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Geophysical Signatures of the Milford, Utah FORGE site

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ABSTRACT

Geophysical data have been used in a preliminary characterization of the Milford FORGE site in southeastern Utah. The site is situated over Tertiary-Quaternary granitic intrusions and Precambrian gneiss that crop out in the Mineral Mountains and are at 3.1 km depth in the Acord-1 well near the center of Milford Valley 10 km to the west. Modeling of the 20 mGal gravity low, caused by basin fill overlying the granite, was accomplished using a decreasing density contrast with increasing depth based on Acord-1 geophysical logs. 2D models show the granite gently dipping to the west beneath the surficial fan deposits on the western edge of the Mineral Mountains. This dip increases farther out, forming a more localized basin beneath the center of the valley. At the proposed deep drilling site, the granite is at about 500 m depth. A residual, reduced-to-pole aeromagnetic map is featureless near the proposed site due to the burial depth of the relatively magnetic granite. Long-wavelength, magnetic-high anomalies west of the site may originate from buried Tertiary andesite which occurs in the Acord-1 well. The andesite crops out in the Beaver Lake Mountains 18 km to the west. Several magnetotelluric soundings close to the site show that the basin fill sediments have a resistivity of about 2–3 ohm-meters (Ωm) due to both their clay content and to the warm geothermal groundwater they host.

1. INTRODUCTION

A site near Milford, Utah, has been chosen by the U.S. Department of Energy (DOE) as one of five possible sites for testing and demonstrating new technologies that advance geothermal heat extraction from low permeability host rocks. The initiative, known as FORGE (Frontier Observatory for Research in Geothermal Energy), is discussed in more detail by Boyd et al. (2016). This paper reviews the geophysical characteristics of the Milford site (figure 1), including the gravity, magnetotelluric (MT), magnetic, and thermal signatures. Two additional papers accompany this paper: the geology and hydrology are reviewed by Simmons et al. (2016) and the geothermal characteristics are reviewed by Allis et al. (2016).

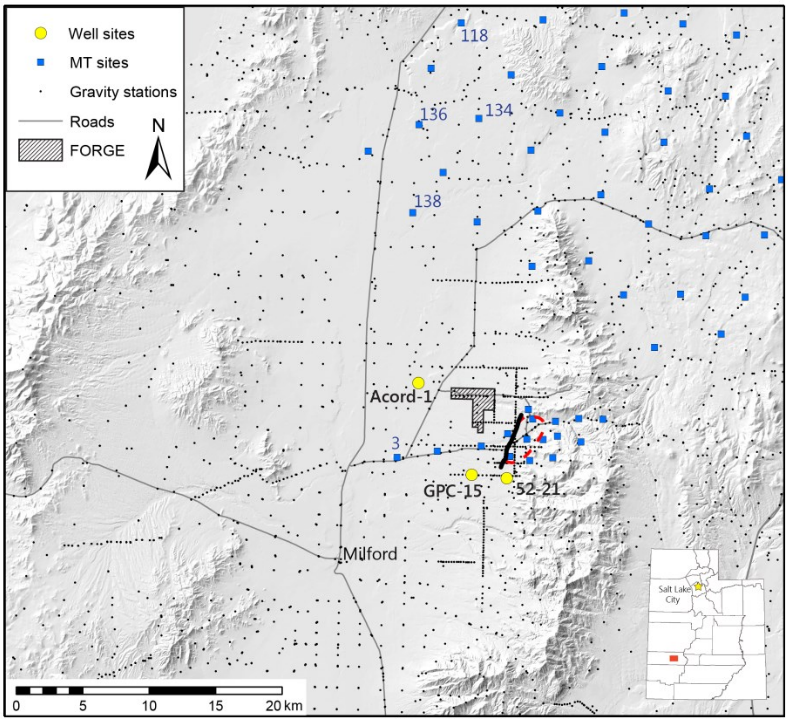


Figure 1. Map of the Milford, Utah FORGE study area. The black shaded area indicates the location of the FORGE site, the heavy black line is Opal Mound fault, and the red dashed line is the Roosevelt Hot Springs hydrothermal system.

2. GRAVITY

New gravity measurements in the vicinity of the FORGE site were previously reported by Hardwick and Chapman (2012) and Hardwick (2013). The complete gravity data set for this area is comprised of data collected by the Utah Geological Survey (UGS) and legacy data from the national data repository. All data were reprocessed for terrain corrections and a Complete Bouguer gravity anomaly (CBGA) was calculated according to the methods of Hinze et al. (2005) and described in detail by Hardwick (2013). Figure 2 shows a map of the CBGA for the Milford Valley and surrounding area. A 20 mGal low in the CBGA is located in the central part of the Milford valley which indicates that there is a significant thickness of low-density material (basin fill).

