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EGS Concept Testing and Development at the Milford, Utah FORGE Site

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ABSTRACT

The Milford FORGE site, located 16 km northeast of Milford City, Beaver County, and 350 km south of Salt Lake City, is ideal as an Enhanced Geothermal System (EGS) field laboratory. The site is underlain by large volumes of granite and gneiss at temperatures in the range of 175–225°C at 2 to 4 km depth. A deep exploration well, Acord-1, drilled in 1979 to 3.8 km depth 5 km from the proposed deep drill site, encountered granite and gneiss at 3.1 km depth and a temperature at total depth of 230°C. The well did not produce fluids and its conductive temperature profile indicates the crystalline rocks at depth are impermeable. Several deep wells are situated between the eastern edge of the FORGE drill site and the Roosevelt Hot Springs geothermal system supplying the 35 MW Blundell plant located about 4 km to the east. These wells confirm the near-surface presence of granite and gneiss, high temperatures, and poor permeability at depth, demonstrating the FORGE site is outside any active hydrothermal system. All of the wells have been extensively logged, with data and cuttings available for further analysis. The existing Acord-1 well, which was plugged and suspended, will be entered and cleaned out to provide open-hole access to hot crystalline rocks prior to the drilling of the FORGE wells. Considerable infrastructure is available near the FORGE site, including power and fiber-optic cable for real-time data streaming, a major paved road, airport, graded gravel roads that are maintained year round, a rail line, and supportive private landowners. A motel and eating establishments are available in Milford and in the larger community in Beaver, Utah, located 35 km farther away. Environmental Impact Statements at neighboring wind, solar and transmission sites indicate no threatened or endangered species, and minimal risk of cultural/historic sites. The project has secured sufficient groundwater, which is not potable for human or agricultural use, but is suitable for drilling, stimulation, and heat exchange testing. The site is adjacent to a 300 MW wind farm, a 240 MW solar photovoltaic plant under construction, and several large transmission lines.

1. INTRODUCTION

A site near Milford, Utah, has been chosen by the Department of Energy (DOE) as one of five possible sites for testing and demonstrating new technologies that advance geothermal heat extraction from naturally 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 geothermal characteristics of the Milford site, including the surrounding infrastructure that is available to support the diverse research that will be carried out. Two additional papers accompany this paper: the geology and hydrology are reviewed by Simmons et al. (2016), and the geophysical characteristics are reviewed by Hardwick et al. (2016).

2. INFRASTRUCTURE

Milford, which is 16 km south of the proposed site, is incorporated as a city in Beaver County, and has a population of 1400 (Figure 1). It has good motel accommodation (with 24-hour diner), a supermarket, hardware store, and a hospital. A major factor in Milford's history is the Union Pacific Railroad (UPR), which passes through the town and has a siding complex and an office to facilitate freight train scheduling in this part of the state. The railroad offers the possibility of shipping drilling and stimulation equipment (e.g. pipe, pumps) by rail and then using truck transport for the final 16 km to the FORGE site. The Milford Municipal Airport, with a sealed 1525 m runway that is suitable for piston or turboprop, single- or twin-engine planes, is located two miles north of Milford. The proposed site is 350 km south of Salt Lake City, and the drive time is about 3 hours. The site is accessible year round, snow is infrequent, with Beaver County providing snow plow service on the graded gravel roads near the drill site and office.

The FORGE project will require significant power for operating pumps for both groundwater supply and the circulation of water through the stimulated reservoir during heat exchange testing. The Milford FORGE site is situated in a major energy corridor linking northern Utah and Wyoming to southern California. On the west side of this energy corridor is the high voltage direct current (HVDC) transmission line between the 1800 MW Intermountain Power Agency (IPA) coal-fired power plant near Delta (central Utah), and southern California. The power plant and transmission line is owned by the Los Angeles Department of Water and Power. The line has a capacity of 2400 MW, and also carries power from the 300 MW wind farm adjacent to the FORGE site (owned by SunEdison, originally FirstWind). On the east side of Milford valley, and crossing over the FORGE site, is a new transmission line recently commissioned by PacifiCorp Energy. This line has a capacity of 600 MW and operates at 345 kV. A third, 138kV line designed to improve transmission capacity in the Milford region was energized in December 2015 (between Beaver and Milford; operated by Rocky Mountain Power, a subsidiary of PacifiCorp Energy; line not shown on Figure 1). A second, 3000 MW HVDC transmission line is proposed to parallel the LADWP line and is waiting for environmental clearance from BLM. This Transwest line will link new wind power generation in Wyoming with the southern California power market. The main natural gas pipeline into Southern California (Kern River) passes between the FORGE site and the Blundell geothermal plants of PacifiCorp Energy (35 MW). In addition to the geothermal and wind power generation, the FORGE site is adjacent to a 240 MW solar photovoltaic array that will be commissioned in July 2016 (operated by SunEdison). The FORGE site is positioned in a possibly unique cluster of utility-scale renewable power generation.

The site offers future private-sector power developers the opportunity to expand geothermal power generation assuming the technology demonstration is successful. Towards the end of Phase 3 of the FORGE project, when a long-duration flow test is planned, it may be possible for power generation to connect to the local grid.

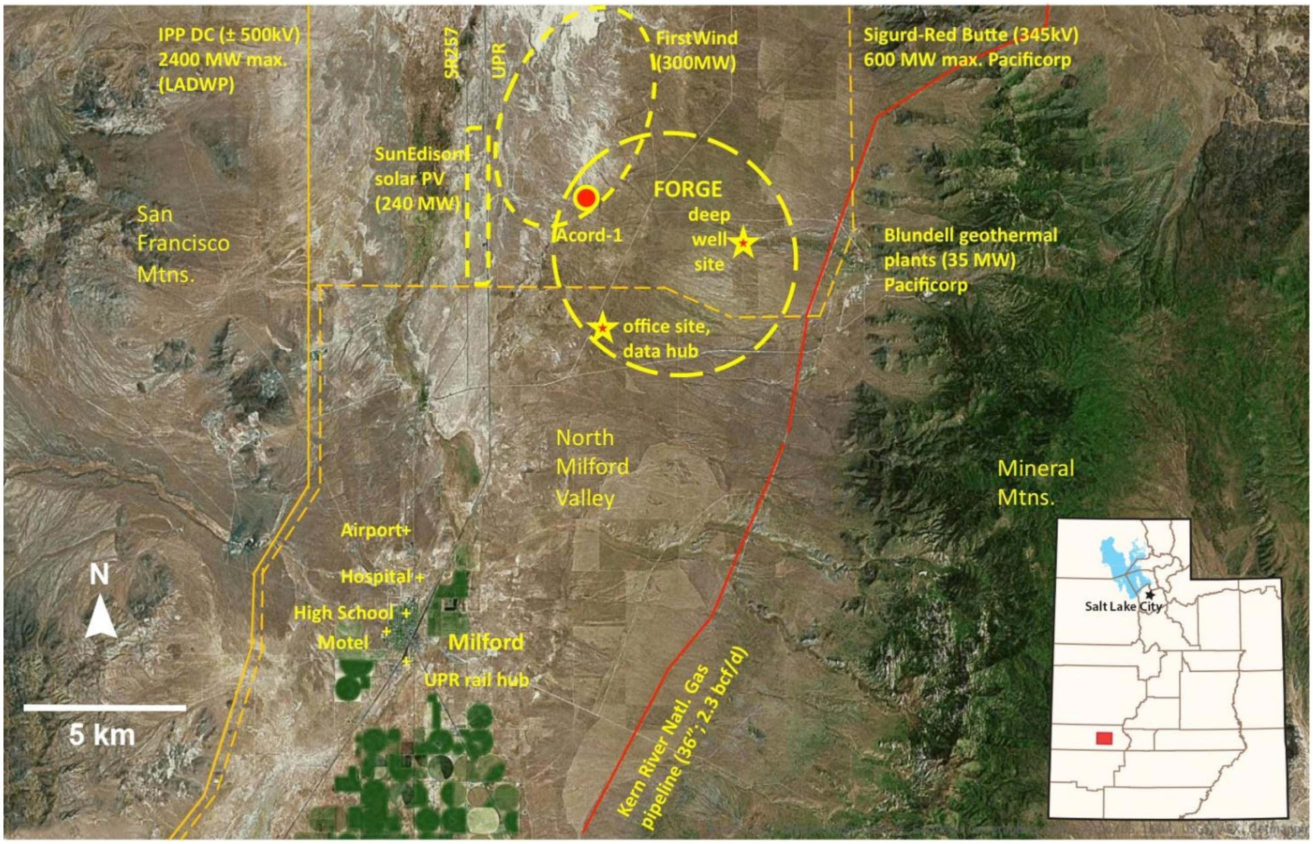

Figure 1: Large-scale infrastructure near the Milford, Utah FORGE site. The site is situated within an energy corridor and is surrounded by several transmission lines, and utility-scale wind, solar-photovoltaic, and geothermal power plants. Roosevelt Hot Springs is situated east of the FORGE drill site. Note the absence of agricultural activity in the vicinity of the drill site due to low-quality groundwater.

