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The Current Geoscientific Understanding of the Utah FORGE Site

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ABSTRACT

The Utah FORGE site is an EGS field laboratory. The current geoscientific understanding has been obtained from synthesis of numerous independent datasets, including new geological, geophysical, and geochemical surveys, plus drilling and logging of three new wells, the deepest being 58-32 which penetrates to 7536 ft (2248 m) depth. The stratigraphy consists of two broad rock types, comprising basin fill sediments and crystalline basement rocks mostly made of Miocene granitoids. The contact between these rock types forms an inclined plane, which dips ~20° west and which likely represents a large-scale normal fault that has been rotated during extension. Anomalous heat flow comprises localized hydrothermal convection east of the Opal Mound fault and regional conduction (~70°C/km, well 58-32) west of the Opal Mound fault. The modern stress regime is extensional, characterized by normal faulting and a maximum horizontal compressive stress oriented approximately N25°E. These are likely responsible for subsidiary faults that have formed outside the EGS reservoir, including the Opal Mound fault, which forms the west boundary of the Roosevelt Hot Springs hydrothermal system, and the Mineral Mountains West fault system, which runs south of the Utah FORGE site. By contrast, the Negro Mag fault runs roughly east west, intersecting the Opal Mound fault and coinciding with the northern boundary of the Roosevelt Hot Springs hydrothermal system. Importantly, no major fault structures have been detected in the Utah FORGE site.

Well 58-32 penetrated the basement at 3176 ft (968 m), and below this depth the dominant lithology consists of granitic rock containing plagioclase, K-feldspar, and quartz. Between 1700 and 7536 ft (518-2248 m), the temperature profile increases linearly with a maximum bottom hole temperature of 197°C. The FMI log shows the predominance of north-south, east-west, and northeast-southwest fracture orientations, with fractures induced by drilling orientations that northeast-southwest with near vertical dips. This is consistent with the northeast-southwest direction of maximum horizontal stress determined from geologic observations.

1. INTRODUCTION

The Utah FORGE site is an underground test facility for advancing EGS technologies. It is located 350 km south of Salt Lake City and 16 km north northeast of Milford, Utah. The site covers 5 km^2, and it is situated on a west sloping alluvial fan in northern Milford valley, roughly halfway between the crest of the Mineral Mountains to the east and the Beaver River to the west. The EGS reservoir, which is to be developed, is entirely hosted by fractured Tertiary granitoid rocks that form the basement unit to the northern Milford valley and that is also exposed throughout the core of the nearby Mineral Mountains.

The Utah FORGE site and nearby Roosevelt Hot Springs have been subject to a number of geoscientific investigations since the late 1970s, and a new phase of study commenced in 2015 as part of the process for site selection for the FORGE laboratory (Allis et al., 2016). In 2017, well 58-32 was drilled to 7536 ft depth to prove temperature and lithology, and to characterize fracture patterns and stress regime. In 2019, two additional shallow vertical wells were drilled close to 58-32 in order to deploy downhole seismometers for stimulation testing; 68-32 was drilled to 1000 ft depth and 78-32 was drilled to 3280 ft depth. The current state of knowledge is now underpinned by a wide range of geological, geophysical, and geochemical data derived from surface and well measurements (Moore et al., 2018; Allis and Moore, 2019).

2. GEOLOGIC SETTING

The Utah FORGE is part of a broad zone of elevated heat flow that lies inside the southeast margin of the Great Basin, in a province that has been the subject of several DOE funded projects related to hot sedimentary aquifers, play fairway analysis, and critical elements in produced fluids (e.g., Allis et al., 2012; Simmons et al., 2015, 2017, 2018a and b; Wannamaker et al., 2015, 2016; 2017). The regional stratigraphy is made of folded and imbricated Paleozoic-Mesozoic strata that has been overprinted by widespread Basin and Range style extension and eruption of Tertiary-Recent mafic-felsic magmatic centers, including in the Mineral Mountains (e.g. Nielson et al., 1986; Coleman et al., 1997; Kirby, 2019). Near the Utah FORGE site, Paleozoic-Mesozoic strata are absent, and consequently the stratigraphy is divided into two broadly defined units, comprising crystalline plutonic rocks that form the basement and younger overlying bedded alluvium and volcanic deposits that fill the basin (Fig. 1). The processing of 3D seismic reflection highlights the westward dipping surface that separates these two units, which forms the basement contact (Fig. 2).

