drift due to calibration problems or borehole conditions. Therefore, before the shale volume was calculated based on the SP curve, a baseline correction was performed in GeoGraphix PRIZMTM utilizing a tool specifically designed for that purpose. Figure D-2 is a screen shot from PRIZMTM showing the original SP curve in blue and the new baseline imposed on the data in red. The new baseline (the so-called shale baseline) is the zero point for the SP curve and all SP values are read relative to it.

SP logs are also affected by thin beds. Corrections can be applied to account for thin bed effects, but no such corrections were applied in the present analysis. After the baseline correction operation was performed, SSP was identified and the volume of shale was calculated from the SP log as described in Equation 5.

In some intervals, the gamma ray and SP logs predict widely different shale volumes. Additionally, the character of the two curves sometimes oppose one another; the gamma ray shows an increase in shale volume while the SP shows a decrease in shale volume in a particular interval, for example. This is especially true in the shallow portions of the well. The agreement between methods is much better in the deeper portions of the well.

When the shale volume calculated using either method was greater than 100%, the maximum value of 100% was imposed. Similarly, when the calculated shale volume was less than 0%, the minimum value of 0% was imposed. In this study, the shale volume at any given depth in the well was taken as the lesser of the gamma ray- and SP-derived shale volumes. The only exception is intervals of volcanic rock. The behavior of SP and gamma ray logs is not well documented in igneous rocks. As such, shale volume was not calculated and, for the sake of further calculations, is assumed to be zero in volcanic rock intervals.

Shale Volume-Corrected Porosity

Density and sonic porosities were corrected for the shale volume according to the equations given in Table D-5 (Dresser Atlas, 1979). Hilchie suggests that shale only begins to affect log values when the shale content is greater than 10 to 15% (Hilchie, 1982). Accordingly, the corrections were applied only where the shale volume is estimated to be greater than 10%. Shale properties (density and acoustic wave travel time) used in Equations 6 and 7 and listed in Table D-5 were taken as the average density log value and the average acoustic wave travel time value recorded between 1135 and 1140 ft for the Cenozoic section and between 3143 and 3145 ft for the Paleozoic section. These properties were used in various calculations throughout the depth of the well.

Table D-5. Equations and parameter values used in calculating sonic and density porosity corrected for shale effects.

|  |  |  |
| --- | --- | --- |
| Porosity Type | Equation | Eq. No. |
| Density (corrected for shale volume) |  | (6) |
| Sonic  (corrected for shale volume) |  | (7) |
| * See Tables 3 and 4 for definitions and parameter values. * Vshl is the shale volume calculated from either the gamma ray or SP logs * Cenozoic shale properties: ρshl = 2.403 g/cc; Δtshl = 59.998 μs/ft * Paleozoic shale properties: ρshl = 2.574 g/cc; Δtshl = 83.216 μs/ft | | |

Shale volume-corrected porosity should always be less than uncorrected porosity since shale causes porosity to calculate erroneously high. In some intervals, the shale volume-corrected sonic porosity was greater than the uncorrected porosity. This is likely due to the non-uniform nature of shale properties and the value of Δtshl used. Where the shale volume-corrected porosity calculated to be greater than the uncorrected porosity, the corrected porosity was discarded. Additionally, as discussed previously, shale volume was not calculated in volcanic rock intervals and therefore, in those intervals, the shale volume-corrected porosity is assumed equal to the uncorrected porosity. Shale volume-corrected density porosity calculated according to Equation 6 was used in all further calculations.

Formation Temperature

The only temperature information available from well 43-045-30001 were bottom hole temperatures recorded on the headers of the various log prints (see Table D-2). The maximum recorded bottom hole temperature in the well was used to define the temperature gradient in the well. Temperature over the depth of the well was determined by linear interpolation between the bottom hole temperature and the assumed surface temperature. As stated previously, no attempt was made to correct the bottom hole temperature for the affects of cooling during drilling.

Formation Water Resistivity

The well file identifies broadly-defined formations. These formations are listed in Table D-6 with their depths and short descriptions of rock type. Formation water resistivity was calculated for each of the formations individually. Geophysical log data is available only below approximately 470 ft. Therefore, formation water resistivities were calculated only in those formations falling below that depth. Within each formation, water chemistry was assumed to be constant and water resistivity was therefore allowed to vary only with temperature within each formation.

Table D-6. Formations identified in the well file.

|  |  |
| --- | --- |
| Description | Depths |
| Lake Sediments | 0-450 |
| Alluvial deposit: conglomerate | 450-500 |
| Volcanic Rocks | 500-1128 |
| Tertiary Shale | 1128-1570 |
| Tertiary Shale | 1570-2970 |
| Paleozoic Carbonates | 2970-4270 |

Formation water resistivity was calculated using three different methods. The first method used is an algorithm put forth by Enikanselu and Adekanle (2008). Their algorithm is an adaptation of the method proposed by Bateman and Konen (1978) which allows formation water resistivity to be calculated based on the SP log. The method requires the use of SSP and allows for the correction of SSP in thin beds.