The Milford FORGE site is situated on gently sloping, undeveloped grass land (Figure 2). Replanting of the grass in northern Milford Valley occurred after the 2007 Milford Flat fire, the largest wildfire since pioneer settlement of Utah. Although there is heavy agricultural development in southern Milford valley (see center pivots in Figure 1), similar development north of Milford has been inhibited by poor groundwater quality. The groundwater west of the Mineral Mountains has a strong geothermal signature due to the outflow from the Roosevelt Hot Springs hydrothermal system, which is now developed by the Blundell geothermal power plants (Capuano and Cole, 1982; Ross et al., 1982; Moore and Nielsen, 1994; Allis et al., 2012, 2015). Chloride and boron are distinctive signatures of this outflow. This was recently confirmed by SunEdison, who drilled a groundwater supply well at their wind farm maintenance facility (well "Q" in Figure 3) and found warm water of poor quality (32°C, total dissolved solids greater than 4000 mg/L; Simmons et al., 2016). A 24 hour pump test of this well has shown this part of the valley is capable of yielding sufficient water for the needs of the project. A water right for as much as 60 million liters per year of groundwater has been secured from the Utah State Engineer for the duration of the project. Smithfield (a commercial hog-farm operator with undeveloped land in the FORGE area) has offered to supply a similar amount in any year when this is insufficient. Two groundwater wells near the proposed project site office are expected to provide the required supply.

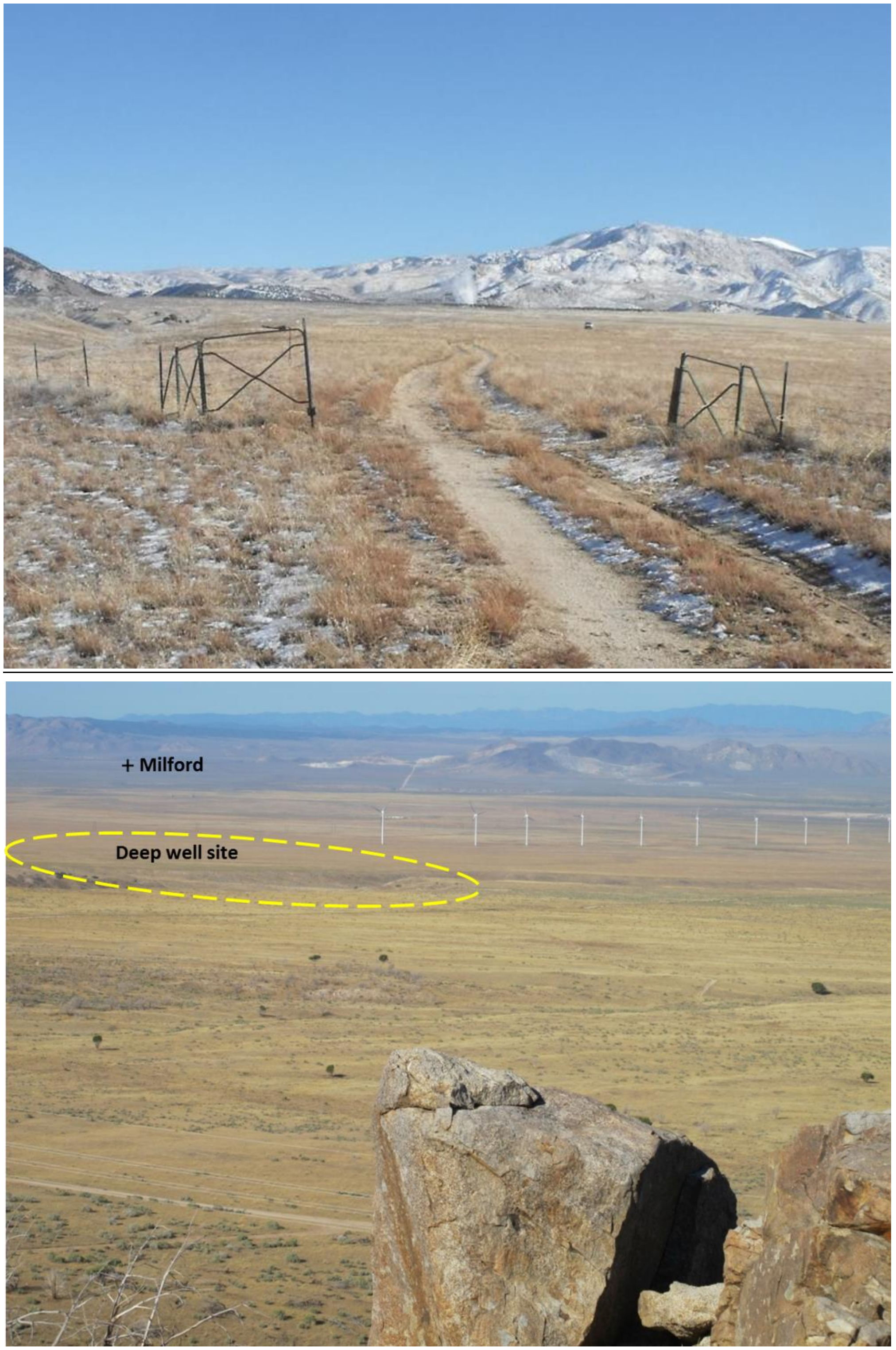

Figure 2: Two views of the Milford FORGE site. Upper photo is looking east, with the vehicle in the middle distance close to the center of the proposed deep well site. The steam plume from the cooling tower of the Blundell power plants is visible (near the center of the photograph) against the western flank of the Mineral Mountains and is 4.5 km from the fence line. The lower photo looks southwest over granite boulders to the deep well site, with Milford City in background, and an array of wind turbines to the west.

The site has a mix of private landowners, including Smithfield (with the largest holdings), Utah School and Institutional Trust Lands Administration (SITLA), and the Bureau of Land Management (BLM) being the main owner of surrounding lands. Smaller parcels are owned by other private landowners. There are three components to the FORGE site: a 5 km^2 (2 mi^2) deep-well site, the 3.8 km -deep Acord-1 well, and a project office site that will include the main groundwater supply wells, and a data collection hub connected to an existing fiber optic line (Figure 1). Smithfield owns the land around Acord-1 and the project office site, and half of the deep well site. Both Smithfield and SITLA, the main landowners of the deep-well site, are very supportive of the project. The BLM field office in Cedar City has indicated they support approval of project activities such as geophysical surveying, drilling thermal gradient wells or wells for downhole seismometers, and a groundwater pipeline with adjacent vehicle access across their land around the FORGE site. They have indicated there are no issues related to threatened or endangered species here, and no known cultural sites where we have proposed “casual use” activities. PacifiCorp Energy is supportive, and has provided access to data collected during exploration and development phases of the power plant. Beaver County has participated in stakeholder meetings and is also supportive.