2.1 Lithologies & Stratigraphy

The basement rocks are made of granitoids, which were emplaced between 26 and 8 Ma (Aleinikoff et al., 1987; Coleman and Walker, 1992; Coleman et al., 2001). They represent products of magmatic processes, which most recently resulted in the eruption of young rhyolite centers (0.5-0.8 Ma) in the Mineral Mountains (Lipman et al., 1978). The granitoid plutons intruded tightly folded Precambrian gneiss (~1720 Ma), but only rafts of this older lithology are preserved, as seen in the western foothills of the Mineral Mountains and intersected in wells 9-1, 52-21, and 14-2 (Glenn and Hulen, 1979; Glenn et al., 1980; Nielson et al., 1986).

The basin fill consists of a layered sequence of sedimentary and volcanic deposits (>3000 m), which range from Tertiary to Recent in age. The strata from youngest to oldest consist of calcareous lacustrine siltstones and sandstones, volcaniclastic sandstones and gravels, tuffaceous deposits, and localized flows of andesitic lavas. On the surface, basin-fill deposits young from east to west, and the youngest ones, in the vicinity of well Acord 1, are composed of fine sediments and reworked alluvium that were deposited in Lake Bonneville (16-14.5 ka), whose shoreline is marked by wave cut escarpments and westward extending point bars. To the east including the area surrounding the FORGE site, late Pleistocene alluvial fans are mainly composed of pea-sized gruss, and scattered fragments of obsidian, derived from the Mineral Mountains. Across the Opal Mound fault, around the area of Roosevelt Hot Springs, the alluvium deposits are older, more than 0.8 Ma as constrained by dates on overlying flows of rhyolite (Lipman et al., 1978); the oldest alluvium likely dates back several million years, and it is restricted to a few isolated exposures (Kirby, 2019; Knudsen et al., 2019).

2.2 Faults & Fault Systems

All of the faults in the vicinity of the Utah FORGE site are products of Basin and Range extension, mostly occurring in late Miocene time well after the main phase of plutonic intrusion (Coleman et al., 2001; Bartley, 2019). Four major faults and fault systems are known, based on field observations, seismic reflection, and correlation of drill logs (Kirby, 2019; Knudsen et al., 2019; Simmons et al., 2019).

The Opal Mound fault extends for ~5 km in a NNE direction, branching in the northernmost part. It has an inferred steep eastward dip (e.g. Nielson et al., 1986); however, the total displacement is difficult to measure, and it could be up to 15 m. The Opal Mound fault marks the western boundary of the Roosevelt Hot Springs hydrothermal system and importantly forms a hydrological barrier to westward hydrothermal flow as revealed by pressure profiles from wells either side of the fault (Allis and Larsen, 2012; Allis et al., 2016). In the past, springs discharged from the southern and northern ends of the Opal Mound fault, but today surface activity is limited to steaming ground with acidic steam-heated water at its northern end. Before 1980, nearly neutral pH chloride water, resembling the reservoir composition, discharged at the surface (e.g. Capuano and Cole, 1982). Approximately 1600-1900 years ago, the discharge of nearly neutral pH thermal water was localized around the south end of the fault, depositing a thick sheet of silica sinter that marks the Opal Mound (Lynne et al., 2005).

The Negro Mag fault is an east-west striking structure that extends several kilometers eastward from intersection with the Opal Mound fault. This relatively short fault can be traced on the surface over a distance of ~1 km where it offsets an old alluvial fan deposit, creating an east-west ridge in the middle of Negro Mag wash. Judging from the orientations of numerous east-west trending joints and fractures in the Mineral Mountains, the fault is probably vertical, with an offset of <10 m downward on the north side (Kirby, 2019; Knudsen et al., 2019).

The Mineral Mountains West fault system represents a corridor of north-south trending fault scarps that are mappable on fan deposits south of the FORGE site. The system is up to 3 km wide, and it runs for at least 40 km, west of and parallel to the range front along the southern part of the Mineral Mountains. Individual strands form scarps, generally having heights <5m, that form coherent traces up to 3 km long. Further information about the northern segment of this fault system is described below.

