

## Update on the Geoscientific Understanding of the Utah FORGE Site

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### ABSTRACT

The EGS reservoir at Utah FORGE is entirely hosted by fractured Tertiary granitoid that forms the stratigraphic basement in the north Milford valley and that is exposed throughout the core of the nearby Mineral Mountains. The top of basement is defined by a gentle west-dipping surface that originated as a tectonic feature, which below the FORGE site was buried beneath that 3000 feet of alluvial basin fill. Fracture patterns in the central Mineral Mountains formed when the maximum compressive stress was vertical, and then rotated, tilting ~40° of eastward, during uplift and exhumation more than 6-10 million years ago. The basement surface probably thus began as a steep west-dipping fracture plane that evolved into a range front fault and rotated into its modern position. Based on the FMI log from well 58-32, fractures in the vicinity of the EGS reservoir are densely spaced and have a wide range of orientations similar to the Mineral Mountains. Multiple independent data sets indicate that the modern stress regime remains 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 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 transect the FORGE site. 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. Shallow groundwater resources comprise westward outflow from Roosevelt Hot Springs that occupies basin fill aquifers. Soil gas CO<sub>2</sub> and He isotope anomalies correlate with Roosevelt Hot Springs, confirming the absence of detectable hydrothermal upflow beneath the Utah FORGE site.

### 1. INTRODUCTION

A large amount of new geoscientific data has been collected from the Utah FORGE site near Milford, Utah (e.g. Moore et al., 2018). These data were obtained from surface surveys and from logging and testing of well 58-32, which is a new vertical well drilled to 7536 ft. The geoscientific results are summarized below focusing on regional geology, fault and fracture patterns, heat flow, groundwater flow, and new soil gas data.

### 2. GEOLOGIC SETTING

The Utah FORGE site is located on gently sloping alluvium, about midway between the crest of the Mineral Mountains to the east and the center of the north Milford valley to the west (Fig. 1). The site lies inside the southeast margin of the Great Basin in a broad zone that is characterized by elevated heat flow, which 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). The local stratigraphy is divided into two broadly defined units, comprising crystalline basement rocks and the overlying basin fill sedimentary deposits (Fig. 1).

#### 2.1 Lithologies & Stratigraphy

Crystalline basement rocks form the host to the EGS reservoir, and they are composed of granitoid, which makes up the core of the Mineral Mountains (Fig. 1). Granitoid is a generic term we apply to all plutonic rocks, ranging from diorite to granite, including those intersected in 58-32. These granitoids were emplaced between 26 and 8 Ma (Alienikoff et al., 1987; Coleman and Walker, 1992; Coleman et al., 1997), and they may be related to the modern magmatic system, which fed the young rhyolite centers (0.5-0.8 Ma) in the Mineral Mountains (Lipman et al., 1978). The regional extent of the granitoid is known from petrographic and x-ray diffraction analysis of drill cuttings and cores from vertical wells across the map, which indicate the predominance of tight interlocking igneous quartz, plagioclase, K-feldspar, biotite, clinopyroxene, hornblende, and magnetite-ilmenite (Jones et al., 2018). 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 (e.g., Nielson et al., 1986). The metamorphic rocks are predominantly composed of biotite, hornblende, K-feldspar, plagioclase, quartz, and very distinctive sillimanite.

The basin fill consists a layered sequence of sedimentary and volcanic deposits (>3000 m), which range from Tertiary to Recent in age. The units penetrated by the Acord 1 well represent the most complete record; below about 1200 m depth down to the contact with the basement, the strata consist of volcanoclastic sandstones and gravels, lacustrine sediments, tuffaceous deposits, and localized flows of andesitic lavas, whereas at shallower depths, calcareous lacustrine deposits made of siltstone and sandstone dominate. Late Pleistocene alluvial fans around the Utah FORGE site are mainly composed of pea-sized gruss, and scattered fragments of obsidian, derived from the Mineral Mountains. The basin fill alluvium is capped by a nearly continuous low angle surface that extends from the shore line deposits of paleo-lake Bonneville to the incised valleys of the Mineral Mountains, reflecting relatively quiescent tectonic conditions in the recent geologic past (i.e. Holocene and older).