3. MILFORD BASIN CHARACTERISTICS

During the late 1970s at least five geothermal exploration companies were drilling in north Milford Valley as they assessed the extent of the Roosevelt Hot Springs hydrothermal system (RHS). The DOE at that time was supporting geothermal research, and there were many projects carried out by staff and students at the University of Utah. Much of the exploration data was preserved and published. Reassessing all the research indicates over 80 shallow thermal gradient wells and 20 deep wells were drilled, over 20 theses were written, and more than 150 reports and papers on the RHS and the surrounding geologic setting were published. Geothermal power generation ultimately focused on a 5 km^2 (1235 acres) area east of the Opal Mound Fault where the most productive, high-temperature wells were drilled. The development and effects of production and injection on the reservoir at the RHS are reviewed by Allis and Larsen (2012). The location of the FORGE site compared to the wells is shown in Figure 3.

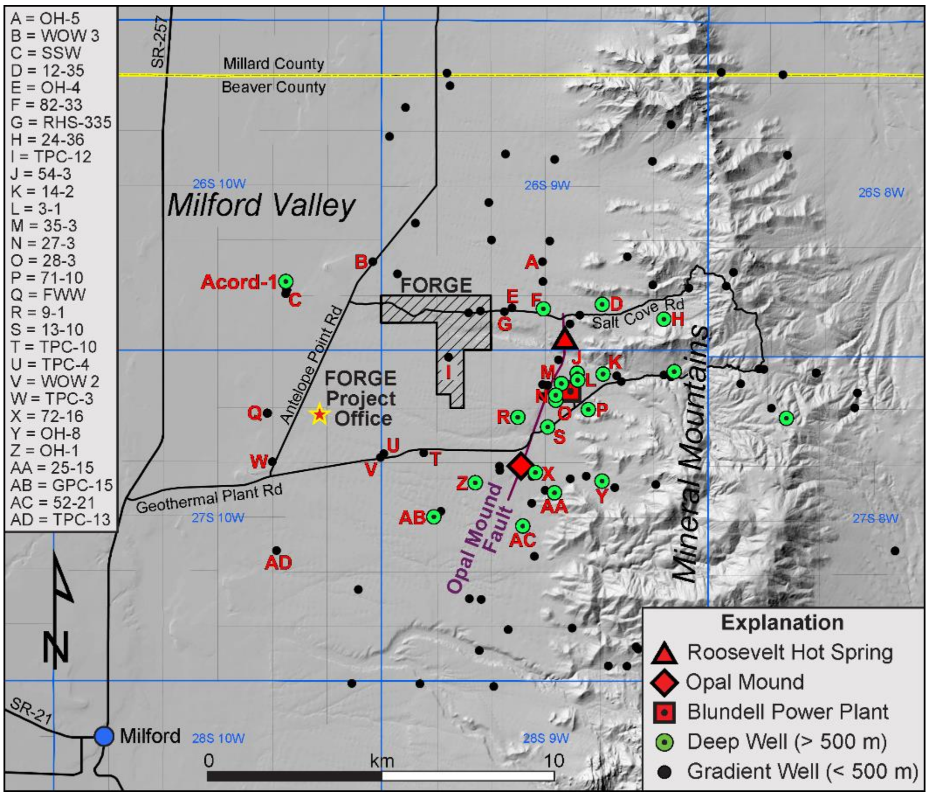

Figure 3. Location of the FORGE drill site and office area, Acord-1 well, and otherwells drilled in the area, on a shaded relief map. Wells referred to in the text are labeled alphabetically. Two additional deep wells are not shown in the cluster around the Blundell Power plant due to space constraints: 45-3 and 58-3. Production wells during the 30 years of Blundell operation have been 3-1, 54-3, 35-3, 45-3, 27-3, and 13-10; injection wells have been 14-2, 82-33, 12-35, and recently, 71-10.

Gravity surveying shows a major basin trending NNE-SSW underlies north Milford Valley (Hardwick et al., 2016). Alluvial fans derived from erosion of the Mineral Mountains gently slope towards the Beaver River over a distance of more than 10 km. Near the center of the basin are deposits from paleo Lake Bonneville, which had a high-stand 18,000 years ago. The axis of the deepest the part of the basin coincides with the location of Acord-1 at about 3 km depth. Gravity modeling shows the deepest part of basin is relatively narrow compared to the overall width of the valley between the Mineral Mountains and the San Francisco Mountains to the west (Figure 4). The steep flanks of the inner basin are suspected to be fault-controlled. The eastern edge of this inner basin is 2 km west of the FORGE deep well site, and the deep well site is situated over a west-sloping granite surface. The depth to the granite at the center of the deep well site is 400 ± 200 m.

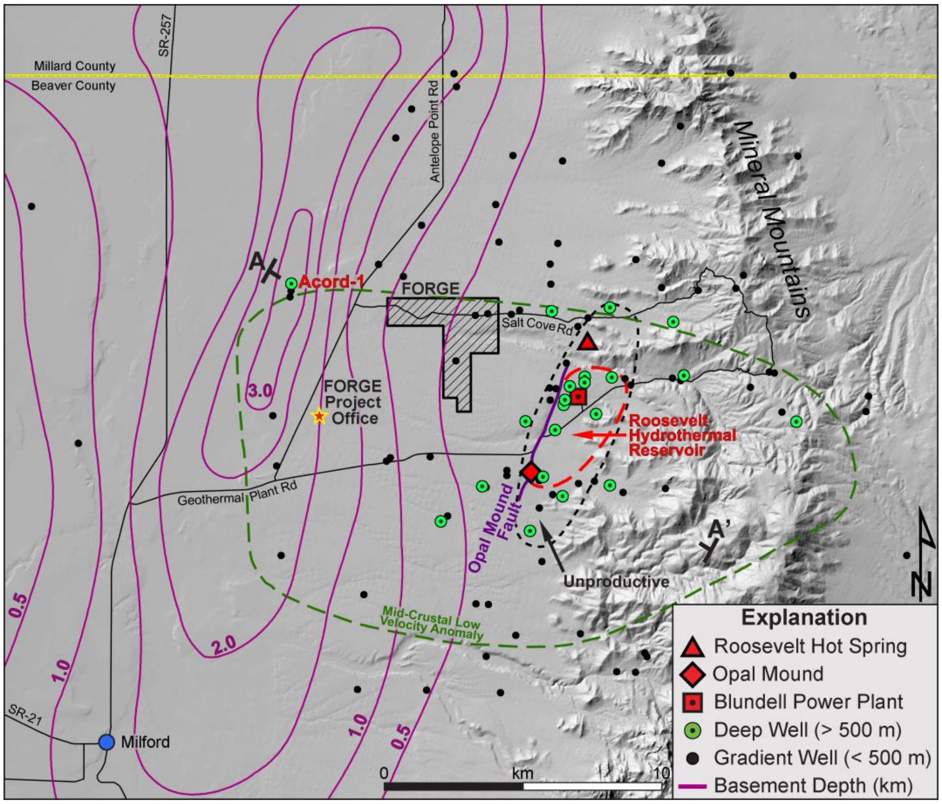

Figure 4. Contours of depth to granite bedrock beneath north Milford Valley (Hardwick et al. 2016) on shaded relief basemap. A – A' mark the line of cross section shown in Figure 10. The mid-crustal low velocity contour outlines a zone of anomalously low P-wave velocity and high attenuation below 5 km depth (Robinson and Iyer, 1981). Potentially productive wells of the Roosevelt hydrothermal system are surrounded by a zone of unproductive pressure-connected wells.

4. THERMAL CHARACTERISTICS

Analysis of the thermal gradient data shows the shallow thermal anomaly extends over most of north Milford Valley (Figure 5). Peripheral wells around north Milford Valley suggest temperatures at 200 m depth are about 20°C. In the Mineral Mountains, non-thermal temperatures range between 5 and 12°C. The area with temperatures above 40°C at 200 m depth covers about 100 km^2 and includes the FORGE deep well site. The pattern of isotherms is similar to the near-surface heat flow map first published by Ward et al. (1978). The 80°C isotherm at 200 m depth approximately coincides with the 1000 mW/m^2 contour on their near-surface heat flow map. Ward et al. (1978) interpreted the high heat flow area east of the Opal Mound fault as the main area of hydrothermal upflow, with the extension of this high heat flow to the northwest from Roosevelt Hot Springs as an outflow feature. The integrated heat output from the hydrothermal system was estimated at 60 MW_{th}. Reinterpretation of all the thermal data suggests subsurface outflow of fluid from the Opal Mound fault zone along at least a 10 km length, which implies it extends 4 km south of the mapped fault (Figures 3, 4). This helps explain the widespread geochemical signature of geothermal water in groundwater over much of the north Milford Valley.