Intervals were selected from each formation and the formation water resistivity was calculated using data from those intervals. Formation temperature was also taken from those intervals. Table D-7 gives the results of the calculations and the intervals from which data was taken in each of the formations for the calculation of formation water resistivity by the SP method. While the formation between 500 and 1128 ft is mostly volcanic rock, the calculation of formation water resistivity was performed using data from a limestone interval.

Table D-7. Results of formation water resistivity calculations by the SP method.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Description | Depths  (ft) | Data Interval  (ft) | Rw  (ohm-m) | Temp  (°F) |
| Volcanic Rocks | 500-1128 | 580-590 | 0.093 | 72.7 |
| Tertiary Shale | 1128-1570 | 1382-1386 | 0.087 | 90.1 |
| Tertiary Shale | 1570-2970 | 1655-1665 | 0.083 | 96.2 |
| Paleozoic Carbonates | 2970-4270 | 3862-3866 | 0.017 | 144.2 |

Jorgensen (1989, 1990) presents an algorithm similar to that of Bateman and Konen (1978) and reports that the method is only accurate to within plus or minus one half an order of magnitude. He also notes, however, that formation water resistivity may vary over three orders of magnitude and, in the absence of any better information, the SP method can be used to predict Rw.

Formation water resistivity was also calculated using the so-called Rwa method. The apparent formation water resistivity, *Rwa*, can be calculated according to Equation 8 (Asquith, 1983):

|  |  |  |
| --- | --- | --- |
|  |  | (8) |

where *Rt* is the true formation resistivity and *F* is the formation factor. The formation factor is a function of rock type and porosity. The general form of the formation factor is (Asquith, 1983):

|  |  |  |
| --- | --- | --- |
|  |  | (9) |

where *a* is the tortuosity factor and *m* is the cementation factor. In clean, water-saturated intervals, Rw can be assumed equal to Rwa. However, Serra (1986) cautions that the results will be incorrect in the absence of water-bearing intervals, if the formation contains clay or if drilling fluids invade the formation deeply enough that they affect the measurement of true formation resistivity. Obviously, the results will be negatively affected by incorrect formation factor values.

The true formation resistivity, *Rt­*,was taken from the deep-reading induction log. Porosity was taken from estimated shale volume-corrected density porosity values. Standard values of the Archie equation parameters *a* and *m* (a=1; m=2) were used in the calculation. Table 8 gives the results of the calculations and the intervals from which data was taken in each of the formations for the calculation of formation water resistivity by the Rwa method. As stated previously, data for the formation water resistivity calculation in the volcanic rocks formation was taken from a limestone interval.

Table 8. Results of formation water resistivity calculations by the Rwa method.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Description | Depths  (ft) | Data Interval  (ft) | Rw  (ohm-m) | Temp  (°F) |
| Volcanic Rocks | 500-1128 | 580-590 | 0.087 | 72.7 |
| Tertiary Shale | 1128-1570 | 1382-1386 | 0.148 | 90.1 |
| Tertiary Shale | 1570-2970 | 1655-1665 | 0.131 | 96.2 |
| Paleozoic Carbonates | 2970-4270 | 3862-3866 | 0.016 | 144.2 |

Finally, formation water resistivity was calculated using the cross-plot method as outlined in Hilchie (1982) and Jorgensen (1989). Using this approach, porosity values are plotted over resistivity values on a log-log plot (see Figure D-3). A best fit line is drawn through the data and extrapolated to the 100% porosity line. The extrapolated line intersects the 100% porosity line at the formation water resistivity value. In the present work, shale volume-corrected density porosity and deep-reading induction log resistivity were used in the analysis. Porosities below 1% and formation resistivities above 1000 ohm-meters were excluded as were values from intervals where the borehole was enlarged and other intervals in which the validity of the density log was questioned.

Since the cross-plot method estimates formation water resistivity through a regression scheme, the resultant Rw value is a type of average over all the data points used in the analysis. However, the method assumes, among other things, that lithology is constant. Therefore, in each formation, only data from intervals of certain rock types were used. Other assumptions of the method include uniform water resistivity and 100% water saturation. Table D-9 contains the results of the calculations and also indicates the rock types involved in the analyses. The temperatures associated with each resistivity value are the average temperatures of the data included in the particular cross-plots and regression analyses.

Table D-9. Results of formation water resistivity calculations by the cross-plot method.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Description | Depths  (ft) | Rock Types Included | Rw  (ohm-m) | Temp  (°F) |
| Volcanic Rocks | 500-1128 | Sedimentsa | 0.063 | 75.8 |
| Tertiary Shale | 1128-1570 | Sedimentsa | 0.069 | 89.7 |
| Tertiary Shale | 1570-2970 | Sedimentsa | 0.044 | 96.2 |
| Paleozoic Carbonates | 2970-4270 | Carbonatesb | 0.011 | 138.7 |
| a) Sandstone, siltstone, mudstone, claystone, chert, and conglomerate  b) Dolomite and limestone | | | | |

The formation water resistivities calculated using the three methods were then extrapolated over varying formation temperature within each formation according the standard equation (Asquith, 1983):

|  |  |  |
| --- | --- | --- |
|  |  | (10) |

where *Rw,T1* is the formation water resistivity measured or calculated at a specific temperature *T1* and *Rw* is the formation water resistivity as a function of formation temperature, *Tf*.