The most significant fault in the vicinity of the FORGE site is marked by the contact between overlying basin fill and the underlying crystalline basement rock. It forms an inclined undulating ramp that dips 20-35° west and intersects the surface near the Opal Mound fault (Figs. 1 and 2). This structure and related subparallel structures in the basement are believed to have accommodated large-scale down-dip displacement of >10 km (Bartley, 2019). The evidence that supports such interpretation includes seismic reflection data, regional outcrop patterns, the uniform eastward dip of stratified rocks in the Mineral Mountains, the uniform westward dip of late Miocene dikes in the Mineral Mountains, paleomagnetic data, and cooling patterns interpreted from thermochronology (Smith and Bruhn, 1984; Nielson et al., 1986; Smith et al., 1989; Coleman and Walker, 1992, 1994; Coleman et al., 2001). Furthermore, thin section of analysis of 58-32 and 78-32 drill cuttings shows clear evidence of intense shearing, brecciation, and cataclasis in the footwall directly beneath the basement contact (Jones et al., 2019). Most of the extension accommodated along this and related structures occurred during a short period of accelerated displacement in the late Miocene (10-8 Ma), which resulted in uplift, exhumation, and tilting (Nielson et al., 1986; Coleman and Walker, 1994; Coleman et al., 2001). What is now a shallow dipping fault surface probably initiated as a moderate to steeply dipping plane (Wernicke and Axen, 1988; Buck, 1988; Coleman and Walker, 1994; Bartley, 2019). Once the surface and related subparallel structures acquired shallow dips, the propensity for new fault slips greatly diminished because of cohesion. Erosion derived sediments probably started covering this surface shortly after movement ceased.

2.3 Fracture Patterns in the Mineral Mountains

The crystalline plutonic rocks that are exposed in the Mineral Mountains are directly analogous to the rocks penetrated by well 58-32, and they were used to validate fracture characteristics in the proposed EGS reservoir (Bartley, 2019). New structural data were acquired across the Mineral Mountains, and the focus here is on results from study sites near Salt Cove and Bailey Spring (Fig. 1), which are closest to the FORGE site. Fracture lengths range from 20 to 200 m, and fracture spacings range from 5-15 m. Fracture azimuths range widely, with about half the population being randomly oriented. The remaining fracture azimuths fall into two predominant populations of 90 to 120° and 0 to 30°. The E-W trending population dips steeply to the north, whereas the NNE-SSW population dips steeply and gently west to form a conjugate set (Fig. 3).