4.1 Acord-1

Acord-1 was drilled to 3.8 km depth in 1979 by McCullough Oil Company. No fluid was produced and the well was plugged and suspended because of lack of production. It was permitted by the Utah State Engineer as a geothermal exploration well, and logging measurements were filed with this office. Cuttings for the entire length of this well are preserved at the Utah Core Research Center of the Utah Geological Survey. Mud temperatures while drilling indicate a steady increase with increasing depth (Figure 6). Correction of bottom-hole temperatures at logging intervals confirms a temperature of 230 ± 5°C at total depth. When combined with the temperature gradient observed in the nearby groundwater supply well 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 6). The geotherm implies a heat flow of 120 ± 20 mW/m^2, with most of the uncertainty originating from uncertainties in thermal conductivity.

Acord-1 is lightly plugged between 300 and 365 m, and between 0 and 15 m depth (Figure 6), with the rest of the well filled with mud. A seven inch liner was cemented in the well between 2409 m and 3400 m, leaving an open hole in the granite and gneiss between 3400 and 3852 m depth. Shannon et al. (1983) identified Acord-1 as a hot dry rock prospect, recommending that it be hydraulic-fractured below 3100 m depth. The present owner of the well, Smithfield, will allow the FORGE project to clean out the well and use it for testing. Although this well is now 35 years old and the condition of the casing and cement is unknown, we hope that this well will be available for testing instruments prior to them being lowered into the relatively expensive, deviated wells in the deep well site.

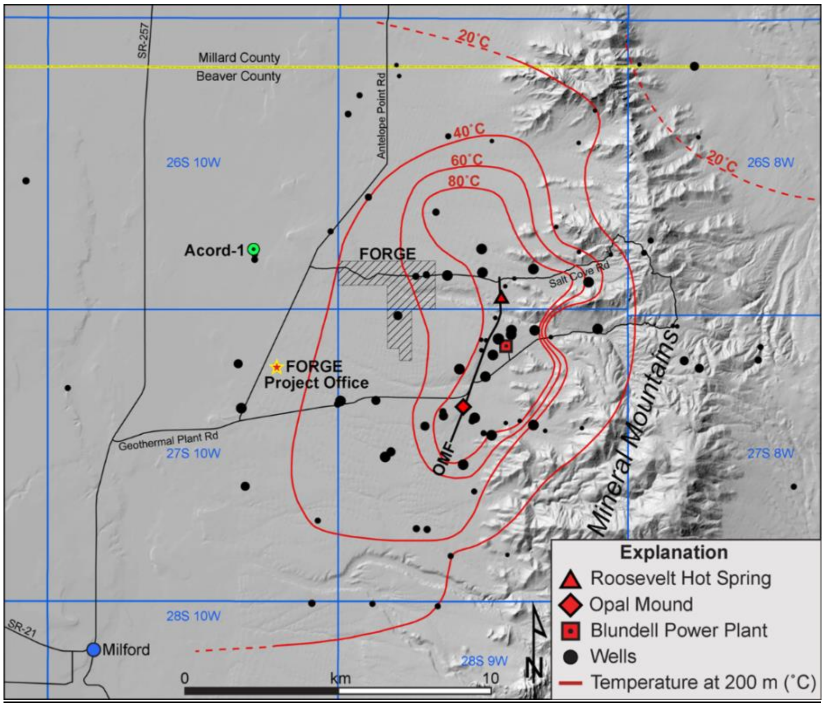

Figure 5. Temperature at 200 m depth in north Milford Valley. The degree of certainty of the thermal data is indicated by the size of the dot for the well location (all wells deeper than 50 m). The largest size is for wells greater than 200 m depth where the temperature was observed. The smallest size is for wells about 50 m deep where the temperature had to be extrapolated to a much greater depth and the temperature is considered the least certain. On the east side of the thermal anomaly, the contours represent the temperature at 200 m below the 1830 m above sea level (6000 ft asl) datum, which is the elevation of the alluvial fan near to where it laps against the Mineral Mountains. This 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 surface). Farther to the west, the contours are at 200 m depth from the surface, and near SR-257 in the middle of the valley this is at about 1325 m asl (4345 ft asl; ground surface about 5000 ft asl or 1525 m asl). OMF is the Opal Mound fault.

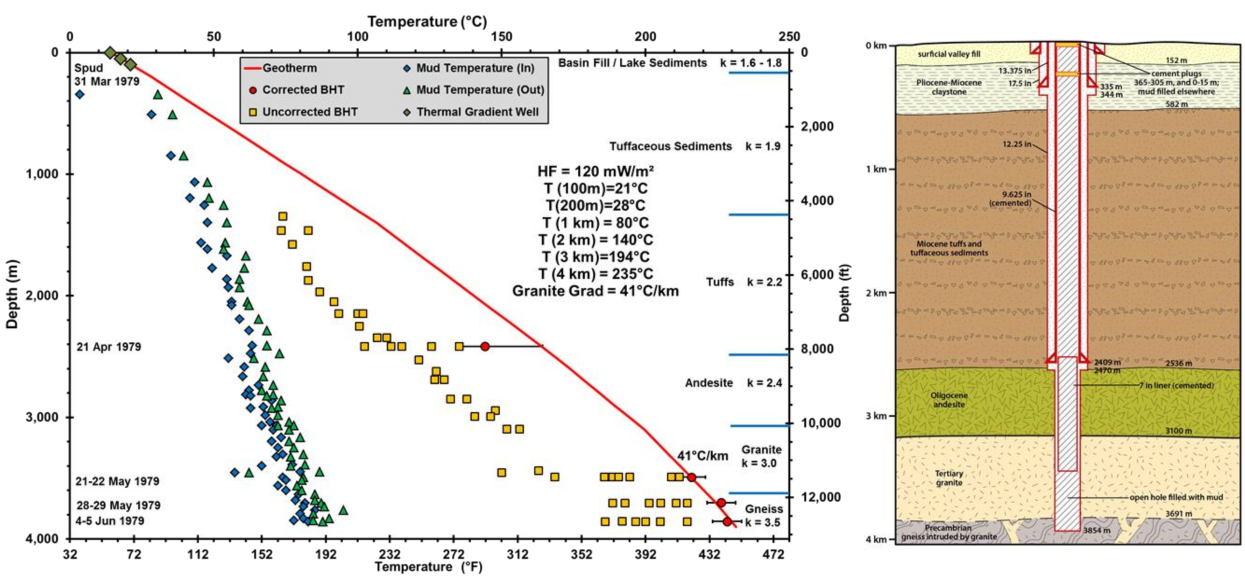

Figure 6. Temperature data from Acord-1 (graph on left) and the casing and cement status after it was plugged and suspended (right). The bottom hole temperatures (BHTs) are consistent with a conductive profile, with the best-fit geotherm having a heat flow of 120 ± 20 mW/m^2 (uncertainty due to thermal 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. Temperatures at depth increments between 200 m and 4 km are used as input to 3-D thermal modeling. The thermal conductivity variation with increasing depth is used to calculate geotherms from other thermal gradient wells in the north Milford Valley.

4.2 Shallow Temperature Gradients

A selection of shallow temperature profiles from wells between the central Milford Valley and the Opal Mound fault is shown in Figure 7 (see Figure 3 for locations). In the central valley, the heat flow increases from 90 mW/m^2 (TPC13 or AD on Figure 3; and TPC-3, W) in the south around Geothermal Plant Road, to 120 mW/m^2 further north in Acord-1. Wells farther north around the county line have heat flows of 70 ± 20 mW/m^2 (not shown on Figure 3). Midway between Acord-1 and the Opal Mound fault the heat flows are typically in the range 180 ± 20 mW/m^2 (TPC-12, I; TPC-4, U; TPC-10, T). These wells are representative of the heat flow beneath the central part of the FORGE deep well site. Farther to the east, the heat flows are significantly higher at depths less than about 500 m. However, comparison with the deep wells 9-1 (R) and 82-33 (F), which are both west of the Opal Mound fault, suggests the shallow temperatures are being affected by outflow from the hydrothermal system. The near-surface gradients exceed 150°C/km and heat flows can be in the range of 300 to more than 1000 mW/m^2 (for example, well RHS-335 (G), Figure 7). These gradients cannot be extrapolated much below 500 m depth, and when RHS-335 is compared to deep well 9-1, the gradients are clearly decreasing with increasing depth.