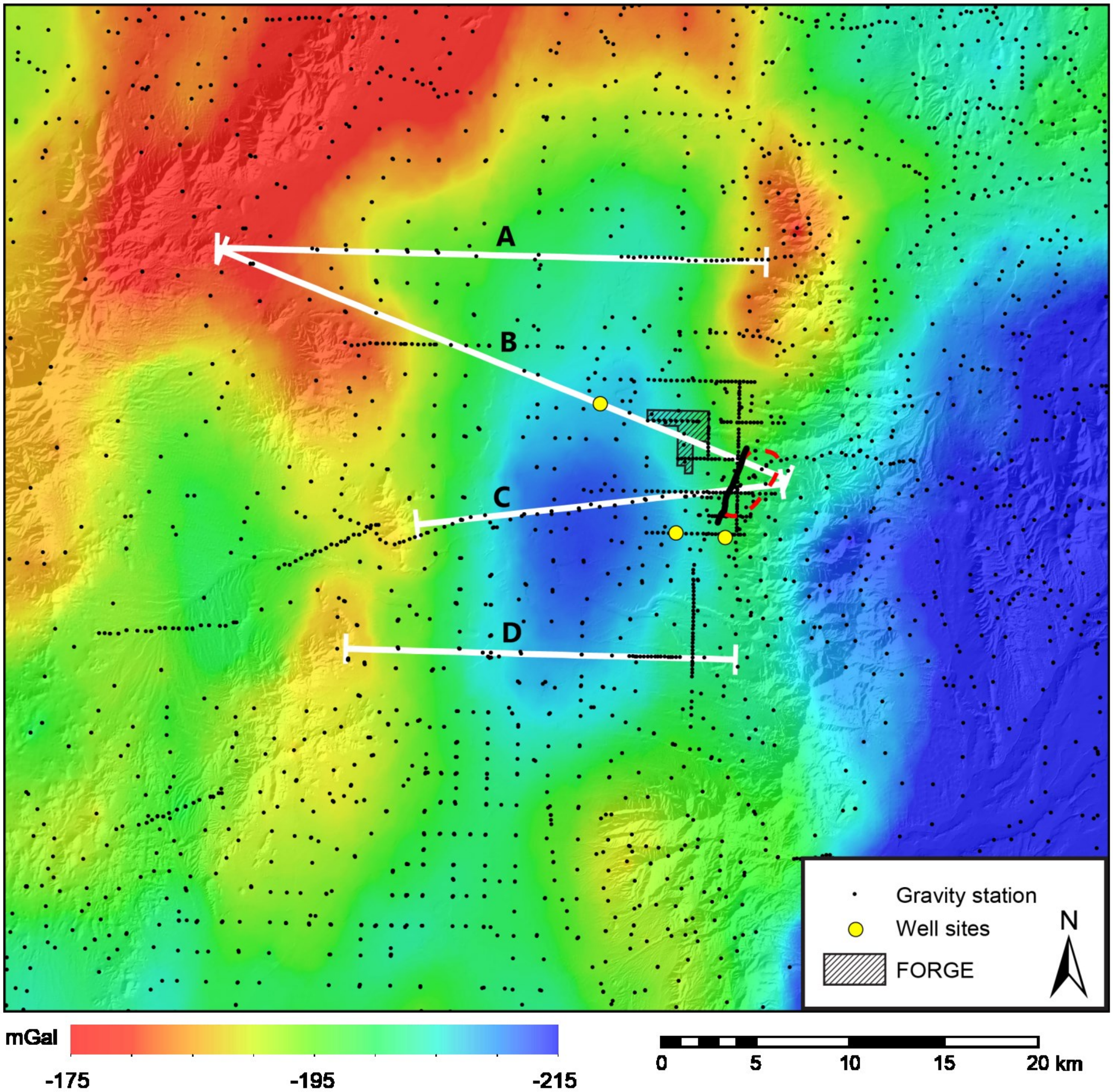


Figure 2. Complete Bouguer gravity anomaly map for the Milford valley. Transects for 2D gravity models (A, B, C and D) are shown as white lines. The black shaded area indicates the location of the FORGE site, the heavy black line is Opal Mound fault, and the red dashed line is the Roosevelt Hot Springs hydrothermal system.

The large gravity low to the east has a regional effect on the local gravity field and its amplitude is enough to mask local gravity anomalies and signatures (i.e., the Mineral Mountains signature) as well as shift the inferred center/axis of the basin to the southeast. The wavelength suggests this regional anomaly is most likely associated with a large structure deep in the crust/upper mantle. This would be beneath the transition zone between the physiographic provinces of the Basin and Range and the Colorado Plateau. The work of Wannamaker et al. (2008) offers an explanation of the deep structures observed in MT resistivity modeling of the transition zone. A complicated process of rifting/faulting, basaltic melt underplating, and possibly a piece of detached Colorado Plateau crust could be the cause of the gravity low (mass deficiency).

Figure 3 shows a map of the slope (gradient) of the CBGA for the area. A map of the slope field highlights the major gradients of the gravity field which can be useful in finding subsurface structures and/or density contrasts. By removing amplitude information of the CBGA field we are also able to get an idea of the shape of the basin, orientation, and the locations of any small and large gravity related features. We observe large gravity gradients in areas north of the FORGE site and southeast of the Mineral Mountains. Milford basin is primarily trough-shaped, with the northern end being wider than the southern end. A small arm extends to the west at the northern end.

