

A New Look at the Thermal Regime Around Roosevelt Hot Springs, Utah

Mark Gwynn¹, Rick Allis¹, Christian Hardwick¹, Jay Hill¹, and Joe Moore²

¹Utah Geological Survey, Salt Lake City UT

²Energy & Geoscience Institute, University of Utah, Salt Lake City UT

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ABSTRACT

Recent re-evaluation of thermal data from over 100 wells drilled mostly during the 1970s and 1980s in the area of Roosevelt Hot Springs (RHS) has refined earlier interpretations of the thermal regime. These data have been combined with pre-existing gravity and magnetotelluric data to construct a 3-D model of the area as part of the site characterization phase of U.S. Department of Energy's Frontier Observatory for Research in Geothermal Energy (FORGE) initiative. The project goal is to create an enhanced geothermal system (EGS) reservoir in crystalline rock where temperatures of 175 to 225°C are present at depths between 1.5 and 4 km to test development concepts and technology. The 3-D model is amply supported by well data, both in terms of suitable temperatures and depth to crystalline basement (Precambrian gneiss and Tertiary plutons), and shows that FORGE temperature and lithologic requirements can be met over an area of at least 100 km². The total volume of crystalline basement rock with temperatures over 175°C above 4 km depth is more than 100 km³. Temperatures greater than 175°C within plutonic basement rock are expected at depths ranging from about 1.8 to 3.0 km, depending on the specific location, over most of the area best suited for deep FORGE drilling based on land ownership, existing roads, and topographic features. Nearly all of the FORGE area achieves 175°C by 4 km depth. While RHS is an active hydrothermal system, heat transport farther to the west, on the opposite side of the Opal Mound fault, is primarily conductive. The thermal regime based on deep temperatures and reservoir rocks suggests the site is ideal for FORGE development.

Introduction

Roosevelt Hot Springs (RHS) and the surrounding area has been extensively studied since the 1970s. At least five companies, as well as several universities and governmental agencies, have been involved in these efforts, which resulted in the 1984 commissioning of the Blundell Power Plant—the first liquid-dominated geothermal plant in the US (Forrest, 1994). Those early studies, as well as many others undertaken since then, have produced a large quantity of geothermal and other geologic data (Allis et al., 2016). These data are summarized in Ward et al. (1978), Wilson (1980), Ross et al. (1982), Nielson et al. (1986), Faulder (1991, 1994), Moore and Nielson (1994), and many other works. Allis et al. (2015) used pre-existing data to re-evaluate the thermal regime in the RHS area while investigating the suitability of the area for development as the U.S. Department of Energy's (DOE) FORGE site. Most of the gradient data outside of the RHS hydrothermal system used by Allis et al. (2015) were from Wilson (1980) along with some unpublished data from Dr. David Chapman at the University of Utah. Allis et al. (2016) discuss the many obvious geological and logistical benefits of the location as the FORGE site. In addition to the gradient data from Dr. Chapman and Wilson (1980), new FORGE site characterization efforts include gradient data from Sill and Bodell (1977) and AMAX (1998), which were compiled by Edwards (2013), along with other types of pre-existing data. The additional data and new interpretations highlight a need to further report on the thermal regime in and around RHS.

The Milford FORGE site and RHS are located about 15 km and 19 km, respectively, northeast of the City of Milford in southwestern Utah (Figure 1). Both are located near the western flank of the Mineral Mountains, which are comprised largely of Oligocene-Miocene plutonic rocks (intermediate to felsic compositions) and Precambrian gneiss. The plutonic rocks and the gneiss both extend westward into the basin at depth and are here considered as basement. Basin fill consists of Tertiary volcanic strata overlain by Quaternary fluvial-lacustrine deposits (Glen and Hulen, 1978; Glenn et al., 1980; Sweeny, 1980; Welsh, 1980; Nielson et al., 1986; Coleman and Walker, 1992; Coleman et al., 1997; Hintze and Davis, 2003; Jones and Moore, 2016).

Thermal Regime

Measured Temperature Profiles

Geothermal exploration efforts in Milford Valley have resulted in the drilling of over 100 thermal gradient, exploration, and production/injection wells, most of which were drilled in the 1970s and 1980s. Our database consists of 82 shallow or intermediate (< 500 m) depth wells and 22 wells deeper than 500 m (Figure 1). However, 11 undocumented, plugged gradient wells have been found, so the actual number of wells drilled in the area is likely greater. The mapped locations of these wells strongly suggest they are not simply wells from our database with flawed location data. Hopefully, records for these additional wells will be located in the future. An interactive map showing the location of the 104 known wells and their associated thermal data, along with hydrologic and geochemical data, has been developed and can be viewed at <http://www.forgeutah.com/site/>.