East of the Opal Mound fault, many of the shallow temperature profiles exhibit boiling-point-for-depth profiles, indicative of hydrothermal upflow. Although conductive heat flows can be calculated, the total heat flow is actually convective and the temperature profiles are controlled by steam-water saturation conditions, that is, pressure.

4.2 Deep Thermal Regime

Figure 8 shows temperature profiles in non-productive deep wells drilled around the Roosevelt Hot Spring system, the profile of wells drilled into the hydrothermal upflow, and two intermediate-depth wells on the adjacent alluvial fan (east of Opal Mound fault). With the exception of Acord-1, all deep wells are in granite or gneiss with less than 100 m of alluvium on top. Intermediate depth RHS-335 and GPC-15 (AB) did not reach granite basement. The trend of decreasing temperature gradients with increasing depth in the upper kilometer near the Opal Mound fault highlights the potential error in extrapolating shallow gradients to greater depth. Below about 1 km depth, the profiles trend towards gradients of 50 - 70°C/km, indicating temperatures of 150°C to more than 200°C at 2 km depth, and 200°C to more than 250°C at 3 km depth. Well 12-35 (D) is near the northern end of the Opal Mound fault and may be sensing vertical fluid movement at 190 - 200°C. Well 82-33 is northwest of the Opal Mound fault and is in the middle of the shallow outflow from the hydrothermal system shown on Figure 5, but it confirms conductive thermal gradients and higher temperatures at greater depth. Well 24-36 (H) is the easternmost deep well near the northern end of the hydrothermal system, and is distinctive with a concave-upwards temperature signature. Another intermediate-depth well that is east of the southern end of the hydrothermal upflow (OH-8, Y on Figure 3; profile not plotted here) has a similar signature of increasing temperature and gradient with depth. This pattern is repeated in other wells in the Mineral Mountains, and is indicative of cold meteoric recharge depressing the near-surface temperatures.

Deep (productive) wells inside the Roosevelt Hot Springs hydrothermal reservoir have boiling point profiles at less than 500 m depth, and trend toward the system upflow temperature of about 270°C at greater depth (Figure 8 and Faulder, 1994). Outside of the hydrothermal reservoir, the wells are unproductive and have deep temperature gradients of 50 - 70°C/km, indicating deep conductive heat flows of 150 to more than 200 mW/m^2. Despite the similarity in gradients at depth, the temperatures at 2 km depth between wells vary by up to 100°C depending on the near-surface thermal conditions related mainly to the hydrothermal outflow. It is not known how deep or how hot the temperature profiles can be extrapolated to. Thermal models for this FORGE project assume a maximum temperature of 270°C. The pattern of deep conductive temperature gradients surrounding the hydrothermal reservoir is consistent with a large volume of low permeability, hot granite, which is the target of the FORGE project.

Modeling of the deep thermal regime on the alluvial fan between Acord-1 and the Opal Mound fault is based on calculating heat flows and fitting geotherms to the thermal gradient wells with apparently reliable data. The trend of increasing thermal conductivity with depth derived from the best-fit geotherm through the basin fill for Acord-1 has been assumed to apply to all wells. This implicitly assumes the basin fill everywhere has similar lithologies and a similar compaction trend with increasing depth. Once the geotherms reach the granite surface (depth from gravity modeling, Hardwick et al., 2016; and Figure 4) a thermal conductivity of 3 W/m°C is assumed. Compilation of the geotherm trends has allowed maps of isotherms to be compiled at 1 km increments down to 4 km depth. Here we show the maps at 2 and 3 km depth (Figure 9). Because of the thermal and depth constraints for the FORGE deep well site provided by DOE, the area of each map where there is granite exceeding the lower temperature limit for the FORGE laboratory, 175°C, has been highlighted. The 2-km depth isotherms indicate that the eastern edge of the FORGE deep well site satisfies this condition. At 3 km depth, most of the site has a temperature of more than 175°C, and the eastern side of the site may exceed the high-temperature limit of 225°C. The deep well site therefore provides a range of depths for optimizing reservoir stimulation and thermal heat recovery.

A NW-SE cross-section of the thermal regime is shown in Figure 10. The figure shows the deep wells deviated towards the southeast from the western side of the deep-well site. Final decisions on the best location and deviation direction for the deep wells will await the characterization research in Phase 2 of this project. The 100 and 150°C isotherms are near-horizontal and cross from granite to tuffs without obvious deflection despite a thermal conductivity contrast (2.0 to 3.0 W/m°C) because of the compensating effects of increasing heat flow from east to west (120 mW/m^2 at Acord-1 to 180 mW/m^2 at the FORGE site).

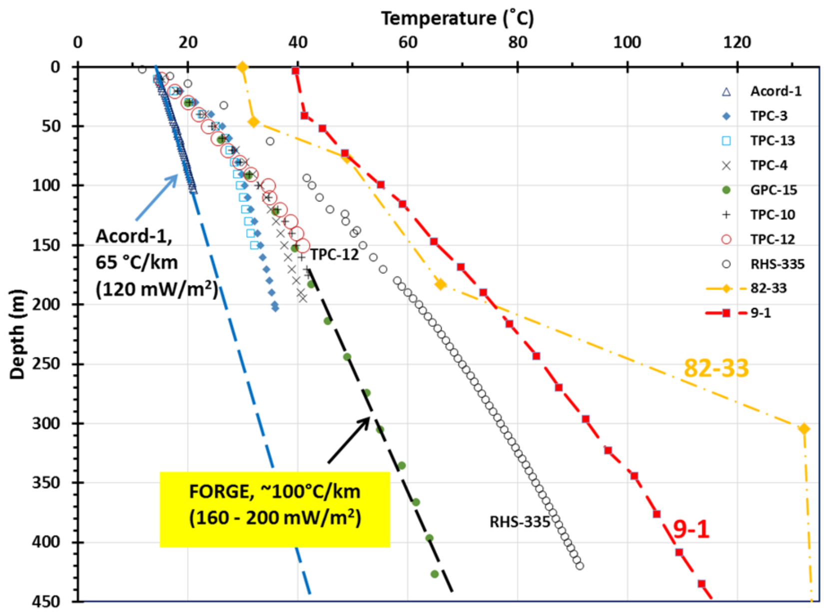

Figure 7. Details of the thermal regime in selected geothermal gradient wells, together with the upper portion of thermal profiles from the three deep wells west of the Opal Mound fault zone. The thermal gradients vary from 50–65 °C/km in the central valley and increase east towards the Opal Mound fault zone. TPC-12 is within the FORGE deep drilling zone and indicates a deeper gradient of close to 100°C/km. Well RHS-335 indicates higher temperatures and is located 300 m east of the western boundary of the FORGE deep drilling zone. All wells are located on Figure 3. The profiles for 82-33 and 9-1 are from Faulder (1994).