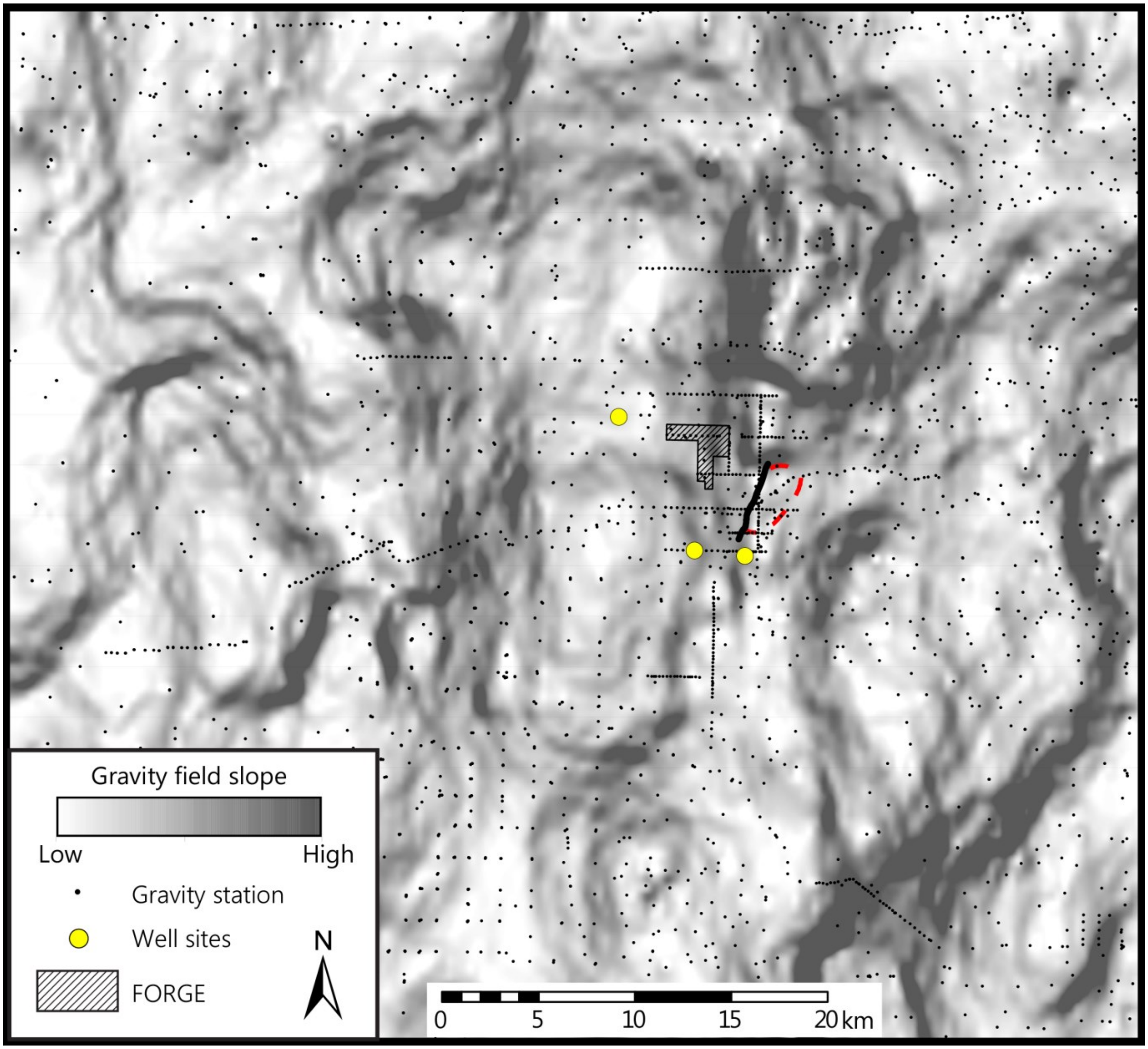


Figure 3. Map of the slope of the gravity field (gradient) for the Milford valley. The black shaded area indicates the location of the FORGE site, the heavy black line is Opal Mound fault, and the red dashed line is the Roosevelt Hot Springs hydrothermal system.

After computing regional isostatic gravity corrections for the area (a function of crustal root thickness based on surface elevation), we still have to compensate for the deep anomaly. Becker and Blackwell (1993) used a low density body representing an intrusion at a depth of 5 km below the surface in their model. We believe that the structure is a regional feature of the transition zone, requiring a deeper, and larger, low-density body on the eastern boundary of our study area. To isolate basin gravity, we use transect lines (A, B, C, and D shown in figure 2) spanning from exposed bedrock on opposite sides of the valley that are nearly perpendicular to the gravity field gradient. From these transects we approximated a linear correction of the gravity data and proceed to 2-dimensional (2D) modelling using the Semi-Automated Marquardt Inversion code (SAKI) (Webring, 1985).

Initial models were created using a single layer of average basin fill density to establish a general shape of the basement. From the initial model we differentiated the basin fill into a maximum of 6 density layers (decreasing density with increasing depth) derived primarily from the density and porosity logs of the Acord-1 well (figure 4).

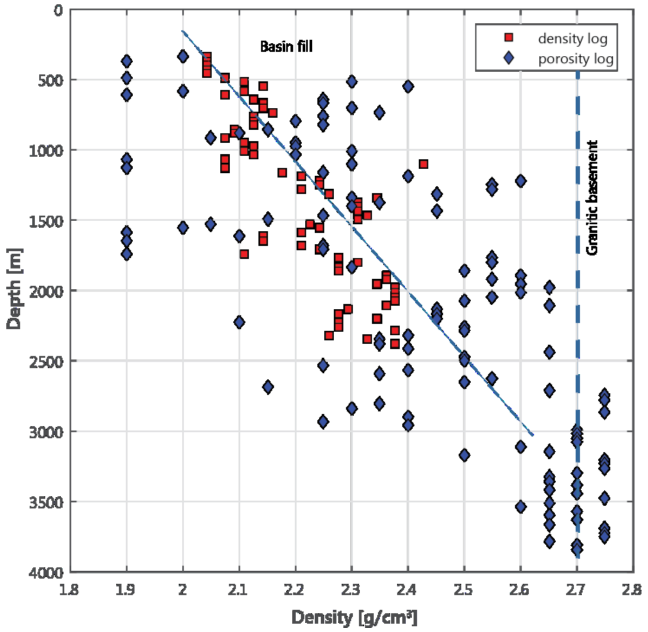


Figure 4. Plot of density values from downhole log data of the Acord-1 well.

The Acord-1 well penetrates 3.1 km of basin fill before reaching the basement and has a total depth nearing 3.9 km. Well data are used on transects, where available, to constrain basin-fill thickness and to augment densities for the basin fill layers in the models. Figure 5 shows transects A, B, C, and D where the basin-fill density contrasts range from -0.1 to -0.65 g/cm3 with respect to bedrock density (2.7 g/cm^3) to model the 20 mGal gravity signal.

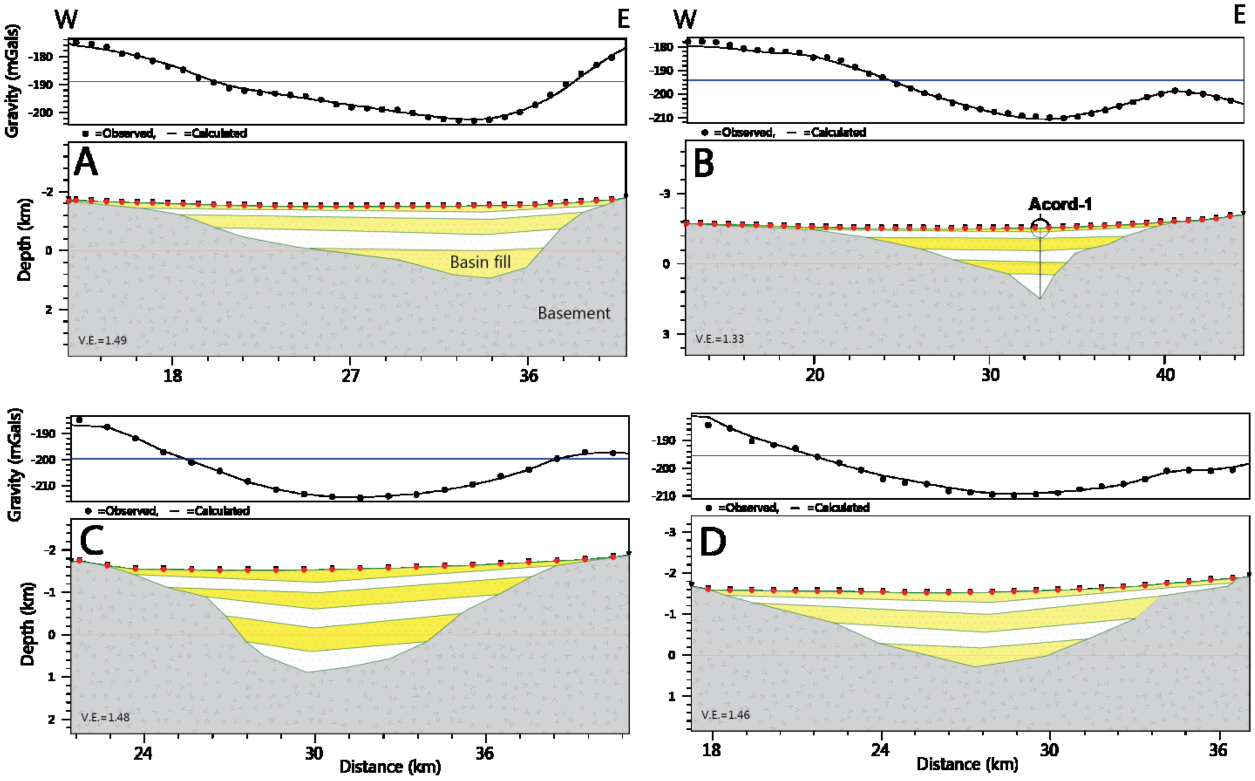


Figure 5. Models of the gravity transects A, B, C, and D from figure 2. Yellow and white layers are basin fill and gray is basement.