A comparison of the results of the three methods shows relatively good agreement. In each case, formation water resistivity is allowed to vary with temperature only with each formation. Table 10 lists the average formation water resistivity within each formation.

Table D-10. Comparison of the results of Rw calculations from SP, Rwa and cross-plot methods.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Description | Depths (ft) | Average Rw by method (ohm-m) | | |
| SP | Rwa | Cross-plot |
| Volcanic Rocks | 500-1128 | 0.088 | 0.082 | 0.062 |
| Tertiary Shale | 1128-1570 | 0.087 | 0.145 | 0.068 |
| Tertiary Shale | 1570-2970 | 0.074 | 0.117 | 0.039 |
| Paleozoic Carbonates | 2970-4270 | 0.018 | 0.017 | 0.011 |

Of the results of the SP and Rwa methods, Serra (1986) states that the Rwa method is considered more accurate and indicates that the SP method should be used only as a last resort. However, both the SP and Rwa methods are sensitive to the selection of data from individual intervals with which to perform the calculations. The cross-plot method, however, gives an average value of Rw. Since the methods show relatively good agreement and since the average formation water resistivity within a formation provided by the cross-plot method may be preferable to results from limited intervals within the formations, the results of the cross-plot method will be used in all further calculations and analyses.

*Water Saturation*

Water saturation, *Sw*, was calculated using three different methods. First, water saturation was calculated using Equation 11, originally published by Schlumberger (1975) for use in shaly formations:

|  |  |  |
| --- | --- | --- |
|  |  | (11) |

where *Vshl* is shale volume, *Rshl* is formation resistivity of a shale bed, *Rw* is formation water resistivity, *Rt* is formation resistivity and *ϕ* is porosity. Shale volume was determined, as outlined previously, as the minimum shale volume predicted by the gamma ray and SP methods. True formation resistivity *Rt* was taken from the deep-reading induction log. The porosity used was the shale volume-corrected density porosity. The resistivity of the shale, *Rshl*, was taken as the deep-reading induction resistivity values averaged over the interval from 1135 to 1140 ft for the Cenozoic section and from 3143 to 3145 ft for the Paleozoic section. These are the same depth intervals from which density and acoustic wave travel time of shales were taken for use in the shale volume-corrected porosity equations.

Water saturation was next calculated according to the Archie equation (Asquith, 1983):

|  |  |  |
| --- | --- | --- |
|  |  | (12) |

where *Rt* and *Rw* are the resistivities of the formation and formation water, respectively; *n* is the saturation exponent and was assigned the standard value of 2; and *a* and *m* are the toruosity and cementation factors, respectively. Standard values of *a* and *m* (a=1; m=2) were used. Porosity in the Archie equation was taken from the shale volume-corrected density porosity and formation resistivity was taken from the deep-reading induction resistivity log, as discussed previously.

Finally, water saturation was calculated using the ratio method as outlined in Asquith (1983). The ratio method allows for the calculation of water saturation based exclusively on resistivity data according to Equation 13:

|  |  |  |
| --- | --- | --- |
|  |  | (13) |

Here, *Rxo* is the resistivity of the flushed zone and can be read from a shallow-reading resistivity log; *Rmf* is the resistivity of the mud filtrate. For the present calculations, resistivity of the flushed zone was taken from the Laterlog-8 log. Resistivity of the mud filtrate was read from the resistivity log header and extrapolated over varying temperature. *Rw* and *Rt* are as described previously.

Asquith (1983) cautions that one of the difficulties with shaly formation analysis is the determination of shale resistivity. In the present application of the shaly formation equation (Equation 11), a single value of Rshl was used in calculating water saturation throughout the Cenozoic section of the well and another value of Rshl was used for calculations in the Paleozoic section, thus assuming that shale properties remain essentially unchanged through the two sections, an assumption that is likely not fully justified. Nevertheless, the water saturations calculated by the shaly formation equation compare reasonably well with the saturations calculated by the other methods.

The shaly formation equation and the Archie equation yield results that are qualitatively similar through much of the well with the Archie equation yielding water saturations generally higher than those calculated by the other methods. The saturations calculated from the ratio method are generally the lowest and saturations from the shaly formation equation are typically intermediate between the saturation values from the other methods. The water saturations estimated by the shaly formation equation were used in all further calculations.

Bulk volume of water was calculated according to Equation 14:

|  |  |  |
| --- | --- | --- |
|  |  | (14) |

In bulk volume of water calculations, water saturation was taken from the shaly sand equation and porosity was taken as the shale volume-corrected density porosity. When the water saturation was calculated to be greater than 1, the maximum value of 1 was imposed.