One of the most important wells in the area is Acord-1, drilled to 3.8 km in 1979 by McCullough Oil Company and located about 9 km WNW of RHS (Figure 1). No fluid was produced and the well was plugged and suspended. Mud temperatures obtained while drilling indicate a steady increase with increasing depth as do uncorrected temperatures recorded during numerous deviation surveys. These trends are characteristic of a conductive thermal regime (Figure 2).

Bottom-hole temperatures obtained during downhole logging operations at four depths were corrected for drilling disturbances using the method of Henrikson and Chapman (2002) and confirm a temperature of $230 \pm 5^\circ\text{C}$ at total depth. When combined with the temperature gradient observed in the nearby groundwater supply well (McCullough) used for the drilling of Acord-1, a geotherm can be fitted to all the data, which allows the increase in thermal conductivity with increasing depth to be calibrated (k values in Figure 2). The geotherm implies a heat flow of $120 \pm 20 \text{ mW/m}^2$, with most of the uncertainty originating from thermal conductivity estimations.

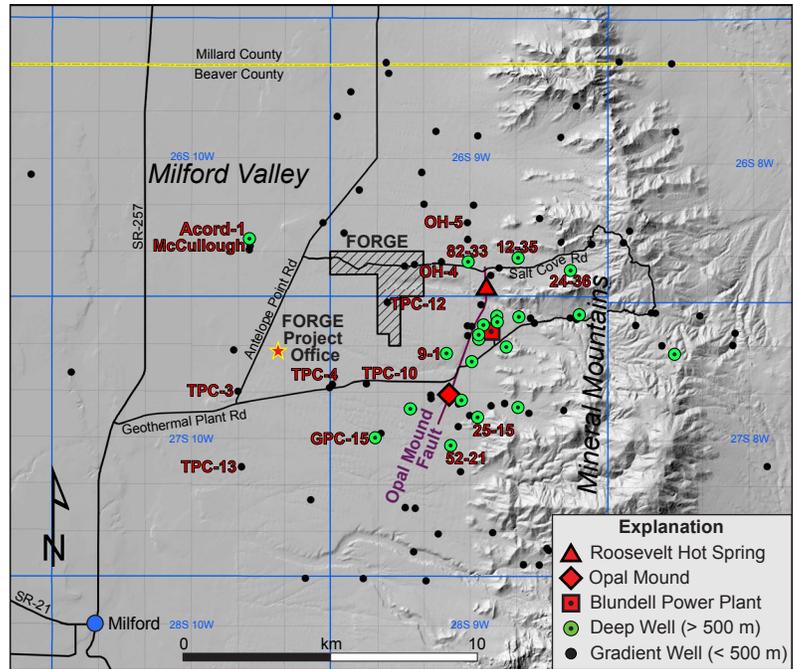


Figure 1. Location of the FORGE drill site (hatched polygon), FORGE office area, Acord-1 well, and other wells drilled in the area.

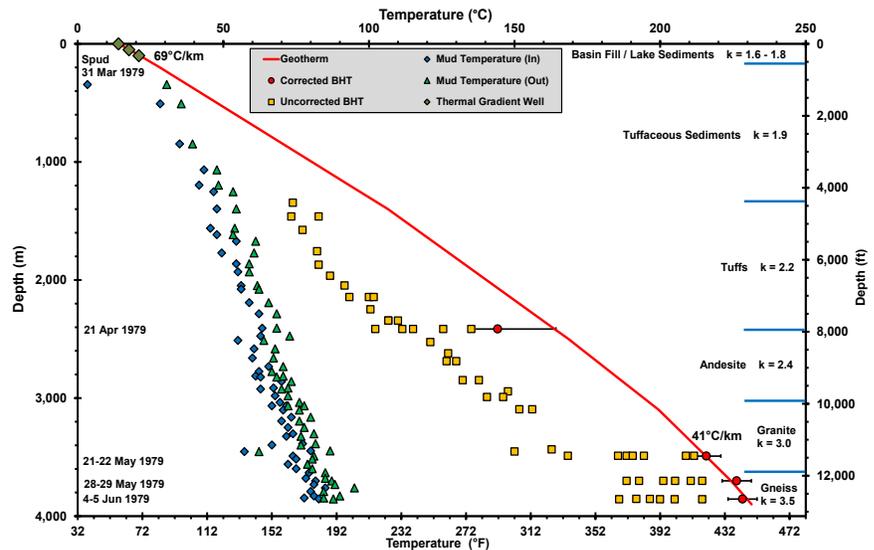


Figure 2. Temperature data from Acord-1. The bottom hole temperatures (BHTs) are consistent with a conductive profile, and the best-fit geotherm has a heat flow of $120 \pm 20 \text{ mW/m}^2$ (uncertainty due to thermal conductivity [k] assumptions); geotherm fits both the observed shallow thermal gradient at the site and the deep, corrected BHTs). The temperature gradient in the granite is 41°C/km . The thermal conductivity variation with increasing depth is used to calculate geotherms from other thermal gradient wells in northern Milford Valley.