3. MAGNETOTELLURICS

Near the FORGE site (figure 1), existing magnetotelluric (MT) data acquired by the UGS in 2012 and 2014 for geothermal studies in sedimentary basins (Hardwick and Chapman, 2012, Hardwick, 2013, Hardwick et al., 2015) have been incorporated into this study. Analyses of the MT data allow us to estimate the characteristic electrical resistivity properties and to provide information on the dimensionality of the study area, providing clues to the deeper structure and geometry of the Milford basin. Of the existing MT stations, 16 are in, or adjacent to, the Milford basin. We use these data to help characterize local resistivity values and constrain depth-to-basement. The data were analyzed using the phase tensor method of Caldwell et al. (2004). Figure 6 shows the MT response (right panel) and phase tensors (left panel) for MT stations 118, 134, 136, 138, and 3. The data were prescreened to ensure that they meet the appropriate criteria for the method. We check the quality of the data as well as assess the dimensionality to ensure it is suitable for 1-dimensional (1D) modeling using the phase tensor method.

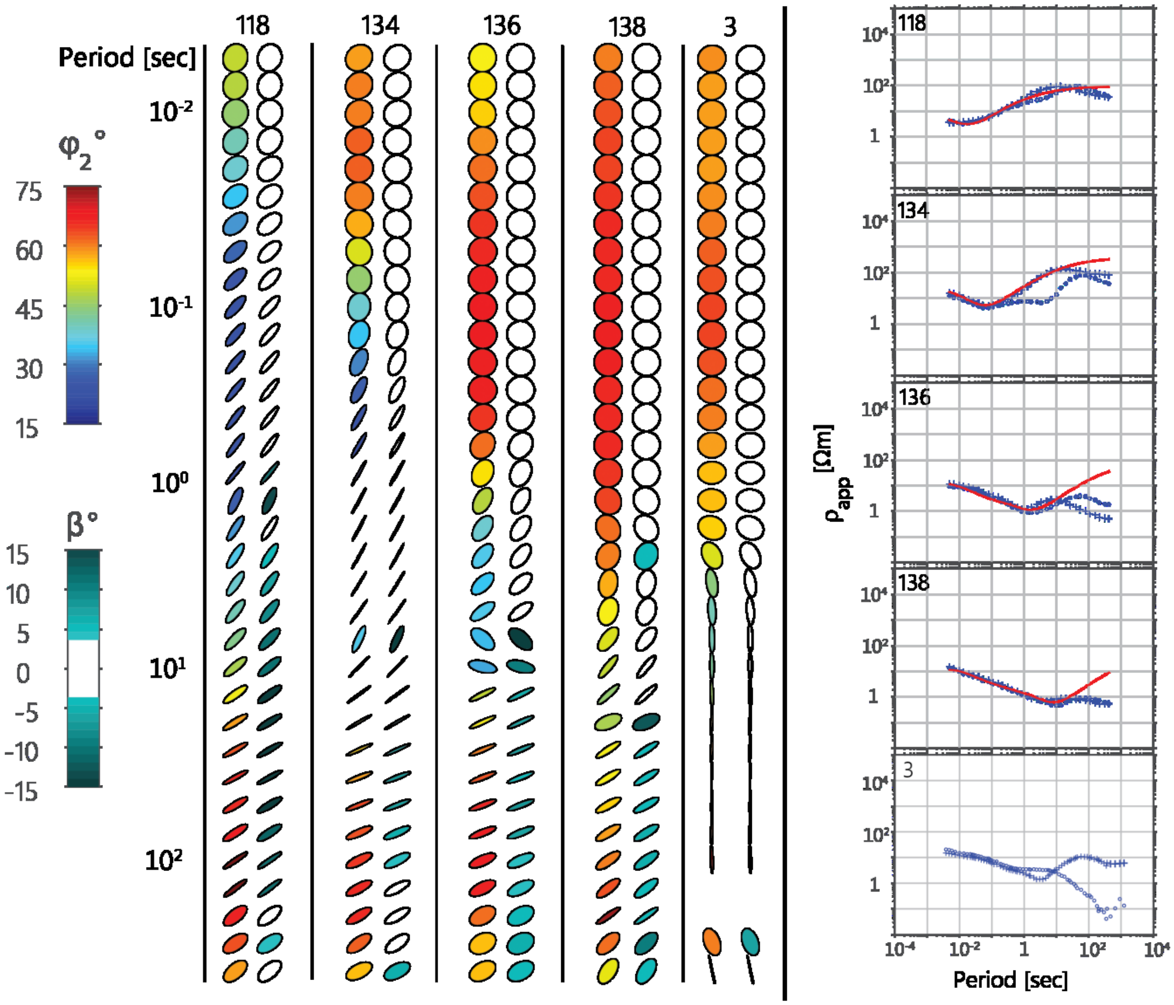


Figure 6. MT Phase tensor profiles plotted by period for sites (locations in figure 1) used in the 1D models (left panel) and MT response data (right panel). Phase tensor colors in the left-hand column for each station (118, 134, 136, 138, 3) are the geometric mean of the minimum and maximum phases and the right-hand column shows the skew parameter. In the MT response plots, open circles are TE (transverse electric) mode, crosses are TM (transverse magnetic) mode, and red curves are 1D forward models.

For each of the 5 stations shown as an example, the small variation and smooth transitions by period indicate the data is continuous and of high quality, with the exception of station 3 beyond a period of 1 second. The brightly colored phase tensors in the left-hand column for each station are colored according to the geometric mean of the minimum and maximum phases which represents the conductivity gradient. Low phase values indicate a transition to resistive material (bedrock) whereas high phase values indicate conductive material (clays, saline pore fluids, etc.). The shape of the phase tensor indicates the dimensionality of the data. While circular tensors imply 1D, elliptical tensors imply 2D and 3D conditions with the major axis of the ellipse indicating the geoelectric strike direction (90 degree ambiguity is resolved by external information such as geologic structures or gravity data). The right-hand column of each station is colored according to the skew (β) parameter. The skew value is a way to determine when dimensionality transitions from 2D to 3D. Phase tensor ellipses that are uncolored ($|\beta| \leq 3°$) are generally accepted as the boundary of quasi-2D conditions (as suggested by Booker, 2014). In this 1D case, we are limited to using periods of the MT data where phase tensors indicate 1D dimensionality.