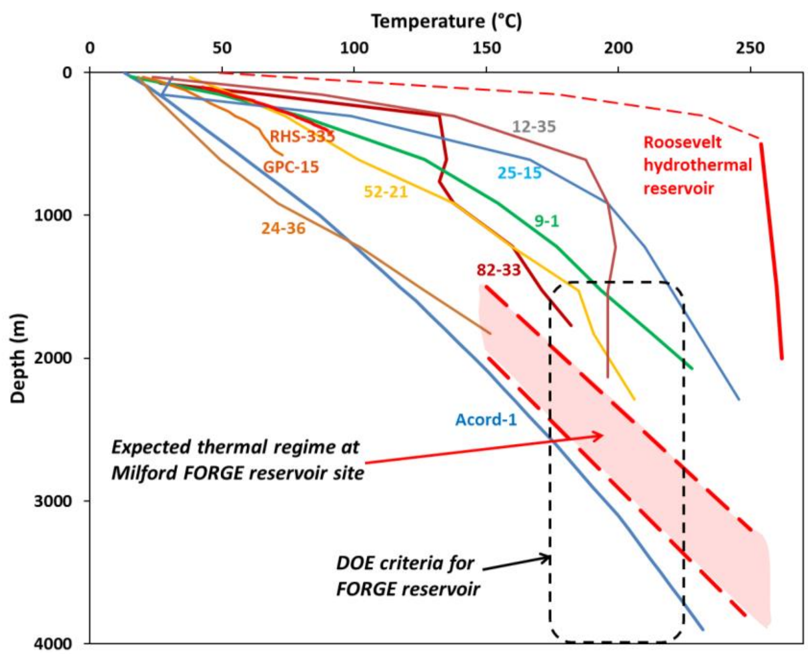

Figure 8. Likely thermal regime at the FORGE deep drilling site based on profiles in surrounding deep wells, and the thermal gradients in shallow wells shown in Figure 7. The expected thermal regime beneath the site lies centrally within the bounding constraints specified by DOE. The two dashed lines 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 RHS-335. The locations for all wells can be found on Figure 3. Productive wells tapping the Roosevelt hydrothermal system lie east of the Opal Mound fault with near-surface temperature profiles that follow boiling-point-for-depth conditions. The hydrothermal well profiles represent pre-development conditions; development of the reservoir has lowered these profiles by more than 300 m.

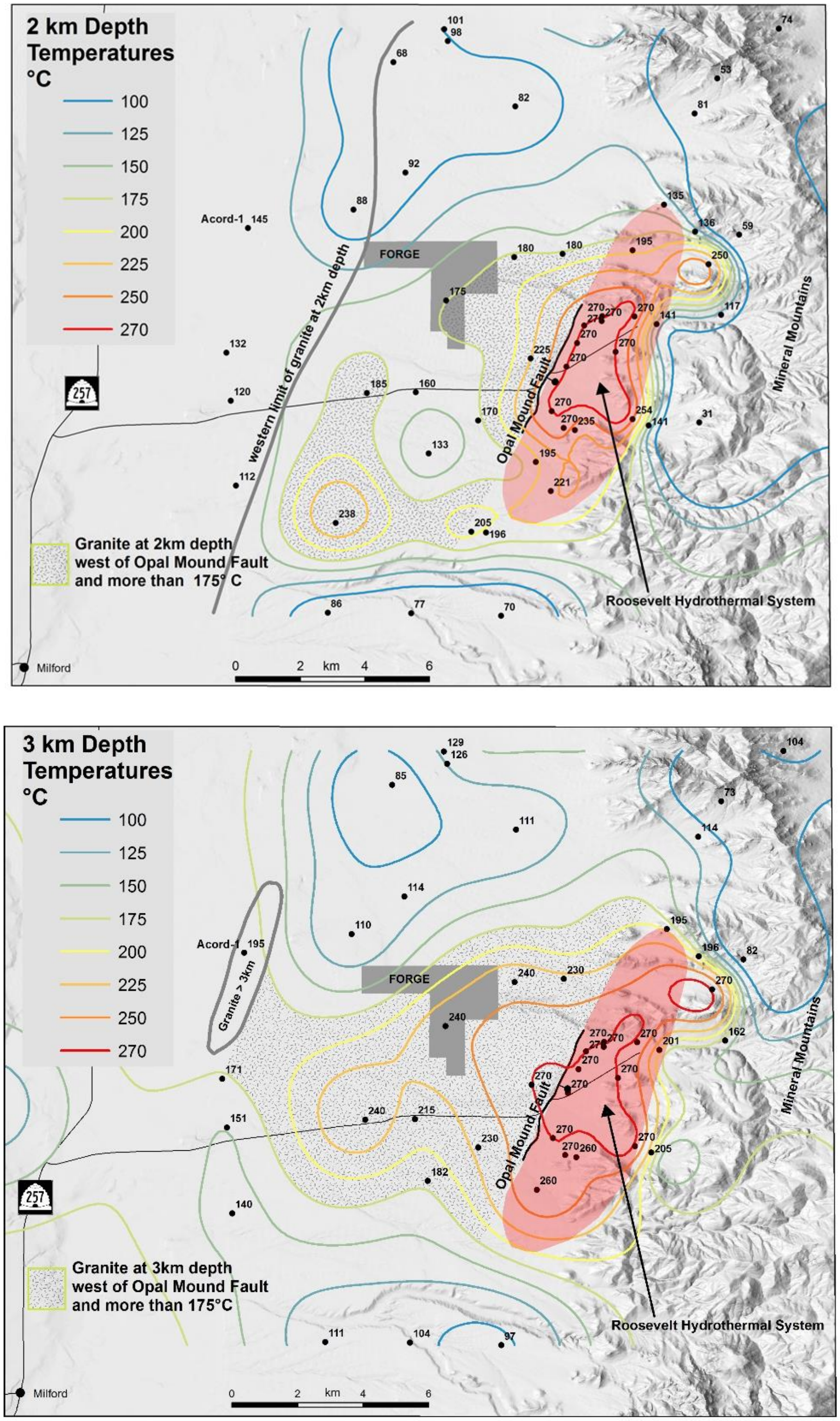

Figure 9. Contours of temperature at 2 and 3 km depth derived from observations in deep wells and geotherms fitted to thermal gradient wells. Temperature contours have been smoothed using kriging options in ESRI's ArcMap software, and typically have an uncertainty of ± 10°C depending on adjacent well data. The appropriate contour for the granite surface has been superimposed from Figure 4. The stipple highlights where granite at that depth is hotter than the minimum reservoir temperature constraint of 175ºC. On the 3 km map, granite hotter than 175ºC extends significantly west and north of Acord-1, but has not been shown because of poor well control.

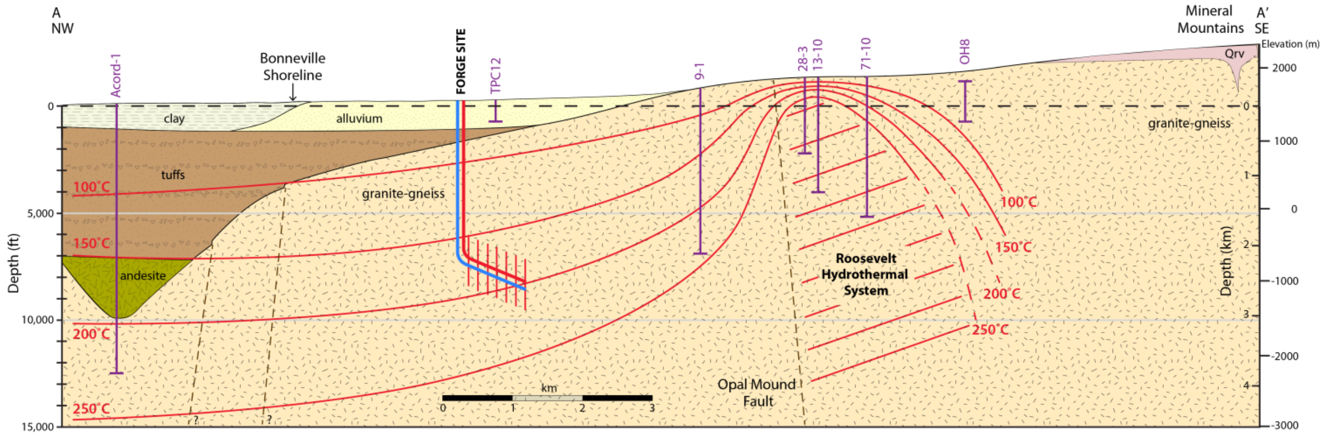

Figure 10. Cross-section showing granite with a temperature of more than 175°C extends at least 10 km west of the Opal Mound fault. The Roosevelt Hot Springs hydrothermal system appears to be about 2 km in width east of the Opal Mound fault. The zero datum for the depth axes is at 1525 m asl (5000 ft asl). The line of cross-section is shown on Figure 4. The isotherms between Acord-1 and the FORGE site cross the granite surface without major deflection because the change in heat flow compensates for the thermal conductivity contrast.