Figure 3 shows the temperature-depth profiles for a selection of shallow-intermediate depth wells along with the shallow segments of several deeper wells. Thermal gradients (and heat flows) increase from the middle of Milford Valley toward Opal Mound fault and the RHS hydrothermal system. Conductive gradients range from about 65°C/km (Acord-1) to over 100°C/km. Near-surface gradients are higher (>150°C/km) in some wells such as 82-33 and 9-1, both located west of Opal Mound fault, that are influenced by shallow outflow from the hydrothermal system. Many of the shallow temperature profiles from wells east of the Opal Mound fault exhibit boiling-point-for-depth curves indicative of hydrothermal upflow and suggest reservoir temperatures as high as 270°C (Faluder, 1994; Figure 4). Although conductive heat flow can be calculated, the total heat flow is convective and the temperature profiles are controlled by steam-water saturation conditions and hydrostatic pressure gradients. Well 24-36 is the easternmost deep well near the northern end of the hydrothermal system and exhibits a concave-upwards temperature profile representing near-surface temperatures depressed by meteoric recharge from the Mineral Mountains. This trend can also be seen in some other wells in or near the mountains.

Extrapolated Temperatures

Wells deeper than 50 m were used to map temperatures at 200 m depth in northern Milford Valley (Figure 5). Shallower wells were not used due to the greater uncertainty associated with extrapolating their gradients to 200 m. Most wells between 50 and 200 m deep showed well-established conductive gradients that could be extrapolated to 200 m or more with reasonable certainty. Because of the topographic highs and lows for wells on the eastern side of the study area (on the flank of the Mineral Mountains), these wells were extrapolated to a depth of 200 m below the 1830 meters-above-sea-level (asl) datum (6000 ft asl), which is the approximate elevation of the alluvial fan at the base of the mountains. This approach smooths the contours across the ridges and valleys of the Mineral Mountains, but does require some higher-elevation wells be extrapolated to as much as 405 m below the actual

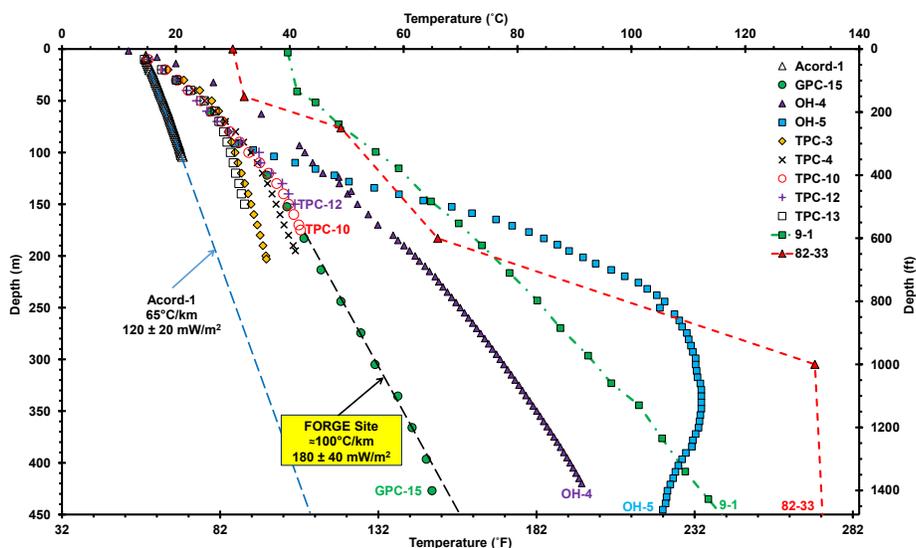


Figure 3. The thermal regime in selected geothermal gradient wells, together with the upper portion of thermal profiles from the three deep wells west of the Opal Mound fault zone. The thermal gradients vary from 50 to 65°C/km in the central valley and increase east towards the Opal Mound fault zone. TPC-12 is within the FORGE deep drilling site and indicates a deeper gradient of close to 100°C/km. Well RHS-14 indicates higher temperatures and is located 300 m east of the western boundary of the FORGE deep drilling site. The profiles for 82-33 and 9-1 are from Faluder (1994).