The 1D MT models of the station data (subset shown in figures 1 and 6), generate depth-to-basement estimates of 120, 250, 710, and 1130 m for stations 118, 134, 136, and 138 respectively. Station 3 could not to be modeled in 1D for a depth-to-basement value since the longer period data doesn't seem to detect a definitive basement signal. This has been observed in MT data from other deep basins in Utah and is thought to be the effect of thick accumulations of very conductive basin sediments starting at the surface. These situations require special treatment in 2D and 3D, and possibly more MT measurements in the vicinity, to resolve deeper structure. Station 3 phase tensors do, however, have a very similar signature to station 138 for shorter periods (> 1 second). In general, the simplified best-fit 1D models use 10–20 Ωm for the near surface sediments, 2–3 Ωm for the deeper basin fill, and 80–200 Ωm for the basement rocks.

4. BASIN MODEL

Geophysical data, their respective models, and well data were used to construct a pseudo 3D basement-depth model for the Milford valley basin (figure 7). Depth information from 4 2D gravity cross-sections and 16 1D MT models were combined with a zero-depth boundary to serve as control points for the 3D basin model. MT station data were analyzed and then modeled in 1D (independently from gravity modeling) and used to verify 2D gravity models along transect lines and to help constrain basement depth in parts of the Milford valley where no well data are available. The modeled basin axis runs primarily north-south, which aligns with the majority of fault strikes related to Basin and Range extension. Modeled basin geometry suggests large, gently-dipping, surfaces are present at the margins of the basin. The surfaces steepen abruptly near the center of the valley, showing a "basin within a basin". The basement depth varies at the FORGE drilling area from about 300 m on the eastern boundary to 1 km on the western boundary. The depth to basement is about 500 m near the deep drilling site. The deepest part of this basin model is located near the Acord-1 well, which happens to be the only deep control point in the middle of the basin. It is possible that there are other deeper areas in the basin, but examination of the geophysical data do not furnish any indication of their existence outside the vicinity of Acord-1.

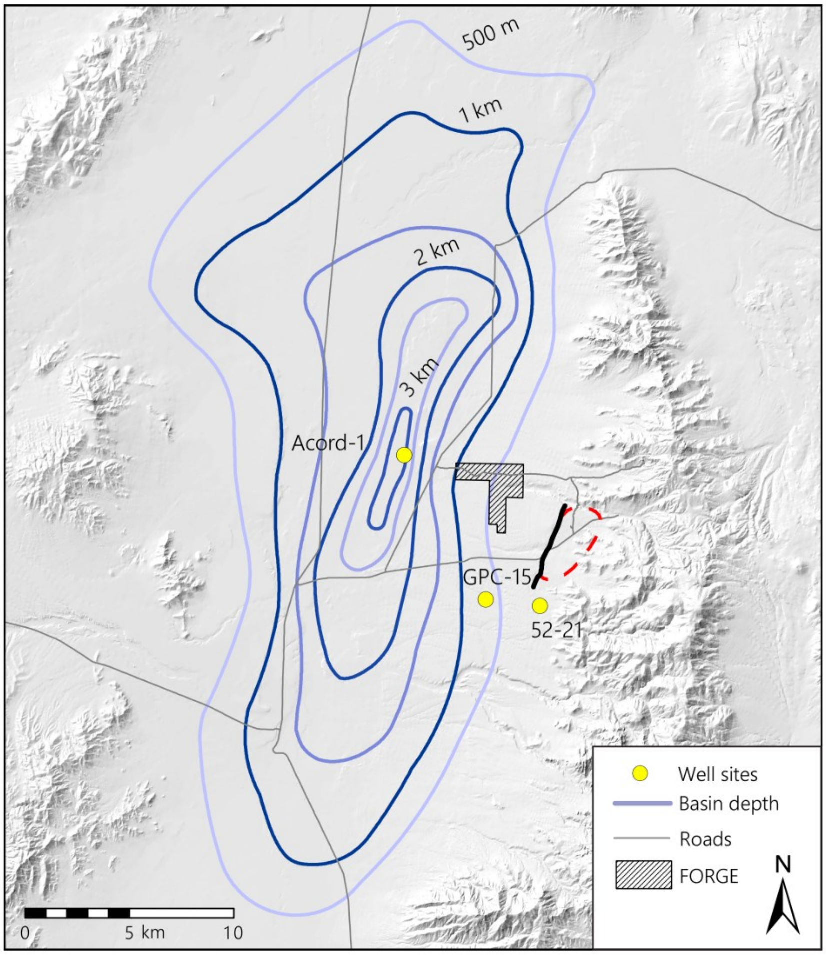


Figure 7. Map of the basin depth model derived from geophysical data. The black shaded area indicates the location of the FORGE site, the heavy black line is Opal Mound fault, the red dashed line is the Roosevelt Hot Springs hydrothermal system.

5. OTHER GEOPHYSICAL DATA

Other geophysical data relevant to determining the geophysical characteristics of the Milford area include aeromagnetics, teleseismic, and downhole geophysical logs. A low-level aeromagnetic survey over the region with lines spaced one-quarter mile apart and draped at a nominal 330 m above the terrain was flown for the University of Utah in 1978 (Carter and Cook, 1978). These authors removed the International Geophysical Reference Field to produce residual anomalies and then used a reduction-to-pole technique to remove bipolar effects. The resulting map is shown as figure 8. The intrusive rocks, cropping out in the Mineral Mountains, and mid-Tertiary volcanics are relatively magnetic compared to the Paleozoic outcrops to the north and south and the buried granite in the valley. Quaternary rhyolite flows immediately east of Roosevelt Hot Springs are thought to be reversely magnetized. The featureless magnetic signature over the FORGE site is due to the great depth to the relatively magnetic granite compared to the elevation of the survey. Long-wavelength, magnetic-high anomalies west of the site may originate from buried Tertiary andesite which occurs in the Acord-1 well (recorded by Hintze and Davis, 2003) and also outcrops in the Beaver Lake Mountains 18 km to the west.

Robinson and Iyer (1981) used a teleseismic survey to assess the nature of the heat source of Roosevelt Hot Springs. The study concluded that the low-velocity patterns observed indicate there is a region of relatively low-velocity material which extends from the upper mantle to depths of about 5 km beneath the Mineral Mountains. The preferred explanation for this anomalous region is that it is the result of "abnormally high temperature and a small fraction of partial melt." The region of -2% velocity change for the depth layer of 5–15 km is shown in figure 8.