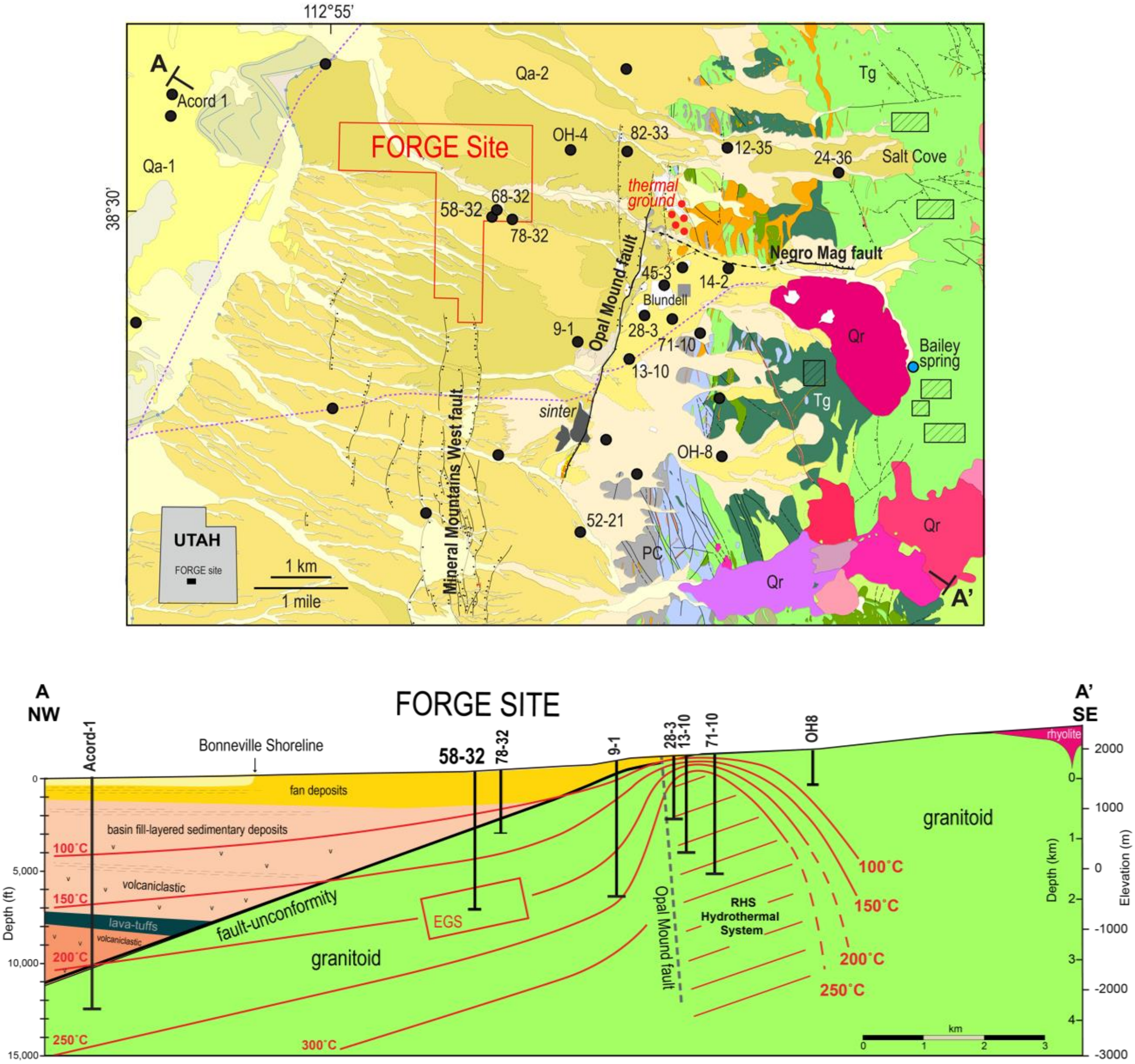

Figure 1. Geological map and cross section for the Utah FORGE site based on the integration of legacy reports, new field observations, seismic reflection profiles, temperature surveys and gravity data interpretation (Allis et al., 2019; Kirby, 2019; Knudsen et al., 2019; Simmons et al., 2019). The rhyolite flow (red) west of Bailey spring makes up Bailey ridge. Rectangular outlines with hatched fill represent study areas for fracture analysis. Abbreviations: QA-1=Lake Bonneville silts and sands; QA-2=alluvial fan deposits; Qr=Quaternary rhyolite lava and pyroclastic deposits; Tg=Tertiary granitoid; PC=Precambrian gneiss; black filled circles=wells.

The geometry of the conjugate NNE-SSW fracture set likely formed in a regime where the maximum compressive stress was initially vertical, followed by ~40° of eastward tilt in the footwall of the normal fault that formed Milford Valley. This implies that the conjugate set formed before large displacement had accumulated across the basin-bounding fault which probably initiated in late Miocene time (Bartley, 2019). Because fracture intersection relationships indicate that the conjugate set formed after the E-W steep fractures, all three main fracture sets appear to have formed before or early during Basin and Range faulting, and therefore in the middle Miocene shortly after the pluton was emplaced. Slickensided fault surfaces are generally very sparse, with three exceptions. Outcrops in the northern end of the range contain numerous faults, including at least one meter-thick cataclastic zone that dips gently westward; exposures on the northern wall of Negro Mag wash contains numerous thin (1-5 cm) cataclastic zones, as do exposures on the western slopes of Bailey Ridge.

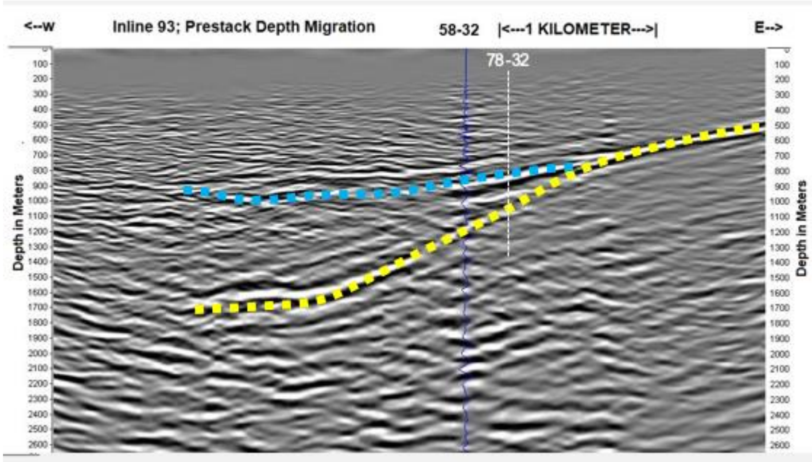

Figure 2. West-East seismic reflection profile through wells 58-32 and 78-32, showing the major reflectors that represent the west-dipping contact with the basement granitoid (yellow dashed line) and the subhorizontal bedding in the basin fill alluvium.