## 2.2 Faults & Fault Systems

Four faults and fault systems have been defined, based on field observations, seismic reflection, and correlation of drill logs. The Opal Mound and Negro Mag faults are relatively short length structures that intersect at an orthogonal angle to form the boundaries of the Roosevelt Hot Springs reservoir. The Mineral Mountains West fault system comprises a series of parallel north-south trending, normal fault segments with small offsets. These three faults are represented in the geological map of the FORGE site (Fig. 1). The fourth fault is unnamed, but it has a large amount displacement, and it probably accommodated much of the extension required to form the North Milford valley in the late Miocene. It, however, is inactive due to cohesion resulting from having been rotated to a low-angle during uplift and exhumation of the Mineral Mountains. No other faults are known, consistent with the absence of scarps and faceted spurs along the Mineral Mountains range front.

The Opal Mound fault extends for ~5 km in a NNE direction, branching in the northern most 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 <10 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 described below (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, near 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 near neutral pH thermal water was localized around the south end of the fault, where it deposited a thick sheet of silica sinter deposit that marks the Opal Mound (Lynne et al., 2005).

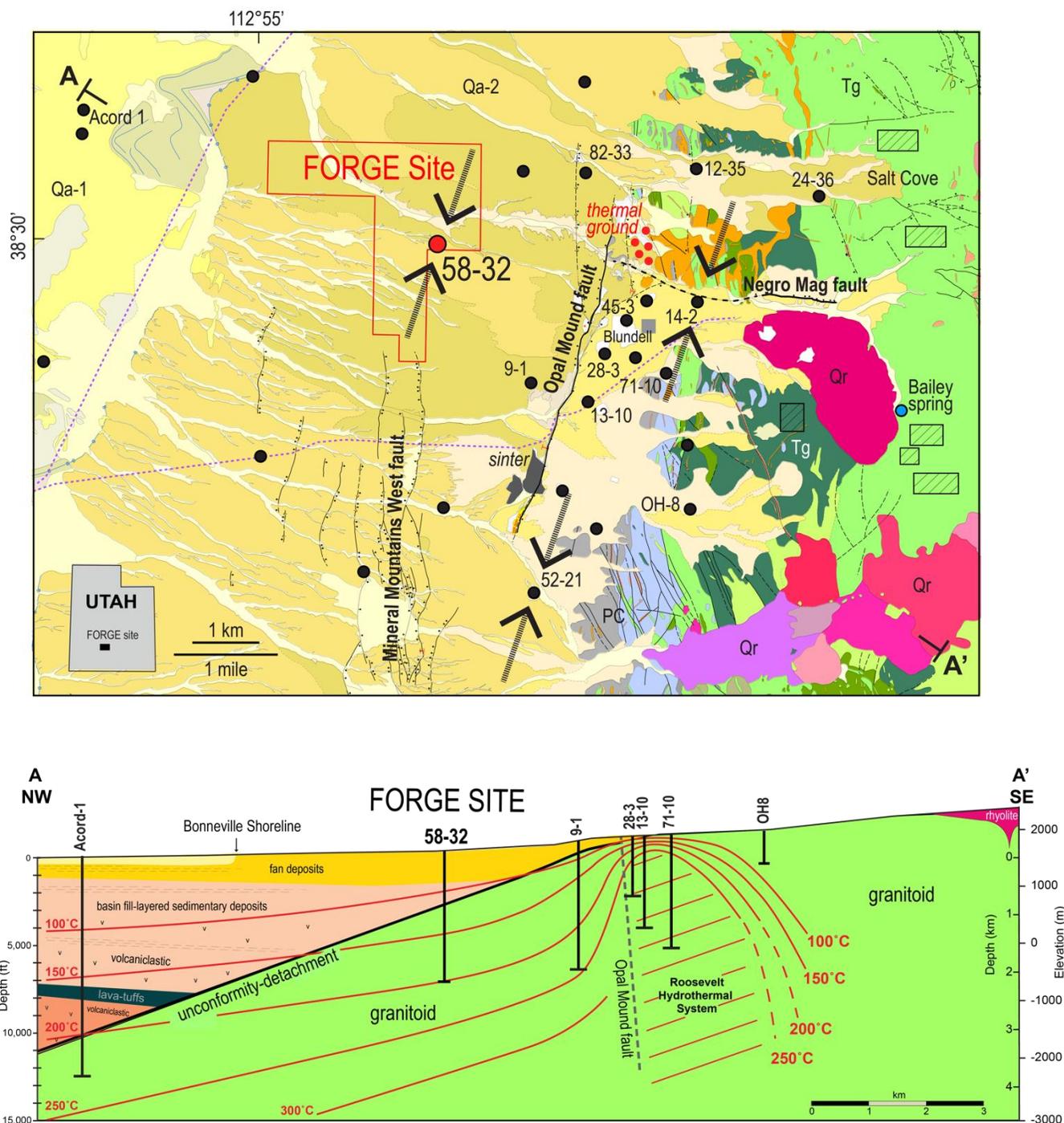
The Negro Mag fault is an east-west striking structure that extends several kilometers eastward from intersection with the Opal Mound fault. This relatively short fault can be traced on the surface over a distance of ~1 km where it offsets an old alluvial fan deposit, creating an east-west ridge in the 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 to the north.