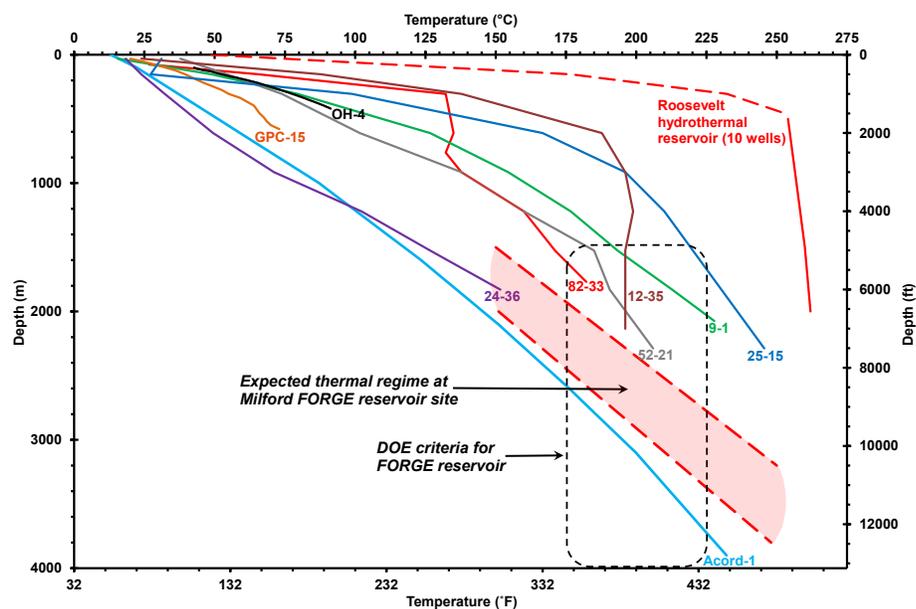


Figure 4. Likely thermal regime at the Milford FORGE deep drill site based on profiles in surrounding deep and thermal-gradients wells (locations in Figure 1). The expected thermal regime beneath the site lies centrally within the bounding constraints specified by DOE. The two red dashed lines bound the likely uncertainties. The nearest wells to the site are 9-1 and 82-33, and are mostly in granite; the only wells mostly in basin fill are Acord-1, GPC-15 and OH-4. Productive wells tapping the Roosevelt hydrothermal system lie east of the Opal Mound fault and have near-surface temperature profiles that follow boiling-point-for-depth conditions. The hydrothermal well profiles represent pre-development conditions; subsequent fluid production has lowered some of these profiles by more than 300 m (Allis and Larsen, 2012).

land surface. Farther to the west, the contours are all at 200 m depth from the surface, which is at about 1525 m asl (5000 ft asl) near SR-257 in the middle of the valley. Thus wells to the east are extrapolated to about 1630 m asl and wells to the west are extrapolated to elevations as low as 1325 m asl. As expected, the highest temperatures occur around the RHS hydrothermal system just to the east of the Opal Mound fault. The map shows that an 80°C lobe extending to the northwest from the northern end of Opal Mound fault is an outflow feature, although the thermal regime west of Opal Mound fault is primarily conductive and isolated from the RHS hydrothermal system. The area with temperatures greater than 40°C at 200 m depth is about 100 km². Allis et al. (2015) presented a similar map based on fewer and lower quality data that was superficially similar, except for the more truncated northwest outflow plume.

A heat flow map of northern Milford Valley was developed from the abundant gradient data (mainly from wells less than 200 m deep) and the very detailed thermal data extending to almost 4 km depth in Acord-1 (Figure 6). Thermal conductivity increases with depth, and the trend that was determined to generate the best-fit geotherm through the basin fill in Acord-1 is assumed to apply to the basin fill sequences in all wells. This implicitly assumes that the alluvium and lake sediments all have uniform physical characteristics and a similar compaction trend with increasing depth. Geotherms were then developed and matched to the temperature profiles in all wells having reliable data to calculate the heat flow. A thermal conductivity value of 3.0 W/m°C was used for the appropriate portions of any geotherms that penetrated basement rock (granite and gneiss).

We estimated that the heat flow value for each data point is about ±20 to 30% based primarily on uncertainties inherent in using assumed thermal conductivity values and whether the well had recovered to thermal equilibrium at the time of temperature logging. As many of

Figure 6. Contours of conductive heat flow derived from wells around the Roosevelt Hot Springs hydrothermal system (mW/m²). Most values are from the gradients in wells less than 200 m deep. Very high heat flows over the hydrothermal system reflect high temperature gradients overlying upflowing hot water, which at shallow depth is constrained by boiling-point-for-depth conditions. West of the hydrothermal system (the Opal Mound fault) the thermal regime is conductive at depth and follows a pattern of decreasing heat flow towards the west. A-A' defines the ends of the geologic cross section shown in Figure 9.