Both the Rwa and cross-plot methods of calculating formation water resistivity and all three methods of calculating water saturation rely upon the true formation resistivity, a value that may be obtained from the deep-reading induction log. However, in some cases (thin, resistive beds) the deep-reading resistivity log may not give an accurate reading of true formation resistivity. Charts exist for the correction of the deep-reading resistivity log; however, when the data were examined in comparison with the correction charts, it was concluded that no correction was necessary.

*Permeabililty*

Permeability was calculated according to the empirical model of Jorgensen (1989). Jorgensen developed his model by curve-fitting experimentally-derived permeabilities. The samples used in the regression exhibited permeabilities between 4.5 mD and 1.1 D. The model defines an approximate relationship between permeability and porosity and cementation factor (Equation 15):

|  |  |  |
| --- | --- | --- |
|  |  | (15) |

where *ϕ* is porosity in fractional units, *m* is the cementation factor and *k* is the permeability in milli-Darcies.

The model also matches typical values of cementation factor, porosity and permeability for various lithologies including carbonates. Jorgensen states that the model is applicable to sandstone, siltstone and most porous carbonates. The model was applied in volcanic intervals even though Jorgensen gives no indication about the appropriateness of the model for volcanic rocks.

In the present application, the shale volume-corrected density porosity was used. When Jorgensen did his original work, he used cementation factors unique to each sample; however, the permeability calculations reported here were performed for the whole depth of the well using the standard value m=2.

Results of Analysis of Well 43-045-30001

The results of the calculations of porosity, water saturation and matrix permeability are shown plotted with respect to depth in Figures 4 through 6. Logs can be adversely affected by borehole effects when the wellbore is out of gauge. The caliper log was used to identify intervals in which the wellbore was enlarged. The data from these intervals and other intervals in which the log data were deemed suspect are not included in the plots.

The porosity data presented here is the shale volume-corrected density porosity (Equation 6) as pore volume per total volume. Porosities in the Paleozoic section (below 2970 ft) range from 15% to less than zero. Negative values in the limestones indicate that the limestone matrix density value used in calculating porosity is less than the actual value. In contrast, porosities in the Cenozoic section of the well range from 15% to over 40%. Estimated porosities in the volcanic rocks range from near 10% to just over 35%, but values above 30 to 35% are uncommon and must be viewed with caution.

Water saturation was calculated using the shaly formation equation (Equation 11) and has units of liquid-filled porosity volume per total porosity volume. Calculated water saturations range from 40% to 100% in the Cenozoic section. In the Paleozoic rocks, calculated water saturations are much lower, ranging from approximately 10% to 80%, with the majority falling below about 50%. These values are lower than expected but the reason for this is unknown.

The estimated matrix permeability data presented here were calculated according to the model of Jorgensen (Equation 15) and are shown in units of milli-Darcies. Matrix permeabilities in the Cenozoic section range from approximately 10 mD to more than 10 D. Because permeability was determined from porosity, in intervals in which estimated porosities are likely unreliable (greater than 30 to 35%), the permeabilities derived from these high porosities (eg. greater than 3 D) are also questionable. Furthermore, prediction of permeability outside the range of data used by Jorgensen in developing his model (4.5 mD to 1.1 D) may not be justified. In general, all calculations of parameters in the Cenozoic section of the well must be considered approximate only. Permeabilities estimated in the Paleozoic section were much lower, generally below 100 mD. The permeabilities reported here estimate matrix permeability and likely do not reflect any fracture permeability which might be present.

The graphical representations of the well logs, including calculated logs of porosity, water saturation and permeability can be found in Appendix B.

*Summary of Results for well 43-045-30001*

* Estimated average porosities in the Cenozoic section of the well range from 15 to 40% but results greater than 30 to 35% may be unreliable. The calculated porosities range from 15% to less than 0% in the Paleozoic section. There is an overall decrease in porosity with depth from 2970 to 3500 ft. At greater depths, porosities are less than 10%.
* The estimated average permeabilities in the Cenozoic section range from greater than 10 mD in to more than 10 D, however, calculated values above 1 D are suspect. Estimated permeability in the Paleozoic section decreases in the shallow intervals of the section and is more stable in the deeper intervals. Permeabilities are generally less than 100 mD in the shallow interval of the Paleozoic section and below 10 mD in the deeper interval.
* As discussed previously, data from the Cenozoic section of well 43-045-30001 is suspect and all results from the Cenozoic section must be considered approximate only.

**Analysis of Well 43-045-11076**

Methodology

Well 43-045-11076 was drilled in 1956, making it one of the oldest wells among the seven discussed previously. Well logs were run in the well but a different suite of logging tools was used, thus requiring a different analytical approach.

*Well Log Suite*

The log suite from well 43-045-11076 consists of an old style Gamma Ray / Neutron log and an Electrical log. The former log records the gamma ray response as micro-grams of radon-equivalent per ton. The neutron response of the old style Gamma Ray / Neutron log is reported in counts per second. Newer neutron porosity logs report a calculated porosity as volume per volume.