The Mineral Mountains West fault system represents a corridor of north-south trending fault scarps that are mappable in fan deposits south of the FORGE site. The system is up to 3 km wide, and it runs for at least 30 km, west of and parallel to the range front along the southern part of the Mineral Mountains. Individual strands are marked by scarps, having heights <5m, that extend continuously for several km. None of these faults have been detected in seismic reflection profiles (Smith and Bruhn, 1984. Smith et al. 1989).

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 (Fig. 1). It forms a continuous inclined ramp that dips ~20° west and intersects the surface near the Opal Mound fault; reprocessing of new and legacy 2D and 3D seismic reflection data show no direct evidence that this surface has been cross cut or offset by younger faults. The case for large scale down-dip displacement of >10 km in the form of a one or more subparallel detachment structures is deduced from seismic reflection, 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., 1997, 2001). From these studies, it appears that most of the large-scale extension occurred during a short period of accelerated displacement in the late Miocene, and this caused uplift, exhumation, and tilting of the Mineral Mountains (Coleman and Walker, 1994; Coleman et al., 2001). This implies that the detachment fault(s) probably initiated as a moderate to steeply dipping plane(s). As extension advanced, the faults rotated in response to a rolling hinge (Wernicke and Axen, 1988; Buck, 1988; Coleman and Walker, 1994), but after acquiring low angle orientations, slip along these structures greatly diminished because of cohesion.