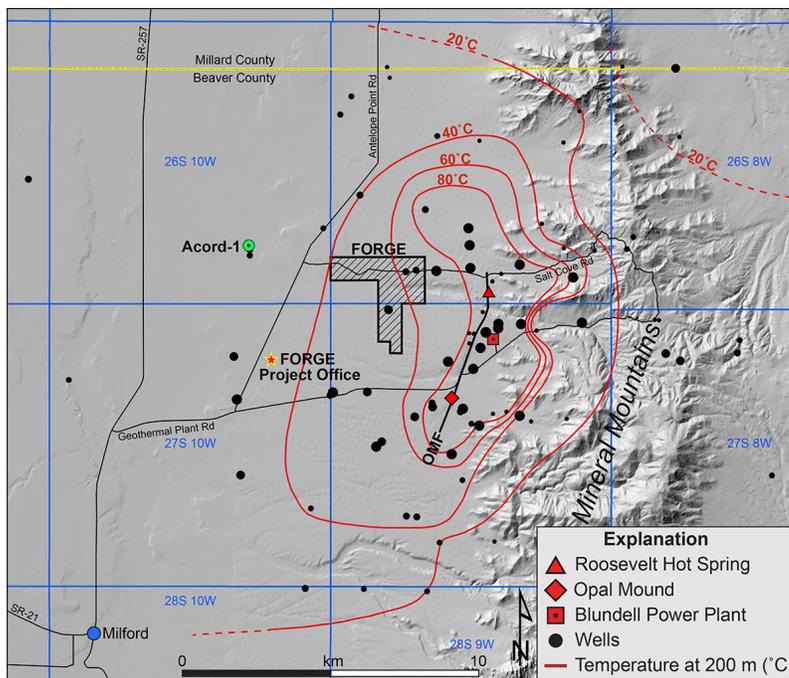


Figure 5. Temperature at 200 m depth beneath and in the vicinity Roosevelt Hot Springs and the FORGE deep drill site in northern Milford Valley. The size of the filled circle at each well location represents the degree of certainty of the temperature data, which constrain the geometry and positions of isotherms. The largest diameter circle represents wells greater than 200 m depth where the temperature was measured. The smallest diameter circle represents wells at least 50 m deep where the temperature had to be extrapolated to depth. On the east side, the contours represent the temperature at 200 m below the 1830 m above sea level datum, the approximate elevation of the alluvial fan near the Mineral Mountains. This approach allows the contours to be smoothed across the ridges and valleys, but requires that higher-elevation wells be extrapolated to greater depths (up to 405 m from the actual ground surface). Farther to the west, the contours are at 200 m depth from the surface, which is about 1325 m asl near SR-257 in the middle of the valley. OMF is the Opal Mound fault.