The old style Electrical log run in well 43-045-11076 consists of spontaneous potential, normal, long normal and lateral logs. The former three logs record the resistivity of the formation; the spontaneous potential log is comparable to modern SP logs.

*Shale Volume*

Shale volume was calculated according to the procedure discussed previously in reference to well 43-045-30001. As before, shale volume was not calculated in intervals described as containing volcanic rocks. An SP log baseline correction was performed in much the same way as was done in well 43-045-30001 (Figure 7). In well 43-045-11076, the relative resistivities of the drilling mud and the formation water resulted in an inversion of the SP curve; here, the SP shale baseline falls on the left and permeable intervals are indicated by deflections to the right.

*Correlation with Well 43-045-30001*

Well 43-045-11076 is located approximately 7 miles west southwest of well 43-045-30001. The two wells are separated by a southwest trending normal fault down to the northwest. They display similar stratigraphic relationships.

The gamma ray logs from the two wells were recorded in different units (micro-grams of radon-equivalent per ton in well 43-045-11076 and API units in well 43-045-30001). To allow for comparison, the gamma ray curves were scaled between 0 and 1 and plotted on the same set of axes. The gamma ray signatures show a reasonable correlation when 43-045-11076 is offset vertically by 950 ft. Figure 8 shows the gamma ray curves of the two wells before and after the 950-ft depth shift.

*Neutron Porosity*

Modern neutron porosity logs present porosity as volume per volume or percent. The old style of neutron logs, such as that recorded in well 43-045-11076, however, present neutron data as counts per second. Schechter (2003) reports on the method of D. E. Shier which defines a relationship between neutron logs and neutron log-derived porosity that allows porosity to be estimated from neutron counts per second.

Shier’s equation relies upon correlating intervals of high and low porosity between wells. In a well in which porosity is known (the reference well), intervals of high and low porosity are identified. Correlative intervals are then identified in the well in which only an old style neutron log is available. High porosity corresponds to low neutron counts per second and low porosity corresponds to high neutron counts per second. If correlative intervals can be identified in the wells, then the porosity (volume per volume) can be estimated in the well in which only a neutron log (counts per second) was obtained. Shier’s equation is given by the expression:

|  |  |  |
| --- | --- | --- |
|  |  | (16) |

where *N* is the neutron log value (in counts per second) and *ϕN* is the estimated neutron porosity. The other parameters in the equation are found from the high- and low-porosity intervals that can be correlated between the wells: *ϕhigh* and *ϕlow* are the porosities observed in high and low porosity intervals in the reference well; *Nϕhigh* and *Nϕlow* are the neutron log values (in counts per second) in the correlative intervals of the well in which only the neutron log is recorded.

In the present analysis, the approach was somewhat different. Rather than identifing intervals of high and low porosity in well 43-045-30001 and attempting to correlate them with intervals in well 43-045-11076, maximum and minimum porosities reasonably expected were selected. Values of ϕhigh=0.35 and ϕlow=0.05 were selected based on results from well 43-045-30001. The maximum neutron log value (corresponding to ϕlow=0.05) was Nϕlow=314 counts per second; the minimum neutron log value (corresponding to ϕhigh=0.35) was Nϕhigh=166 counts per second. The porosities in well 43-045-11076 were than calculated using Equation 16.

The presence of shale in a formation can result in erroneously high porosity values. Although the shale volume in the well was calculated, no attempt was made to correct for shale effects on the estimated porosity values.

*Permeability*

Permeability in well 43-045-11076 was calculated from the estimated porosity using Jorgensen’s model (Equation 15) as described previously. As in well 43-045-30001, the Archie equation cementation factor *m* was assumed equal to 2 throughout the depth of the well.

Results

Porosities in well 43-045-11076 were estimated using Equation 16 and are shown in Figure 9. Figure 10 is a comparison of wells 43-045-11076 and 43-045-30001 showing the porosities from well 43-045-11076 after the depth offset.

Permeabilities were approximated by the Jorgensen model (Equation 15) based on the estimated porosities (Figure 11). As discussed previously in relation to well 43-045-30001, prediction of permeabilities outside the range of data used in development of Jorgensen’s model (4.5 mD to 1.1 D) may not be justified. The permeabilities predicted by the Jorgensen model represent matrix permeability and do not account for any fracture permeability that might be present.

*Summary of Results for Well 43-045-11076*

* Because appropriate logs were not available, maximum and minimum porosities of 35 and 5% were utilized based on results from well 43-045-30001. Calculated porosities vary with depth and rock type. Between 750 and 1500 ft (Cenozoic sedimentary rocks), the average calculated porosities decrease from 30% to 20%. Between 1500 and 2700 ft (Cenozoic volcanic rocks), the calculated porosities remain relatively stable at about 20%. Below 2750 ft, porosities in the volcanic rocks decrease to between 5 and 10%.
* Permeabilities decrease slowly with depth paralleling changes in the calculated porosity. Values range from over 1 D to 100 mD in the sedimentary interval (750 to 1500 ft) to between 100 mD and 1 D in the shallow volcanic rocks (1500 to 2700 ft). Permeabilities range from 1 and 10 mD in the deep volcanic rocks (below 2750 ft). Calculated permeabilities greater than 1 D may be unreliable.