## 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. 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. 2).

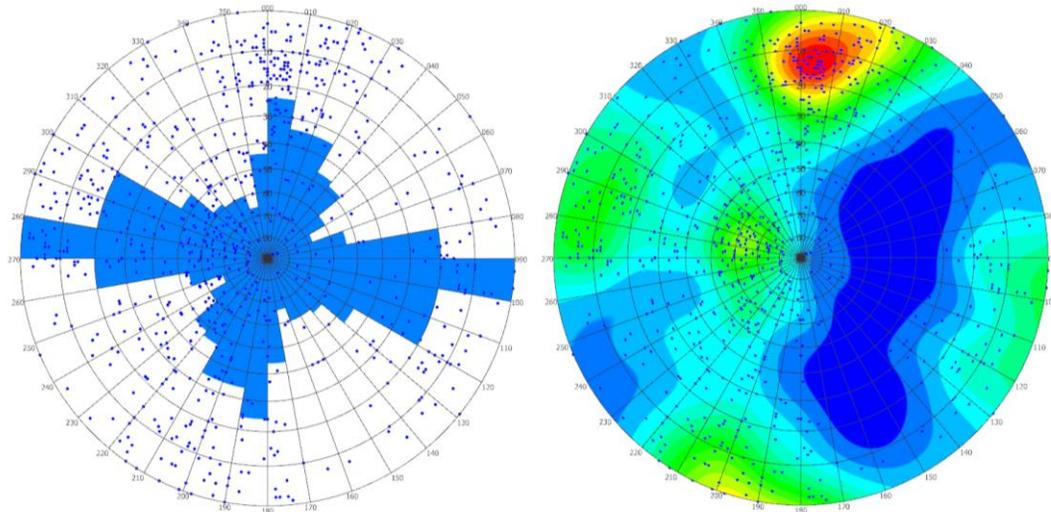


**Figure 1. Geological map and cross section for the Utah FORGE site based on the integration of legacy reports, new field observations, seismic reflection profiles, temperature surveys and gravity data interpretation (Smith and Bruhn, 1984; Nielson et al., 1986; Smith et al., 1989; Sibbet and Nielson, 2017; Allis et al., 2015; 2018a, b; Hardwick et al., 2016, 2018; Kirby et al., 2018). The basement contact appears to be continuous with no disruptions by young faults, based on new processing of a 3D seismic reflection survey. The rhyolite flow (red) west of Bailey spring makes up Bailey ridge. 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 is interpreted to have formed with the maximum compressive stress vertical, followed by  $\sim 40^\circ$  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 (Coleman et al., 2001). 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.

Although fractures that show evidence of shear displacement range in orientation, the majority dip gently to moderately westward with highly variable strikes. 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. Observations of fracture patterns in the Quaternary lavas bear little resemblance to fracture patterns in nearby exposures of granitoid rocks; steep fractures predominate in all of the rhyolite bodies, but otherwise there are few similarities from one body to another.

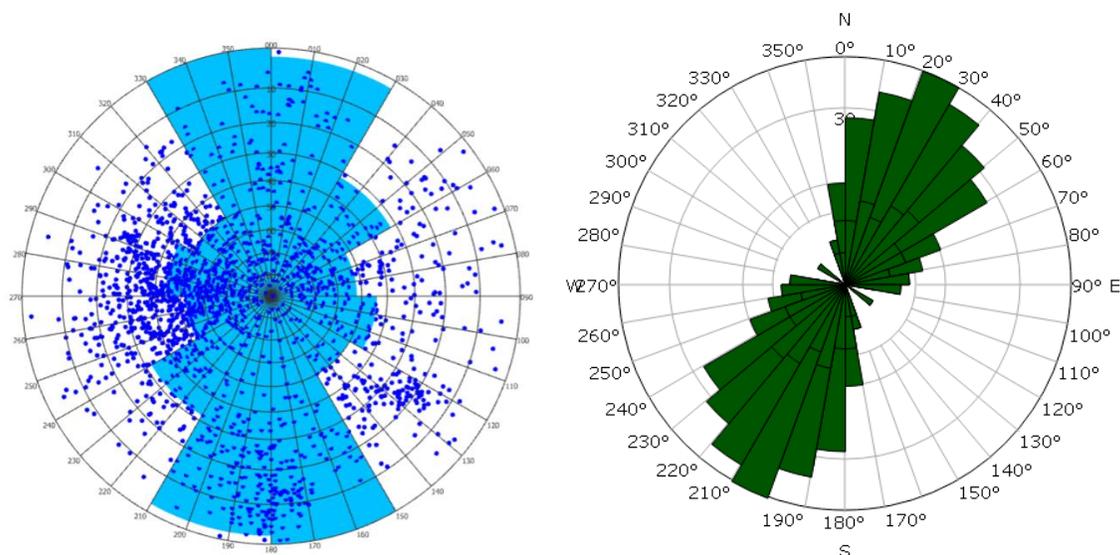
The geometric pattern of fractures, combined with the independent evidence of eastward tilting, strongly suggests that the low-angle normal faults are high-angle normal faults, which after displacement were tilted to low angle subhorizontal dips. The implications of this for fractures in the FORGE area 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 that bedrock surface may be a fault that was initiated along the same joint set. If so, then bedrock in the FORGE area is a deeper level within the same major structural block as the rocks exposed in the range.