5. FLUID PRESSURE TRENDS

Deep wells east of the Opal Mound fault had a uniform pressure profile consistent with hot water with a density of 800 kg/m^3 prior to significant production (Allis and Larsen, 2012; Figure 11). The one deep well west of the Opal Mound fault with reliable pressure data, 82-33, had a pressure profile about 3 MPa lower than wells in the hydrothermal system. The primary pressure control point in 82-33 is at a major loss zone in granite at 600 m. The two pressure points in Faulder (1994) are consistent with cold water with a density of 1000 kg/m^3. The potentiometric head for 82-33 is at about 1600 m asl. This compares to the elevation of the Roosevelt Hot Spring at 1800 m asl, and the potentiometric head of the hydrothermal wells at about 1900 m asl.

There is one other intermediate-depth well west of the Opal Mound fault, GPC-15, with a water level at 165 m depth, implying a head at 1525 m asl (5000 ft asl; Glenn and Hulen, 1979). Several other shallower water wells on the alluvial fan and the central Milford Valley also show water levels of around 1500 m asl. When the information is compiled on a pressure-depth graph, two pressure trends are evident: the hydrothermal system trend east of the Opal Mound fault, and the rest of the Milford Valley west of the fault (Figure 11). There appears to be a major pressure boundary coinciding with the Opal Mound fault, with well 9-1 being unproductive but located on that boundary. This well was recommended by Los Alamos National Laboratory as a candidate for hot dry rock technology testing (Goff and Decker, 1983). PacifiCorp Energy currently has a pressure monitor in the well, and although unproductive, it now provides a long-term monitor of reservoir pressure trends in the hydrothermal system.

We anticipate that naturally fractured granite underlies the FORGE deep well site, and that it may have a pressure regime similar to that shown for the Milford basin west of the Opal Mound fault. For a reservoir centered at 2.5 km depth, the pressure should be at 23 MPa (3300 psi). Although no pressure measurements were recorded during the drilling of Acord-1, based on its depth and temperature profile, the bottom hole pressure should be about 35 MPa (5000 psi) assuming it is successfully cleaned out.

6. SEISMICITY AND STRESS DIRECTION

The University of Utah Seismograph Stations (UUSS) installed a seismic station (NMU) 3 km (2 mi) north of the RHS in 1987. Improved resolution of the station network occurred in 2009, and in late 2015, a three-component broadband seismometer was installed 3 km south of the RHS (UFOR, Figure 12) and incorporated into the network. The estimated minimum magnitude of complete recording for the study area is M 1.5 (Pankow *et al.*, 2004). The new station is expected to lower the detection threshold for future events in the FORGE area, and will allow for better understanding of source mechanisms. Preliminary analysis of the seismicity (occurring from 1988 - 2015) shows no events locate near the FORGE site and that seismicity rates are low in this region.

Seismic events in the UUSS catalog in the Milford region have been relocated using an improved velocity model. Two clusters of events are evident: one near Milford, and the second 10 km NW of Milford (Figure 12). More diffuse seismicity occurs beneath the Mineral Mountains. Waveform analysis and event timing indicates that events in the NW cluster (outlined by the blue ellipse in Figure 12) are the result of quarry blasts, from the quarry mines in the area, not tectonic earthquakes. Evidence for this conclusion includes the limited and small magnitudes (M 0.49 to 2.05), the shallow depths (above 2.5 km below sea level), the restricted timing (all events occur during daylight hours) (Figure 12), and the highly correlated waveforms implying a similar location and source mechanism. The second cluster outlined by the green ellipse (Figure 12) is located near the Milford airport and not far from the M_W 4.1 1908 Milford earthquake (the largest recorded earthquake in the study area). The magnitudes in this cluster range from 0.46 to 3.87, and the events occur throughout the day (without a time bias). This cluster is interpreted as tectonic in origin.

The direction of minimum horizontal stress (T-axis, or SHmin) based on the moment tensor from an M_W 3.8 earthquake (depth 6 km) is NW-SE (Whidden and Pankow, 2012). This is close to the extension direction inferred from structural development of the Milford basin mentioned earlier. Interestingly, the focal mechanism for this event is strike-slip. A compilation of evidence from borehole breakouts from multi-arm caliper logs, the attitude of fractures, dikes and young normal faults all indicate the horizontal compressive stress (SHmax) is primarily directed N-S (170–180º) to NNE-SSW (035º) at Roosevelt Hot Springs.

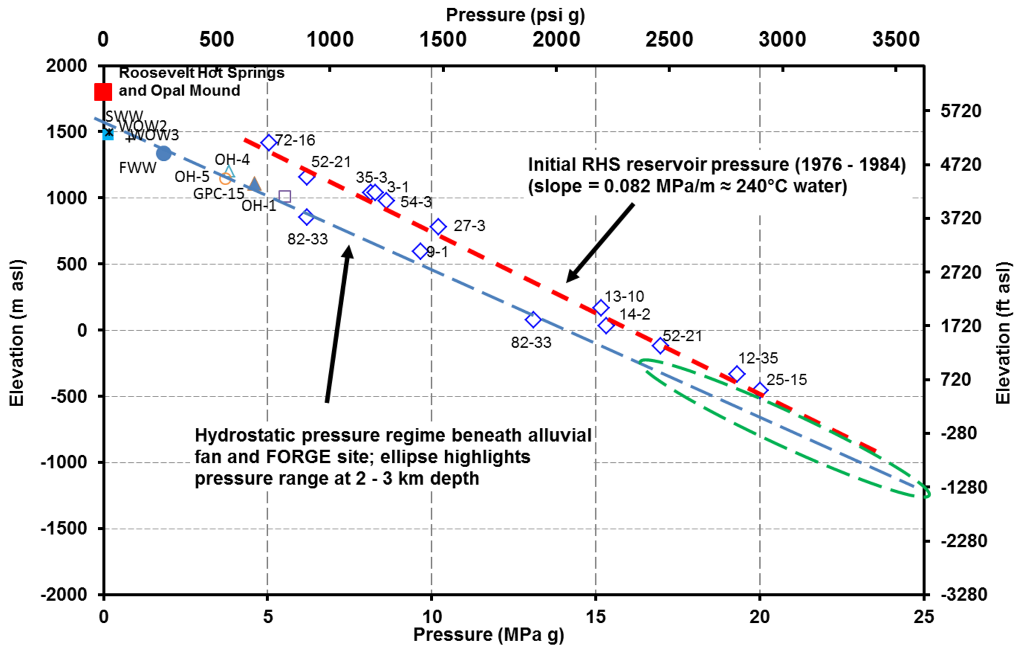

Figure 11. Pressure trends derived from wells in the Roosevelt Hydrothermal System, and in wells west of the Opal Mound fault. Pressure in the hydrothermal wells is from Faulder (1994) and represents pre-production conditions. The cold hydrostatic trend west of the fault is derived from groundwater wells and several geothermal exploration wells. Where no other data exists, the pressure control point is assumed to be at the mid-screen depth (elevation) or at total depth. Well locations are shown in Figure 3.