Although fractures that show evidence of shear displacement range in orientation, the majority dip gently to moderately westward with highly variable azimuths. Slickensides and Riedel shears consistently indicate top-to-the-west shear. Such fractures exposed in Negro Mag wash were interpreted to be map-scale low-angle faults by Sibbett and Nielson (1980). However, new mapping indicates that they represent slip across joints that commonly are bounded by E-W striking steep fractures and thus have small N-S extents. It therefore appears unlikely that any of the low-angle faults in Negro Mag wash are either continuous over significant areas or accommodated tectonically significant displacements. Steep fractures predominate in all of the rhyolite bodies, and there are few similarities from one body to another; the rhyolite-hosted fractures thus appear unrelated to fractures that formed in the underlying granitoid.

The fracture patterns, combined with the independent evidence of eastward tilting, strongly suggests that the low-angle normal faults are high-angle normal faults, which after displacement were tilted to low angle subhorizontal dips. The implications of this for fractures in the FORGE area depends on the structural relationship between exposures in the range and FORGE. Geophysical imaging of the bedrock surface under the basin fill in Milford Valley suggests that that surface is oriented subparallel to joints in the range that underwent top-west shear. This suggests that bedrock beneath the FORGE area represents a level that is deeper than the exposures in the Mineral Mountains.

2.4 Fractures patterns in 58-32

An FMI log was run in 58-32 from 2172 ft to TD at 7536 ft after it was drilled and before casing was emplaced. Approximately 2000 natural fractures were identified, and most are restricted to the basement rocks (>3176 ft depth). Their spacing (<1 to 20 per 3 m interval) and orientation range widely, but there is a predominance of north-south, east-west, and northeast-southwest fracture orientations. The north-south fracture population has moderate dips (<70°) to the west, and the east-west population has dips that cluster between 50-90° to the south; the northeast-southwest population has dips that are scattered, ranging from moderate to steep angles to the southeast and northwest. These patterns strongly resemble the spacings and orientations of fractures in the Mineral Mountains, especially those occurring east of Roosevelt Hot Springs. For comparison, induced fractures produced during drilling show a narrow range of orientations, predominantly northeast-southwest with near vertical dips (Fig. 4). This direction represents σ_{Hmax} and is consistent with other geological observations.

4. REGIONAL THERMAL STRUCTURE

Analysis of about 100 thermal gradient and deep exploration holes, combined with thermal conductivity measurements, provides the basis for calculating regional heat flow and defining the thermal structure within and surrounding the EGS reservoir (Allis et al., 2015, 2019). These results show the partitioning of convective and conductive heat transfer, which are the products of regionally anomalous heat flow (Fig. 5).

Convective heat transfer is a small-scale feature restricted to hydrothermal upflow east of the Opal Mound fault, which forms Roosevelt Hot Springs and the geothermal reservoir supplying the Blundell power plant. Close to the surface, hot water from Roosevelt Hot Springs leaks out around the tips of the Opal Mound fault through shallow aquifers to form an outflow structure that follows the downward sloping hydraulic gradient into the valley. Conductive heat transfer by contrast is a large-scale feature that is regionally developed in the crystalline basement rocks, and this controls the temperature gradient in and around the EGS reservoir.

The predicted FORGE reservoir gradient (e.g. Allis et al., 2016) closely matched the measured temperature gradient of 70°C/km in well 58-32, validating the methodologies used to interpret thermal characteristics surrounding the FORGE site. Integration of all the temperature gradient data shows a large area (100 km^2) of anomalously high conductive heat flow surrounding the FORGE site. It also shows that the total volume of crystalline basement rock >175°C down to 4 km depth is more than 100 km^3. The Roosevelt Hot Springs where convective heat flow prevails covers a much small area (10 km^2), and it is isolated east of the Opal Mound fault. The deep regional thermal structure emphasizes the large area of conductive heat transfer due to low permeability and lack of fluid flow west of the Opal Mound fault (Fig. 5). The integrated thermal output is ~50 MWth (Allis et al., 2019).

5. GROUNDWATER HYDROGEOLOGY

The shallow unconsolidated basin fill forms the primary aquifer, ranging in thickness from 100 to >500 feet (Kirby, 2012). Two distinct pressure regimes exist separated by the north-northeast trending Opal Mound fault. Pre-production pressure profiles for deep geothermal wells are uniform indicating a hydrostatic pressure head that is 3 MPa higher than those measured in exploration/monitoring wells on the west side of the Opal Mound fault. The potentiometric surface slopes steeply to the west away from the Opal Mound fault from 5800 to 4900 feet in elevation over approximately 8 km. Beneath the FORGE deep drill site, the groundwater elevation is approximately 5100 feet and the depth to water is between 200 and 500 feet.