**Figure 2. Fracture patterns in granitoid exposures of the Mineral Mountains with three predominant populations of  $80$  to  $120^\circ$ , dipping steeply to the north, and  $0$  to  $30^\circ$ , dipping steeply and gently west: Left) Rose diagram of fracture azimuths and stereo net showing poles to fractures projected to the upper hemisphere; Right) Contoured stereo net of poles to fractures (upper hemisphere).**

#### 2.4 Fractures patterns in 58-32

An FMI log was run in 58-32 from 2172 ft to TD at 7536 ft. Approximately 2000 natural fractures were identified, and most are restricted to the basement rocks ( $>3176$  ft depth). Their spacing ( $<1$  to 20 per 10 ft 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 ( $<70^\circ$ ) to the west, and the east-west population has dips that cluster between  $50$ - $90^\circ$  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  $\sigma_{Hmax}$  and is consistent with the orientation of  $\sigma_{Hmax}$  determined from other geological observations.



**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.**

#### 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, 2018a, 2018b). 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<sup>2</sup>) 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<sup>3</sup>. The Roosevelt Hot Springs where convective heat flow prevails covers a much small area (10 km<sup>2</sup>), 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., 2017).

#### 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 (Fig. 6). Beneath the FORGE deep drill site, the groundwater elevation is approximately 5100 feet and the depth to water is between 200 and 500 feet.

The compositions of the groundwaters vary systematically according to location and geologic setting. 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 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.

New well test data confirm transmissivities that range from 240 to 1600 ft<sup>2</sup>/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 (Simmons et al., 2016).