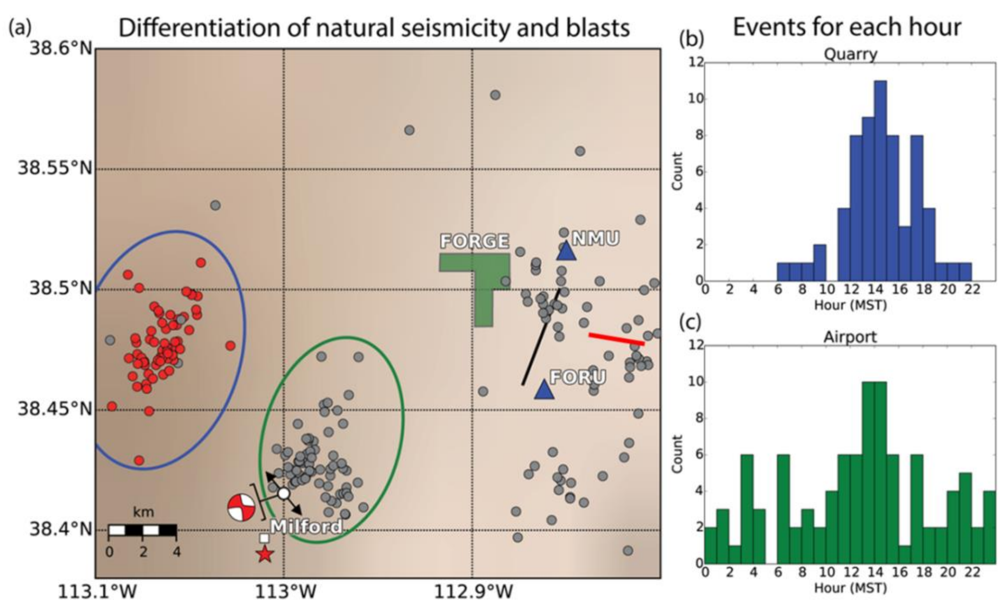

Figure 12 (a) Differentiation between natural seismic events and quarry blasts. Red and gray circles represent blasts and natural seismicity, respectively. The ellipses refer to the events within the histograms. The blue triangles are seismic stations; the green polygon represents the proposed FORGE area. The white square represents the center of Milford, UT and the red star is the epicenter of the 1908 earthquake, magnitude 4.1. The white circle represents the April 10, 1998M_W 3.8 earthquake with T-axis and focal mechanism (displayed offset from T-axis). The red line between NMU and FORU is the earthquake swarm detected by Zandt et al. (1982). This swarm was oriented approximately west-east. (b) shows the blasts as a function of time of day (these events occurring during daylight hours) and (c) shows that the natural seismicity occurs during all hours of the day. 62 of the 201 events displayed are blasts. Point data represents years 1965 – 2012.

6. CONCLUSIONS

The Milford FORGE site in central Utah offers an ideal field laboratory to develop next-generation technologies capable of generating geothermal power from tight crystalline rock. The site is easily accessible year round, with the local infrastructure 16 km away in Milford providing a comfortable base for visiting researchers. The preferred deep drilling location is a 5 km^2 area on non-federal land about 4 km from the hydrothermal system tapped by the Blundell power plants. Required temperatures of 175 to 225ºC exist at 2 - 3 km depth in granite, which occurs at 400 ± 200 m depth below the ground surface at the site. Groundwater rights for the project have been acquired, allowing use of over 600 million L (150 million gallons) for the duration of the project. Pump tests on a groundwater well near the proposed project office site 3 km from the deep well site demonstrate that two wells should be sufficient to supply water at the required rates. Groundwater in north Milford Valley is not potable and has not been extensively used because it has geothermal components that make it unsuitable for agriculture. The deep drill site is largely surrounded by BLM land. Environmental Impact Statements at neighboring wind, solar and transmission sites indicate no threatened or endangered species, and minimal risk of cultural/historic sites. Casual use permits for geophysical surveying around the deep well site during Phase 2 should also be straightforward. An unproductive, 3.8 km well (Acord-1), 5 km from the deep well site can likely cleaned out for testing tools up to temperatures of 230ºC and pressures up to 35 MPa (5000 psi).

The site is in an area of low natural seismicity. There has now been over 30 years of production of hot water and injection of cool water in deep wells tapping the adjacent Roosevelt Hydrothermal System. The circulation rates for most of the time has been in the range 250 - 300 L/s (Allis and Larsen, 2012), with no obvious induced seismicity. At the FORGE deep well site we anticipate the flow rate experiments to be carried out at about one tenth this rate, so the induced seismicity risk should be minimal.

Analysis of the extent of the low-permeability thermal anomaly adjacent to the Roosevelt Hot Springs hydrothermal system demonstrates why developing techniques to extract the heat is so important to future geothermal power development. The area of apparently tight rock with a temperature of over 150ºC could be about 100 km^2, and is more than 10 times the area of the hydrothermal system. The volume of this rock at less than 4 km depth is at least 100 km^3. The power potential here could be as high as 1 GW if this rock can be successfully fractured.

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REFERENCES

Allis R. G. and Larsen, G.: Roosevelt Hot Springs Geothermal field, Utah – reservoir response after more than 25 years of power production. *Proceedings*, 37th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, (2012).

Allis, R.G., Gwynn, M., Hardwick, C., Kirby, S., Moore, J., and Chapman, D.: Re-evaluation of the pre-development thermal regime of Roosevelt Hot Springs geothermal system, Utah. *Proceedings,* 40th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, (2015).

Boyd, L., Vagnetti, V., Metcalfe, E., Vandermeer, W., Porse, S., Henry, S., Frone, Z., and Tew, A.: The U.S. Department of Energy's Frontier Observatory for Research in Geothermal Energy (FORGE); New Directions in Subsurface Research and Development. *Proceedings,* 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, (2016).

Capuano, R., and Cole, D.R.: Fluid-mineral equilibria in a hydrothermal system, Roosevelt Hot Springs, Utah. *Geochimica et Cosmochemica Acta,* **46**, 1353–1364, (1982).

Faulder, D.D.: Long-term flow test #1, Roosevelt Hot Springs, Utah. *Transactions,* Geothermal Resources Council Transactions, **18**, 583–590, (1994).

Glenn, W, E., and Hulen, J.B.: Interpretation of well log data from four drill holes at Roosevelt Hot Springs KGRA. Univ. Utah Research Inst., Earth Science Lab. *Report* **28**, 74 p., (1979).

Goff F., and Decker, E.R.: Candidate sites for future hot dry rock development in the United States, *Jl. Volcanol. Geothermal. Research*, **15**, 187–221, (1983).

Hardwick C.L., Gwynn, M., Allis, R., Wannamaker, P., and Moore, J.: Geophysical Signatures of the Milford, Utah FORGE Site. *Proceedings,* 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, (2016).

Moore, J.N. and Nielson, D.L.: An overview of the geology and geochemistry of the Roosevelt Hot Springs geothermal system, Utah. *Utah Geological Association Publication,* **23**, 25–36, (1994).

Pankow, K. L., Arabasz, W.J., Nava, S.J., and Pechmann, J.C.: Triggered seismicity in Utah from the 3 November 2002 Denali fault earthquake, *Bull. Seism. Soc. Am*. **94**, S332–S347, (2004).

Robinson, R. and Iyer. H.M.: Delineation of a low-velocity body under the Roosevelt Hot Springs geothermal area, Utah, using teleseismic P-wave data, *Geophysics,* **46**, 1456-1466, (1981).

Ross, H.P., Nielson, D.L., Moore, J.N.: Roosevelt Hot Springs geothermal system, Utah – case study. *Amer. Assoc. Petroleum Geologists*, **66**, 879–902, (1982).

Shannon S.S., Goff, F., Rowley, J.C., Pettitt, R.A., Vituaz, F.D.: Roosevelt Hot Springs/Hot Dry Rock prospect and evaluation of the Acord 1-26 well. *Transactions*, Geothermal Resources Council, **7**, 541–544, (1983).

Simmons, S., Kirby, S., Jones, C., Moore, J., and Allis, R.: The Geology, Geochemistry, and Hydrology of the EGS FORGE Site, Milford Utah. *Proceedings,* 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, (2016).

Ward, S.H., Parry, W.R., Nash, W.P., Sill, W.R., Cook, K.L., Smith, R.B., Chapman, D.S., Brown, F.H., Whelan, J.A., and Bowman, J.R.: A summary of the geology, geochemistry, and geophysics of the Roosevelt Hot Springs thermal area, Utah. *Geophysics,* **43**, 1515–1542, (1978).

Whidden K.M. and Pankow, K.R.: A catalog of Regional Moment Tensors in Utah from 1998 to 2011, *Seismological Research Letters*, **83**, p. 775–783. doi: 10.1785/0220120046, (2012).

Zandt, G., McPherson, L., Schaff, S., and Olsen, S.: Seismic baseline and induction studies: Roosevelt Hot Springs, Utah, and Raft River, Idaho, U.S. Dept. of Energy Report DOE/ID/01821-T1, 58 pp., (1982).