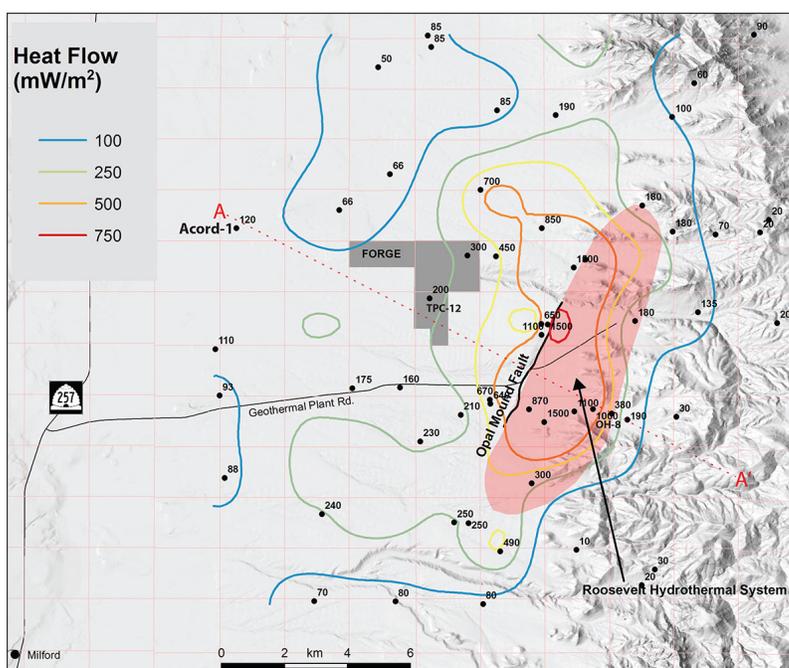
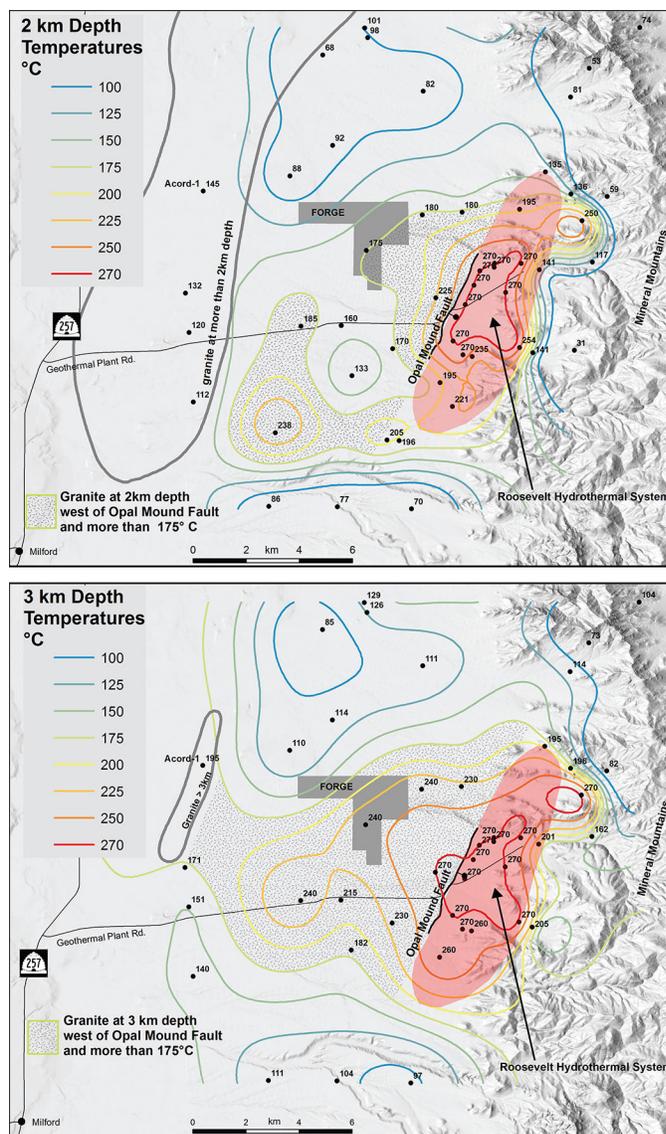


Figure 7. Contours of temperature at 2 and 3 km depth derived from observations in deep wells and geotherms fitted to thermal gradient wells. Temperature contours have been smoothed using kriging options in ESRI's ArcMap software, and typically have a geostatistical mean uncertainty of $\pm 13^\circ\text{C}$ depending on adjacent well data. The stipple highlights where granite at that depth is hotter than the minimum FORGE reservoir temperature constraint of 175°C . On the 3 km map, granite hotter than 175°C extends significantly west and north of Acord-1, but has not been shown because of inadequate well control. The red shading shows the extent of the Roosevelt Hydrothermal System based on pressure measurements in deep wells (see Allis et al., 2016).

these wells were logged quite some time after drilling, we assumed the larger portion of uncertainty can be applied to thermal conductivity values, although drilling disturbances to in situ temperatures likely plays a role in some wells. The contours of the heat flow map are somewhat similar to that produced by Ward et al. (1978), particularly in delineating the northwest outflow zone, although their heat flow magnitudes tend to be somewhat higher. The outflow zone in Figure 6 is also generally coincident with that shown in Figure 5.

The calculated heat flow data was then used, in conjunction with temperature profiles from the deep exploration wells in and around RHS to map temperatures at depths of 1, 2, 3, and 4 km. Figure 7 shows the maps for 2 and 3 km depths. Geotherms for the gradient wells were constructed using the depth-to-granite values determined from gravity modeling and using the thermal conductivity variations with depth obtained from the Acord-1 well. The maximum temperature of 270°C in the vicinity of RHS is limited by measured gradients. With the possibility that the wells were not at thermal equilibrium when measured, errors could be as great as $\pm 10\%$. Contours were fitted for the rest of the subsurface volume using ESRI's ArcMap geostatistical kriging. The mean (geostatistical) contouring error ranges from ± 12 to 14°C .



3-D Visualization Model

Thermal data were combined with topographic and basin geometry data to generate a 3-D thermal model to help visualize and better understand the thermal regime in the FORGE/RHS area. A snapshot of the model is shown in Figure 8, with some modifications and additions to make the snapshot easier to interpret. However, along with the interactive map and other geological/geophysical data, the model can best be viewed and manipulated (rotated in any plane, features turned on or off, etc.) at <http://www.forgeutah.com/site/>. The thermal basis for the model are the five isotherm maps previously discussed (200 m and 1–4 km depths) and the simplified subsurface geology that was derived from gravity, magnetotelluric, and other well data (see Hardwick et al., 2016).