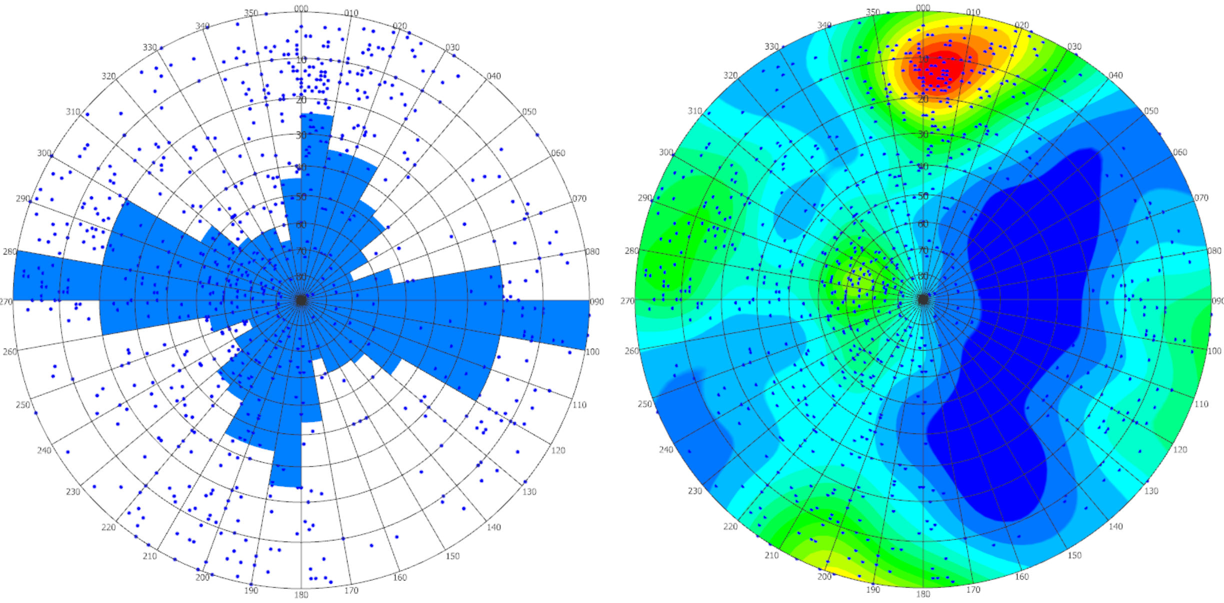

Figure 3. The stereonet upper hemisphere projections of fracture patterns in granitoid exposures of the Mineral Mountains with three predominant populations of 80 to 120°, dipping steeply to the north, and 0 to 30°, dipping steeply and gently west:

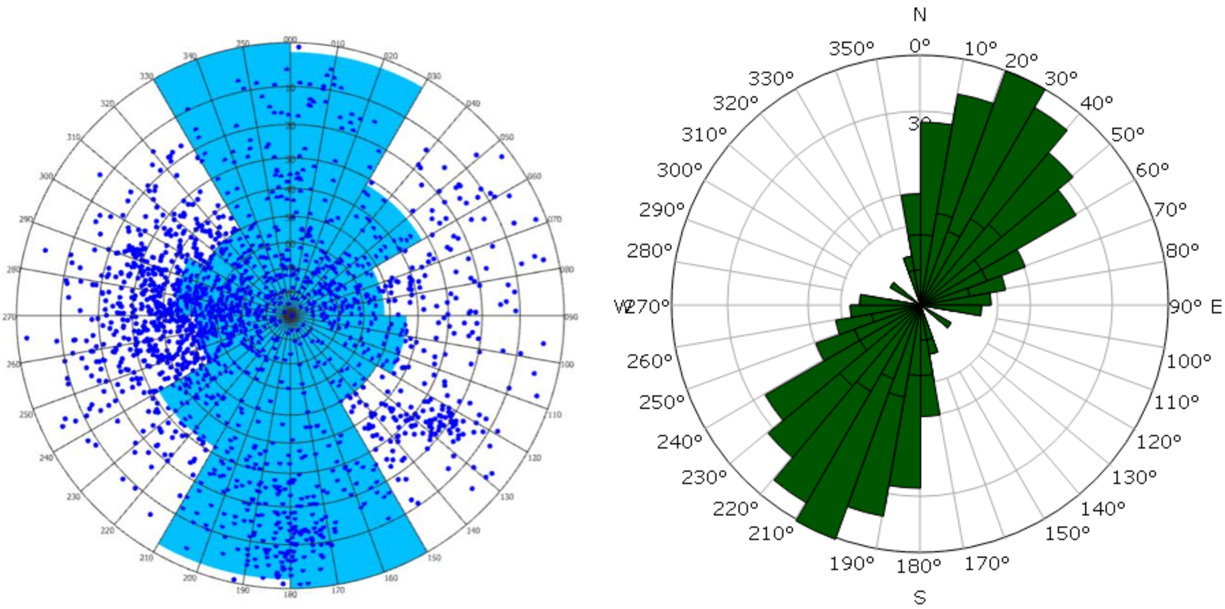

Figure 4. The stereonet upper hemisphere projections of fracture patterns (poles) in 58-32 interpreted from the FMI log. The left image shows the azimuth and dip of ~2000 natural fractures in crystalline basement rocks. The right image shows the azimuth and dip of fractures induced by drilling, reflecting the orientation of regional maximum horizontal stress.