Conclusions

Porosities, permeabilities and water saturations were calculated for two wells near Focus Area 1. The stratigraphic section consists of Cenozoic sediments and volcanic rocks lying above Paleozoic rocks dominated by carbonates. Well 43-045-30001 penetrated the Paleozoic rocks; well 43-045-11076 did not reach the Paleozoic sequence. In general, porosity and permeability decrease with depth. Porosities typically vary from 35 to 15% in the Cenozoic section and are less than 15% in the Paleozoic section. Permeabilities range from 10 mD to greater than 1 D in the Cenozoic section with values greater than 1 D being suspect. Permeabilities in the Paleozoic section are much lower, typically between 100 and 0.1 mD. Permeabilities at the upper end of this range are sufficiently high to support natural geothermal systems, consistent with geochemical data suggesting that limestones host the geothermal system in this area.

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Figure Captions

Figure D-1. Google Earth satellite image showing the seven oil and gas wells in relation to Focus Area 1, which is outlined in red.

Figure D-2. GeoGraphix PRIZMTM was used to perform a baseline correction operation. The original SP curve appears in blue and the new baseline is shown in red.

Figure D-3. Porosity-resistivity cross-plot with a regression line extrapolated to the 100% saturation line, indicating the formation water resistivity value. Plots such as this were generated for each formation.

Figure D-4. Shale volume-corrected density porosity as volume per volume (v/v) with respect to depth for well 43-045-30001. Porosities above 35% are uncommon. Porosities greater than 30 to 35% are suspect (see text).

Figure D-5. Water saturation with respect to depth for well 43-045-30001.

Figure D-6. Matrix permeability with respect to depth for well 43-045-30001. Permeability was calculated as a function of porosity. Calculated permeabilities greater than 1 D are suspect (see text).

Figure D-7. Measured SP response (blue) and the corrected baseline (red). In this case, due to the relative resistivities of the drilling mud and the formation water, the SP shale baseline is on the left and deflection to the right indicates clean intervals.

Figure D-8. Gamma ray responses from wells 43-045-11076 and 43-045-30001. a) Gamma ray curves before correction for fault offset. b) Gamma ray curves after 950-ft offset.

Figure D-9. Estimated neutron porosity as volume per volume (v/v) with respect to depth from well 43-045-11076. Porosities were estimated according to Equation 16. High- and low-porosity values were selected somewhat arbitrarily.

Figure D-10. Comparison of porosities (as volume per volume) between wells 43-045-30001 and 43-045-11076 after the 950-ft depth offset. The figure shows good correlation, particularly between 500 and 900 ft.

Figure D-11. Matrix permeability calculated from the estimated porosities using Jorgensen’s model.

Appendix E  
  
Sample and Analysis of Surface Water and Springs

Tom Wood, Joseph Moore, and Robert Breckenridge

Spring and Well Water Sampling

Thermal waters discharge at several locations in and adjacent to the West Desert of Utah. Analysis of thermal waters can lead to an understanding of the thermal history of the water and give an indication of the deep reservoir conditions. The principle of chemical geothermometry is based on temperature dependent chemical equilibrium between the water and minerals in the geothermal reservoir and it is assumed that thermal water preserves its chemical composition during its ascent from the reservoir to the surface. Geothermometry is a commonly employed geothermal exploration technique; however, the assumption of the preservation of water chemistry may not always hold resulting in some uncertainty in the calculated results.

The compositions of thermal waters have been found to contain a record of temperatures experienced at different times in their evolution. Although many geothermometers have been proposed and are widely in use, most have been calibrated for high temperature environments. Consequently it cannot be assumed these geothermometers will yield reliable results for low temperature waters such as being evaluated in this study. The most appropriate means of estimating reservoir temperatures for low temperature waters include the silica geothermometers (Fournier, 1981), although these geothermometers may be strongly affected by dilution of low silica waters, the K- Na-Mg ternary plot of Giggenbach (1991), and the anhydrite geothermometer (T. Powell, person. comm.).

Geothermometry has been performed on nine water samples for the UTTR Study; four from the Blue Lake area and five from wells located on the southeast flank of the Silver Island Mountains (see Figure E-1). Samples from these sites were collected on September 28, 2011. As a standard procedure, temperature and pH were measured at each location during sampling. Temperatures were measured using a Yokogawa TX10 temperature probe. The pH was measured using a Hanna Instruments combined pH/EC meter that was calibrated the previous day. Three water samples were collected at each sample location; a 500 ml sample of filtered water; a 25 ml sample of filtered water diluted with 225 ml of distilled water; and a 500 ml sample of unfiltered water. The samples were filtered using a peristaltic pump and 0.45 micrometer filter. Sample locations (UTM easting and northing) and elevations were determined using a handheld Garmin GPSMAP 62st device. The water samples were shipped to Thermochem, Inc., Santa Rosa, CA, for analysis.