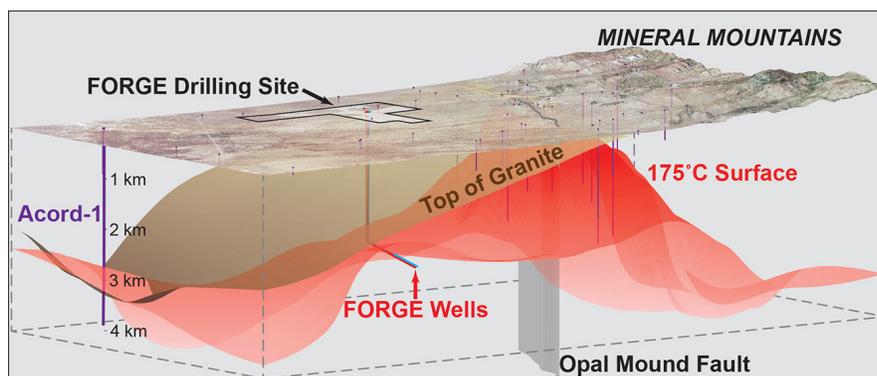


Figure 8. Modified snapshot from the 3-D model showing topography, the brown upper surface of the granite, and the red 175°C surface. Existing wells are purple. View to the northeast with no vertical exaggeration.

The DOE requirements for FORGE specify a minimum temperature of 175°C within a reservoir composed of crystalline rock, so the 175°C surface and the interpreted top of the granitic pluton are primary features of the model. These surfaces were generated using the topo-to-raster tool in ESRI's ArcMap software.

Discussion

Three unproductive deep wells drilled west of Opal Mound fault reveal poor permeability within the granite and conductive thermal gradients, indicating that the fault marks the western extent of the active RHS hydrothermal system. Subsurface temperatures and heat flows are highest in, and adjacent to, the hydrothermal system, but are anomalously high over much of the valley. East of the Opal Mound fault, many of the shallow temperature profiles exhibit boiling-point-for-depth profiles, indicative of hydrothermal upflow (Figure 4).

Maps of the temperatures at 200 m depth and heat flow (Figures 4 and 5) define the limits of the RHS hydrothermal system as well as an outflow plume extending to the northwest from the northern end of Opal Mound fault and show that the area west of the fault is primarily conductive and anomalously hot.

Low heat flows (mostly around 20 mW/m²) in the upper elevations of the Mineral Mountains indicate cool meteoric recharge. Anomalously low heat flows (about 50–70 mW/m²) are found in a few wells in the central part of the valley north of the FORGE deep well site. The mean conductive heat flow in the Great Basin is 85–90 mW/m² (Lachenbruch and Sass, 1978; Blackwell, 1983; Morgan and Gosnold, 1989), and heat flow in the surrounding wells that are beyond the influence of the RHS hydrothermal system generally fall within the expected range. Low gradients of about 30°C/km are found in these low-heat-flow wells at relatively shallow depths of 50 to 100 m. The shallow depth of the gradient measured in each of these wells is a likely reason for the apparently low heat flow and, although these wells were used to calculate deeper temperatures, we suspect actual temperatures are higher.