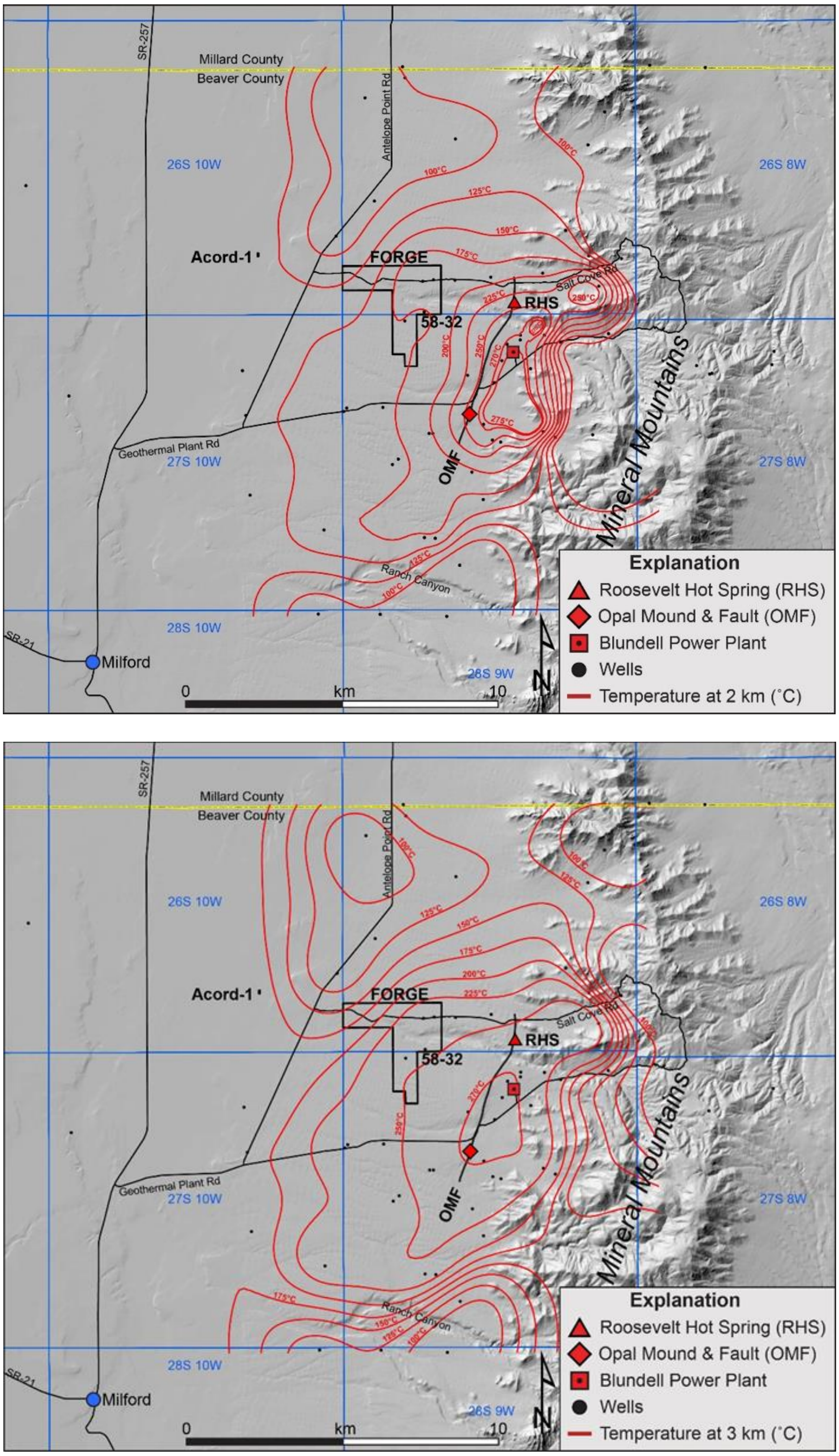

Figure 5. Isotherm maps at 2 and 3 km depth based on analysis of temperature gradients in wells (Allis et al., 2018b). The area at a temperature of more than 200°C in these maps increases from about 25 km^2 at 2 km depth to 70 km^2 at 3 km depth.

The compositions of the groundwaters vary systematically according to location and geologic setting (Fig. 6). The Mineral Mountains cold springs discharge fresh groundwaters representative of modern meteoric waters. Roosevelt Hot Springs consist of boiled neutral pH chloride waters that formed from deep circulation of paleo-meteoric water followed by high temperature water-rock interaction with fractured granitoid, and then boiling before discharging at the surface (Simmons et al., 2018b). Beneath the vicinity of the Utah FORGE site, warm neutral pH chloride groundwaters represent the dispersion and northwesterly outflow from Roosevelt Hot Springs. In the North Milford valley, groundwaters reflect distal outflow from Roosevelt Hot Springs that have been modified by varying amounts of dilution and mineral dissolution that have elevated aqueous concentrations of bicarbonate.

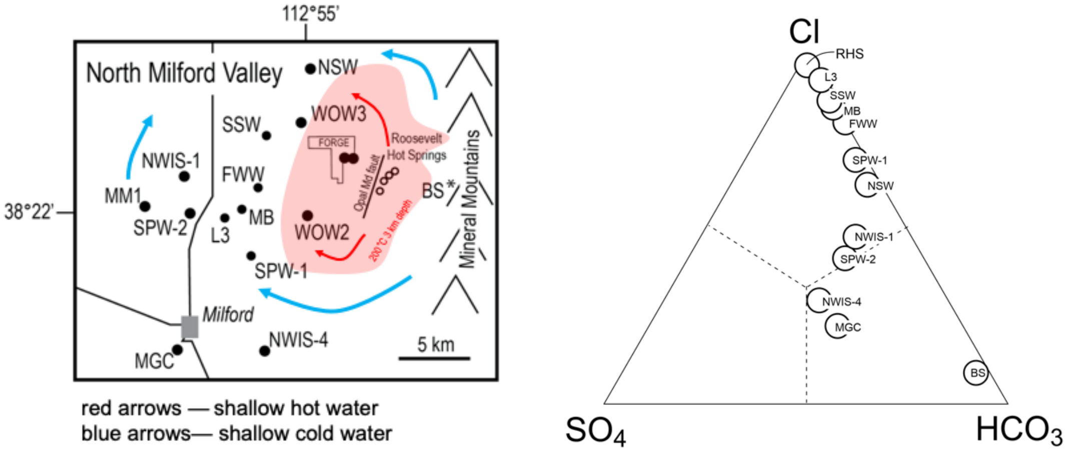

Figure 6. Map of the geohydrology in the North Milford valley, showing shallow wells and groundwater flow paths. Triangular plot showing the variation in groundwater compositions in the vicinity of the Utah FORGE site.

Well test data including measurement on 78-32 confirm transmissivities that range from 240 to 10,000 ft^2/day, which is ample groundwater supply for future EGS activities at the FORGE site. Because this water contains a significant proportion of Roosevelt Hot Springs waters, it is non-potable, chemically benign, and highly suitable for EGS heat transfer experiments.

6. SUMMARY

A large multidisciplinary geoscientific dataset has been acquired at the Utah FORGE site, including the drilling, logging, and testing of a deep vertical test well to 7536 ft (2298 m) depth, plus drilling and stratigraphic logging of two shallower vertical holes used for seismic monitoring. The proposed reservoir occurs between 2 and 3 km (6560 and 9840 ft), and it is composed of hot (175-225 °C) granitic rock that is laterally extensive (~100 km^3). The reservoir rocks are also fractured, but they lack connectivity to support natural flow of water. The geological record indicates that the Utah FORGE site is located in a part of the Basin and Range that is tectonically quiet, consistent with long term monitoring of seismic activity (e.g., Pankow et al. 2019).

7. ACKNOWLEDGMENTS

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