INSERT FIGURE E-1

Intrepid Potash Inc. Well Samples

Water samples were collected from five wells located between one and two miles north of Interstate 80 (see Figure E-2; Table x.1). These wells produce water with temperatures of 25.8 to 32.8°C.

Blue Lake Thermal Area

Blue Lake is located approximately 25.8 km south of Wendover, Nevada (see Figure E-1). It is a deep natural spring fed lake, with a depth of approximately 18 m. Springs discharge thermal water into the bottom of the lake, but the inflow is diffuse and direct sampling of the springs has never been successfully accomplished. Bottom temperatures are approximately 29oC. The area surrounding the lake is characterized by wetlands and ponds of various sizes fed by thermal springs. To our knowledge, there are no deposits (e.g. silica or carbonate) related to the discharge of thermal water in this area.

Water samples were taken from four locations around Blue Lake (see Figure E-3; Table E.1). Blue Lake #1 was collected directly from a spring at the south end of a large pond. The sample location is less than one mile west-southwest of Blue Lake. Blue Lake #2 was collected on the north shore of Blue Lake. Measured temperatures (28oC) were slightly warmer at the sample location than at other shoreline locations in the vicinity, and a mound below the surface of the water about 6 ft from the shore suggest that the sample location is near a spring; however, no direct evidence of discharging thermal water was observed. Blue Lake #3 was collected from the floating dock on the west shore of Blue Lake. Temperatures at the sample location decreased from 27.2 to 26.6°C during the 10 minute sampling period, perhaps due to natural circulation of the lake water. Blue Lake #4 was collected from a pond west of Blue Lake. There was no evidence of a spring at the sample site.

Results

The results of the chemical analyses are presented in Table E-1. The samples were analyzed for major, minor a several trace elements using standard chemical techniques by Thermochem Inc. The analytical results are included in Appendix X. The charge balance as a percentage of the total ionic charge of the solution ((cations-anions)/(cations + anions)) was calculated to assess potential analytical errors. The charge balance is 0 when the cations equal the anions. Differences exceeding 5% suggest an erroneous analysis of a major ionic species or that one of the major ionic species is missing. Charge balances for the analyses shown in Table E-1 range from -2% to +1%.

All of the waters are NaCl in composition with minor HCO3 and SO4. Waters from the Blue Lake area display significantly lower salinities than those from the Intrepid Potash Inc. wells although the measured temperatures of the waters are similar (Table x.1). Total dissolved solids contents of the Blue Lake waters range from approximately 5000-5500 mg/L whereas those from the Intrepid Potash Inc. wells range from 8000-12500 mg/L. Figures E-4 and E-5 show the relationship between Na and Cl and it suggests that the well waters from wells IW6, IW7, IW13, and IW10 could represent mixtures of water from IW12 and Blue Lake waters. The very high Cl contents of the Intrepid Potash Inc. well waters suggests that IW12 water has interacted with salt deposits present in the Bonneville Salt Flats of the west desert. Because of the potential interactions with salt deposits, and their effects on the compositions of the waters, the following discussion is focused on waters from the Blue Lake area, which are more likely to reflect interactions with the sedimentary and volcanic rocks below the salt deposits.

A significant feature of the Blue Lake waters is their relatively high Ca and Mg contents and Ca/Mg ratios near 3. High contents of these cations are typical of carbonate reservoirs. Langmuir (1971) suggested that Ca/Mg ratios >3.0 indicate interactions with limestones. Ratios between 1.5 and 3.0 can indicate the presence of dolomite beds with a dominantly limestone reservoir whereas ratios <1.5 implies interactions with reservoirs consisting mainly of dolomite. Based on the Ca/Mg ratios of the Blue Lake waters we suggest that the reservoir rocks consist primarily of limestone with interbedded dolomite beneath the cover of Tertiary and Quarternary sediments and volcanic rocks.

Figure E-5 shows the K-Na-Mg relationships for the Blue Lake area waters. These waters plot near the base of the region of partial equilibration. Giggenbach (1991) suggested that both silica and K/Mg geothermometers (Giggenbach, 1991) could be applied to samples plotting in this portion of the diagram, although with caution. Temperatures calculated based on the K/Mg geothermometer yield values of 108-111oC. The chalcedony geothermometer, the most appropriate silica geothermometer for low temperature waters, in contrast yields temperatures of 40 to 48oC. Although it cannot be demonstrated that mixing with low silica waters has occurred, the low measured temperatures of these waters and the significantly higher temperatures encountered in XXXXXXXX suggests that dilution is a likely explanation for the low calculated values.

The anhydrite geothermometer is based on equilibria between the fluid and anhydrite. It is calculated from the Ca and SO4 contents of the thermal fluids and assumes the presence of anhydrite in the reservoir. Although the presence of anhydrite was not noted on the well logs of nearby wells, gypsum was observed. Anhydrite is a common mineral in carbonate terrains and is likely to be present. Temperatures calculated from the anhydrite geothermometer range from 138-140oC.