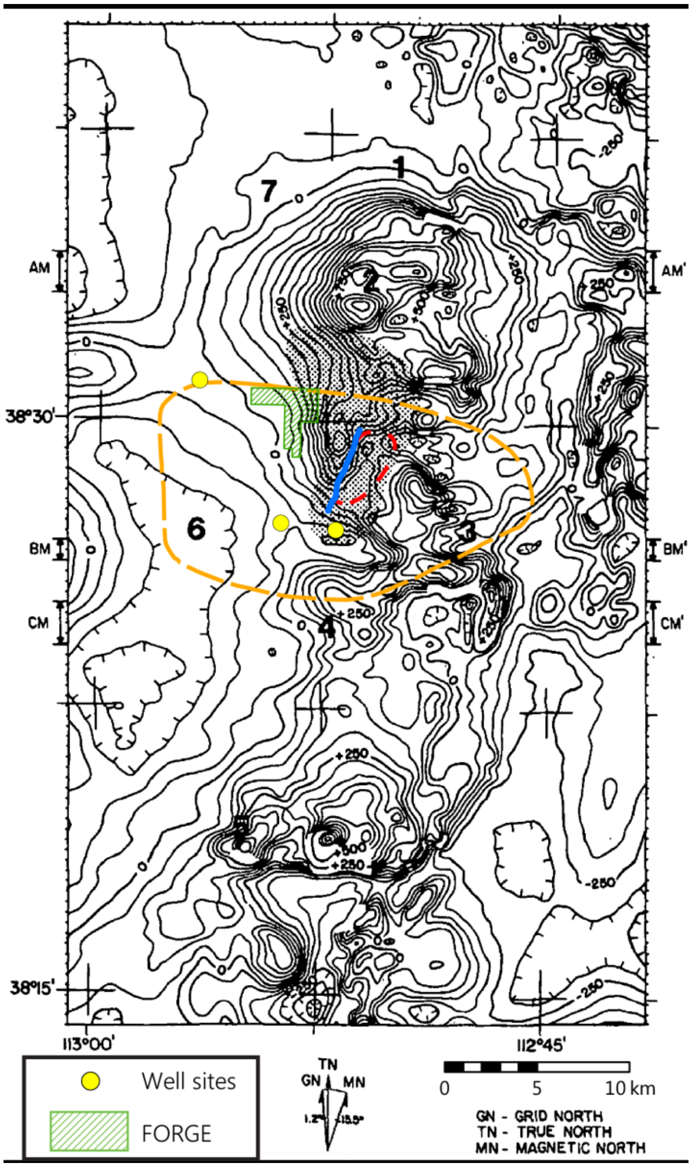
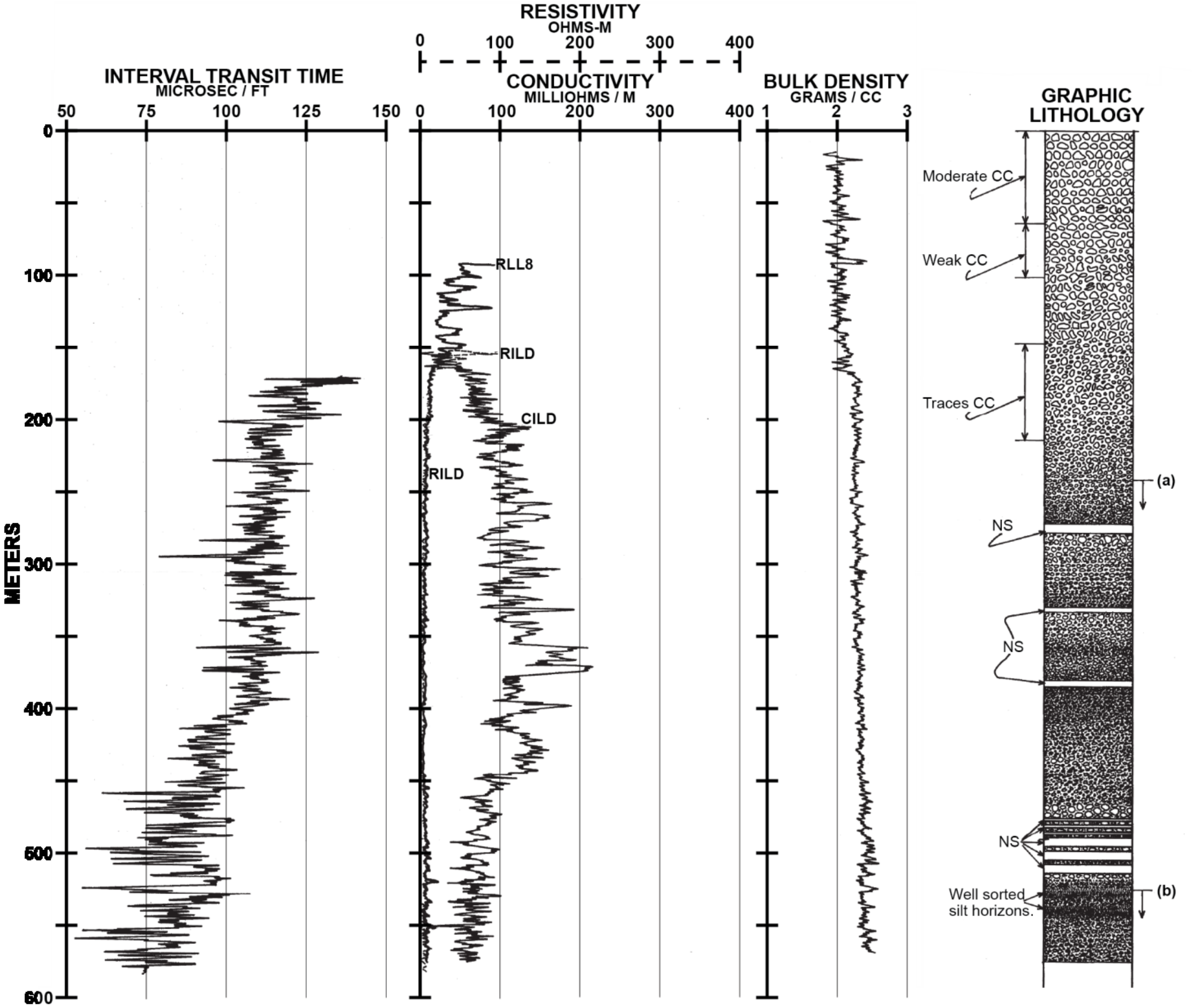


Figure 8. Residual aeromagnetic anomaly, reduced to pole, modified from Carter and Cook (1978; gammas; 330 m draped). Orange dashed line is the -2% seismic velocity anomaly at 5–15 km depth from Robinson and Iyer (1981). The green shaded box indicates the location of the FORGE site, the heavy blue line is Opal Mound fault, and the red dashed line is the Roosevelt Hot Springs hydrothermal system.