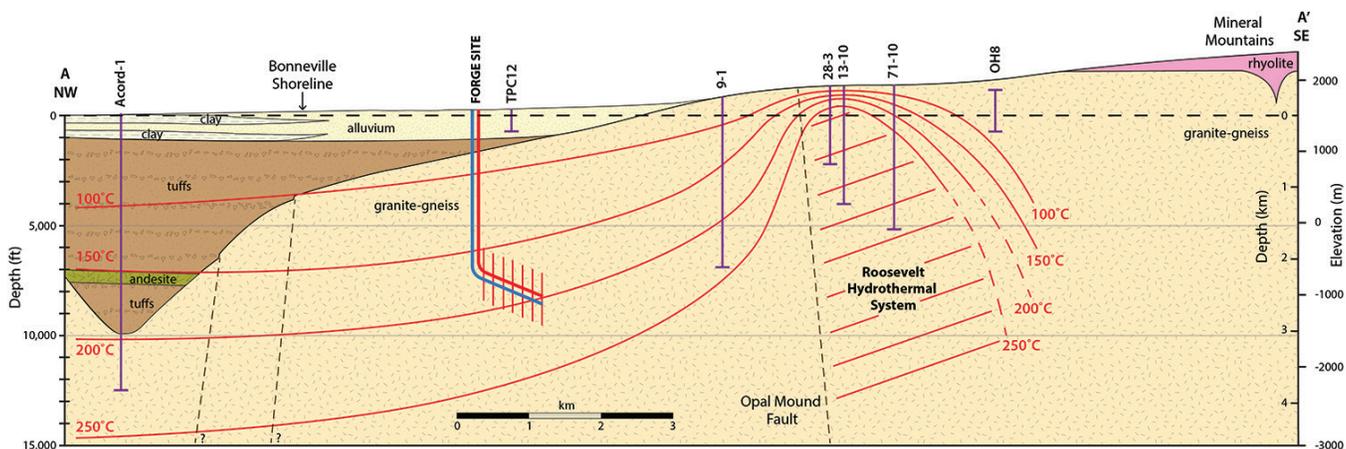


Figure 9. Geologic cross section A-A' from Figure 6, showing the stratigraphy, structure, and the FORGE deep well site. The zero datum for the depth axes is at 1524 m asl (5000 ft asl). Precambrian gneiss and Tertiary plutonic rocks are undifferentiated. The Roosevelt Hot Springs hydrothermal system lies east of the Opal Mound fault. Isotherms are interpreted from well measurements, and the contact between granite-gneiss and overlying basin fill is interpreted from gravity measurements (Allis et al., 2016; Hardwick et al., 2016). The trajectories of the FORGE deep wells deviate towards the southeast from the western side of the deep-well site. The lower part of the basin fill in Acord-1 has been interpreted to contain about 1 km of andesite (Hintze and Davis, 2003), however, subsequent logging and X-ray Diffraction analyses of the cuttings suggests the andesite is much thinner and interlayered with volcanoclastics and tuffs (Janae Wallace, Utah Geological Survey, personal communication, 2016; Jones and Moore, 2016).

Conductive heat flows in many areas are greater than would be expected based solely on the location within the Great Basin, therefore some additional heat source is implied. Robinson and Iyer (1981) attribute an “intensely anomalous region of low velocity and high attenuation”, roughly centered over RHS and extending from a depth of about 5 km to the base of the crust, to be the result of a small fraction of partial melt. Anomalous He³/He⁴ in RHS geothermal fluids support this interpretation (Kennedy and van Soest, 2007).

Integration of all temperature gradient data shows that a large area of anomalously high conductive heat flow, covering about 100 km², surrounds the FORGE deep well site west of the Opal Mound fault. The total volume of crystalline basement rock having temperatures over 175°C above 4 km depth is more than 100 km³. The Opal Mound fault forms the eastern boundary of the conductive thermal regime and isolates it from the Roosevelt Hot Springs hydrothermal system where convective heat flow prevails over a much smaller area of about 10 km². These results are summarized in geologic cross section shown in Figure 9.

Conclusions

The thermal regime around Roosevelt Hot Springs has been extensively studied by the geothermal industry, academia, and governmental agencies since the 1970s. These studies, as well as development of the Blundell Power Plant resulted in a number of databases of various levels of detail and quality. Sorting and compiling these data has yielded temperature and depth data from 104 wells, creating a much more complete set of well data than has ever been available for the RHS area.

The well data reveal that in addition to the hydrothermal reservoir that supplies the Blundell plant, there is an extensive area with high heat flow that is primarily conductive in nature. The conductive thermal regime is influenced by its location within the high-heat-flow Great Basin as well as an additional heat source suspected to be residual partial melt at depths below about 5 km and roughly centered below the hydrothermal system. Conductive heat flow approaches normal Great Basin levels with increasing distance to the west. Well data also decreases to the west, so it is difficult to fully delineate the extent of the above-background thermal anomaly. However, the Acord-1 well shows that heat flow is still at least 100 mW/m² over 10 km west of the hydrothermal system and suggests the anomaly may be around 100 km².

Opal Mound Fault marks the western limit of high permeability associated with the convective Roosevelt hydrothermal system. While heat transport west of the Opal Mound Fault is predominantly conductive, shallow outflow to the northwest does occur beyond the northern tip of the fault, creating a bulge in the mapped heat flow contours. This outflow lobe has been mapped before (Ward et al., 1978), but additional well data used in this study better constrains the heat flow magnitude and areal extent of the lobe. Maps of the overall thermal anomaly (convective and conductive zones) in terms of temperature at depths of 0.2, 1, 2, 3, and 4 km were created from the well data. The 0.2 km temperature map (Figure 5) also shows the RHS outflow to the northwest, but the lobe is not present on the deeper maps, confirming the outflow is restricted to shallow depths within unconsolidated sediments. The temperature maps show that anomalously high subsurface temperatures extend far to the west within the conductive zone comprised of basin fill and crystalline basement, and that over 100 km³ of the basement at depths less than 4 km is at least 175°C. The results of this study further refine our understanding of the thermal regime in and around Roosevelt Hot Springs and show that a large part of the area is geothermally ideal for development as the FORGE site.

Acknowledgments

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