Conclusions

Thermal waters were sampled from springs and thermally fed ponds in the Blue Lake thermal area and from Intrepid Potash Inc. wells to the north. Temperatures of the thermal waters range from 27 to 31oC. The well waters have salinities exceeding 8000 mg/L and are interpreted to reflect mixing of lower salinity water, perhaps similar to the Blue Lake area waters and waters that have interacted with salt deposits. The Blue Lake waters have salinities of about 5000 to 5500 mg/L. Ca/Mg ratios of the Blue Lake waters are close to 3 and suggest the waters have flowed through limestones interbedded with dolomite. Geothermometer temperatures calculated from the Blue Lake water analyses suggest possible reservoir temperatures are in the range of 110 to 140oC.

Table x.1. Compositions, measured and geothermometer temperatures of Blue Lake (BL) area and Intrepid Potash Inc., (IW) well waters. Analytical values in mg/L. See Appendix X for laboratory analytical sheet for each sample.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | **Geothermometer Temperatures** | | |
| **Sample Name** | **Temp (oC)** | **UTM#**  **East** | **UTM\***  **North** | **pH** | **Li** | **Na** | **K** | **Ca** | **Mg** | **SiO2** | **Cl** | **SO4** | **HCO3** | **NH4** | **Rb** | **Chal (oC)** | **K/Mg**  **(oC)** | **Anhy**  **(oC)** |
| BL1 | 29.2 | 750399 | 4487310 | 6.65 | 1.6 | 1640 | 109 | 156 | 49.2 | 25 | 2780 | 256 | 313 | 0.2 | 0.54 | 40**o** | 108**o** | 139**o** |
| BL2 | 28 | 751442 | 4487777 | 6.84 | 1.67 | 1720 | 115 | 158 | 54.7 | 26 | 2810 | 280 | 311 | -0.2 | 0.58 | 42**o** | 108**o** | 138**o** |
| BL3 | 27.2 | 751350 | 4487676 | 6.97 | 1.63 | 1700 | 120 | 149 | 47.2 | 30 | 2840 | 269 | 314 | 0.3 | 0.56 | 48**o** | 111**o** | 140**o** |
| BL4 | 27.8 | 750292 | 4487504 | 6.95 | 1.59 | 1550 | 107 | 152 | 43.8 | 28 | 2550 | 250 | 312 | -0.2 | 0.56 | 45**o** | 109**o** | 139**o** |
| IW6 | 32.8 | 247849 | 4516657 | 6.87 | 1.57 | 2730 | 126 | 134 | 88.7 | 39 | 4350 | 399 | 203 | 0.2 | 0.25 |  |  |  |
| IW7 | 31.3 | 248138 | 4516802 | 6.93 | 1.61 | 2840 | 139 | 143 | 97.9 | 41 | 4630 | 384 | 199 | -0.2 | 0.27 |  |  |  |
| IW10 | 25.8 | 248845 | 4517193 | 7 | 1.93 | 3690 | 172 | 195 | 142 | 37 | 6440 | 460 | 161 | 0.6 | 0.24 |  |  |  |
| IW12 | 27.3 | 249453 | 4517523 | 7.16 | 2.16 | 4160 | 183 | 253 | 193 | 30 | 7100 | 477 | 167 | 0.5 | 0.25 |  |  |  |
| IW13 | 26.8 | 249761 | 4517698 | 7.36 | 1.52 | 2620 | 121 | 141 | 107 | 36 | 4300 | 308 | 182 | 0.3 | 0.17 |  |  |  |

#: UTM Zone 11; \* UTM Zone 12; negative values indicate analytical value less than the detection limit; As = <0.01(see Appendix X for analytical values); Cs = -0.1; Carbonate Alkalinity (as HCO3-) = -2;

References

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Giggenbach, W.F., 1991, Chemical techniques in geothermal exploration in UNITAR/UNDP Guidebook: Application of geochemistry in resources development, p. 119-144.

Langmuir, D., 1971, The geochemistry of some carbonate groundwaters in central Pennsylvania. Geochemica et Cosmochimica Acta, v. 35, p. 1023-1045.

Figure Captions

Figure E-1. Satellite image indicating the locations of the Intrepid and Blue Lake sampling areas.

Figure E-2. Water samples were collected from wells 6, 7, 10, 12 and 13, located adjacent to the southeast flank of the Silver Island Mountains.

Figure E-3. Satellite image of the Blue Lake area showing the locations of the four samples collected for chemical analyses.

Figure E-4. Relationship between Na and Cl in the Blue Lake (BL) and Intrepid Potash Inc. wells (IW). Waters from the Intrepid Potash Inc. wells IW6, IW7, IW13, and IW10 could represent mixtures of water from IW12 and Blue Lake waters.

Figure E-5. K-Na-Mg plot of Blue Lake area waters. The samples group at the lower boundary of the region where partial equilibration with the rock is expected.