Geophysical logs of wells in the Milford valley give insight to the physical properties of basin fill and bedrock material and how those properties differ. This information is useful when qualitatively comparing layers as well as when creating and evaluating models based on geophysical data (density for gravity, resistivity for electromagnetics). Logs from wells GPC-15, 52-21, and Acord-1 (labeled on figures 1 and 7) are illustrated in Figures 9 through 11. Figure 9 shows a set of logs from well GPC-15 which is located 3 km south of the FORGE site. GPC-15 was completed entirely in basin-fill material where interval transit time ranges between 75 to 125 µs/ft, resistivity is <10 Ωm, and bulk density is around 2 g/cm^3. Figure 10 shows parts of a set of logs from well 52-21, located next to the Mineral Mountains 4 km southeast of the FORGE site. The interval shown for well 52-21 is entirely in basement rock where interval transit time is 50 µs/ft and bulk density is between 2.5 and 3.0 g/cm^3. Resistivity for the same interval of bedrock is 100 Ωm (Glenn and Hulen, 1979). Figure 11 shows a set of logs from the Acord-1 well which penetrates 3100 m of basin fill and terminates in bedrock at about 3900 m. Interval transit time deep in the basin fill varies from 50 to 130 µs/ft, whereas the bedrock is more confined at approximately 50 µs/ft. Resistivity values in the Acord-1 well for basin fill range from 1 to 20 Ωm, while bedrock values range from 60 to 200 Ωm. Bulk density in the basin fill is between 2.0 and 2.5 g/cm^3 and basement values are around 2.7 g/cm^3. In the deeper section of the shown density log for Acord-1, there are somewhat noisy data and quality



LITHOLOGY

by M.J. Bullett and J.B. Hulen

0-570 m: Arkosic alluvium. Subrounded to angular grains and fragments consisting dominantly of Tertiary granitic intrusive rocks and their individual crystal constituents, with minor Precambrian gneiss and Pleistocene pumice, perlite, and obsidian. Grains and fragments range from 0.1 mm to 10 mm in diameter; average grain diameter decreases downhole. Alluvium is generally poorly sorted, but well-sorted sands and silts occur locally. Alteration of grains and fragments is erratic and weak and antedates alluvial deposition. Minor carbonate cement above 215 m. Other features of interest as noted.

NOTES:
Patterning approximately represents relative grain size in alluvium.
(a) Chips of fault gouge in trace to minor amounts erratically scattered below 241 m.
(b) Consistently abundant (up to 5% by volume) detrital magnetite / ilmenite below 521 m.
CC = Carbonate Cement
NS = No Sample

Figure 9. Downhole geophysical logs of well GPC-15 (modified from Glen and Hulen, 1979). Logs show physical properties of basin-fill sediments in the FORGE study area. Note that the labels for the electric logs are incorrect (probably on the original logs as well). The electrical logs for other wells in Glenn and Hulen (1979) suggest that the resistivity range is 0–100 Ohms-m and conductivity units are mS/m.

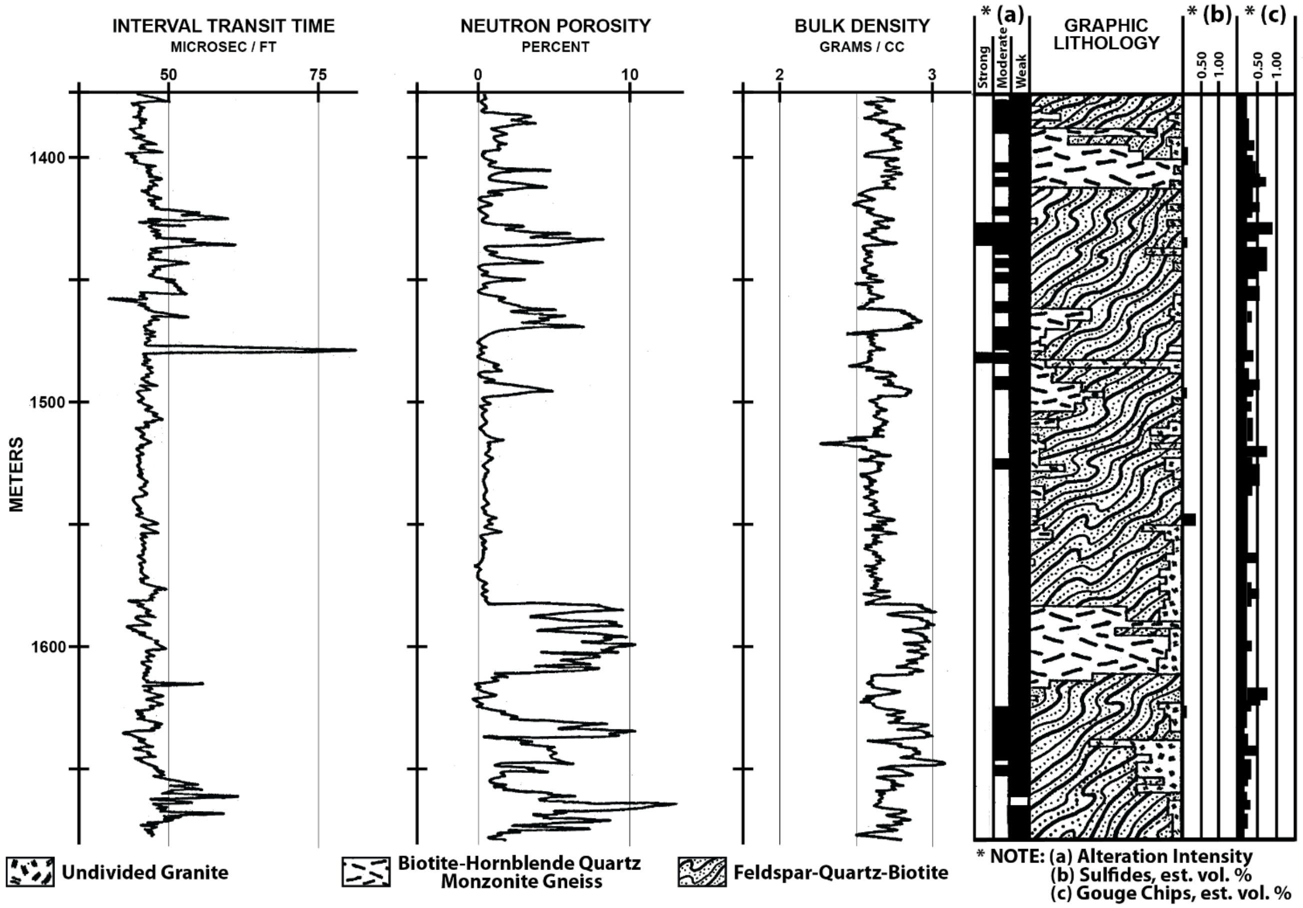


Figure 10. Downhole geophysical logs of well 52-21 (modified from Glen and Hulen, 1979). Logs show physical properties of bedrock in the FORGE study area.

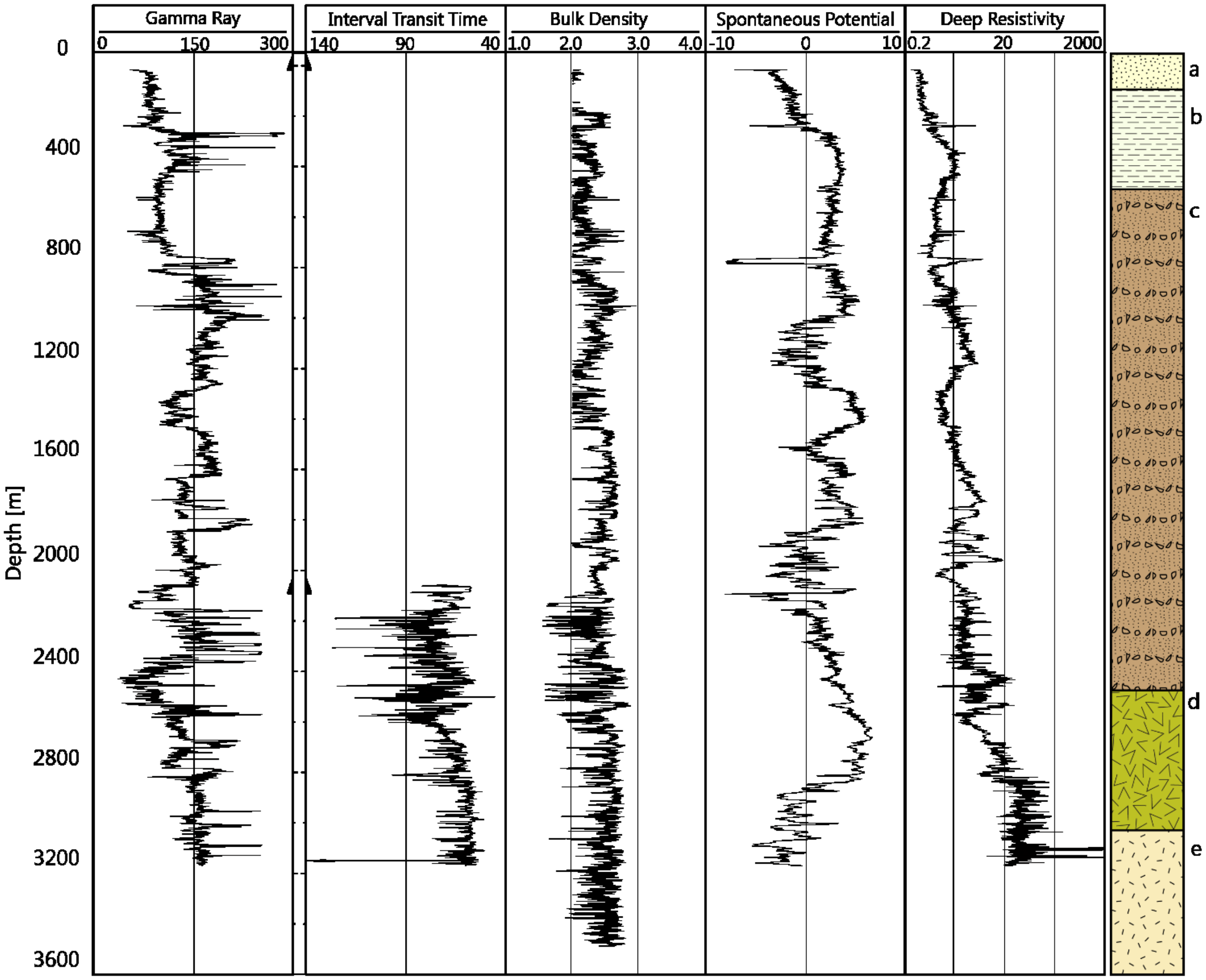


Figure 11. Downhole geophysical logs of Acord-1 well. Logs show physical properties of basin fill and bedrock (3100 m) in the FORGE study area. The stratigraphic column is from the interpretation of Hintze and Davis (2003). Layers are as follows: a) surficial valley fill, b) claystone, c) tuffs and tuffaceous sediments, d) andesite, e) granite.

6. CONCLUSIONS

An extensive suite of geophysical data exists and is available for the FORGE study area near Milford, Utah. The large quality of available data helps to mitigate uncertainties in geophysical models and subsequent interpretations. The gravity anomaly in the Milford valley basin is a low of about 20 mGal. The local gravity field is affected by a regional anomaly related to a physiographic transition zone, which requires more care when computing and modeling the gravity as the standard methods are insufficient. MT data and models indicate that the resistivity of the basin fill is generally 2–3 Ωm and the basement/bedrock is 80–200 Ωm. Such values are consistent with the downhole geophysical logs of wells GPC-15, 52-21, and Acord-1 presented in this paper. Broad, shelf-like structures are observed on the margins of the basin which abruptly change slope, steepening toward the middle of the basin. The deepest area of the Milford basin is in the vicinity of the Acord-1 well. The basement depth from the preliminary model at the Forge drilling area varies from about 300 m on the eastern side to 1 km on the western side with the approximate center being about 500 m ± 200 m. We recently obtained additional downhole logs from exploration wells near the FORGE drilling site that build upon our knowledge and increase our confidence in the preliminary assessment. Logs from a well located near the eastern boundary of the FORGE drilling site show that the granitic basement is at a depth of 500 m and covered by approximately 200 m of re-cemented granite wash. Geophysical data do not indicate that there are other areas as deep as the area near the Acord-1 well, however, further evaluations using true 3D modeling routines and newly discovered data will allow better delineation of basement geometry.

7. ACKNOWLEDGMENTS

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