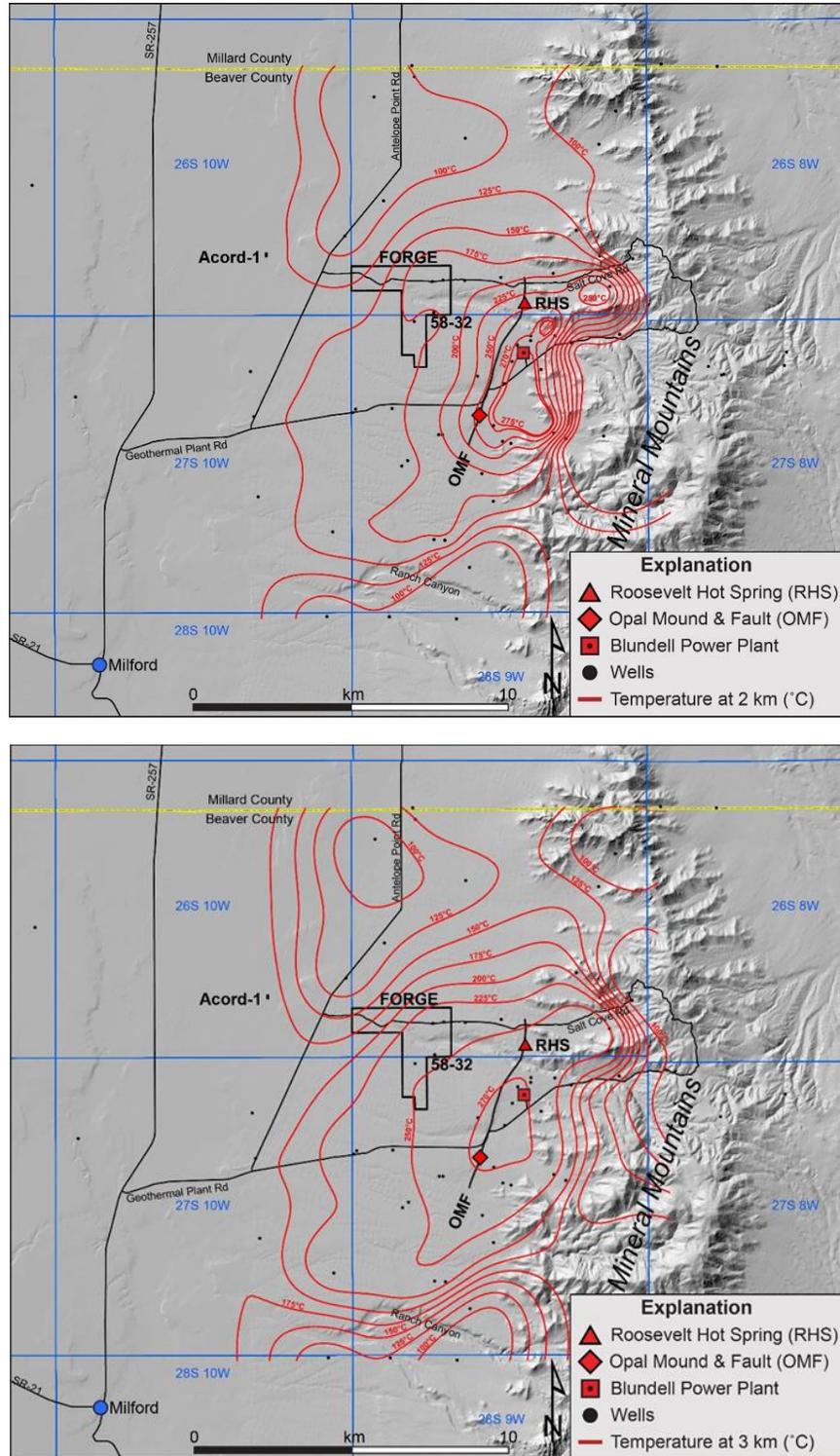
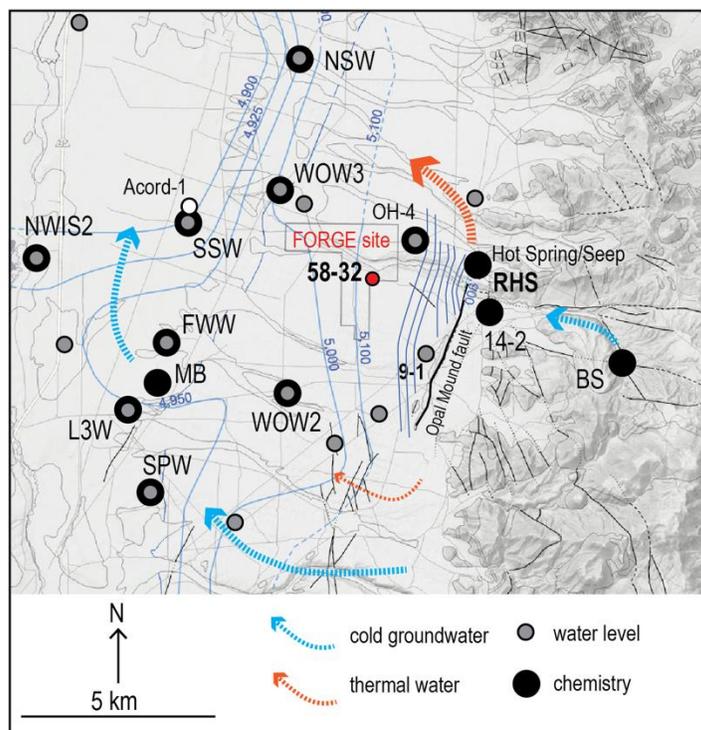


Figure 5. Isotherm maps at 2 and 3 km depth based on analysis of temperature gradients in wells (Allis et al., 2018b). The area at a temperature of more than 200°C in these maps increases from about 25 km<sup>2</sup> at 2 km depth to 70 km<sup>2</sup> at 3 km depth.



**Figure 6. Map showing the geohydrology and groundwater flow in the North Milford valley, showing shallow wells, piezometric level (blue contours), and groundwater flow paths (red and blue arrows); RHS=Roosevelt Hot Springs.**

## 6. SOIL GAS SURVEY

The CO<sub>2</sub> soil gas surveys in summer 2017 and winter 2018 represent over 800 individual measurements that were acquired from sample stations spaced 80-160 m apart. The CO<sub>2</sub> flux around the FORGE site has background values, and these are in contrast to high CO<sub>2</sub> fluxes measured east of the Opal Mound fault in the vicinity of Roosevelt Hot Springs (Fig. 7). Carbon isotope measurements obtained on a small set of soil gas samples give  $\delta^{13}\text{C}$  values of -10 to -12 per mil, which suggest a biogenic source associated with desert vegetation; three samples from Roosevelt Hot Springs gave values of -4 to -5 per mil, which more closely reflect a magmatic mantle isotope signature.

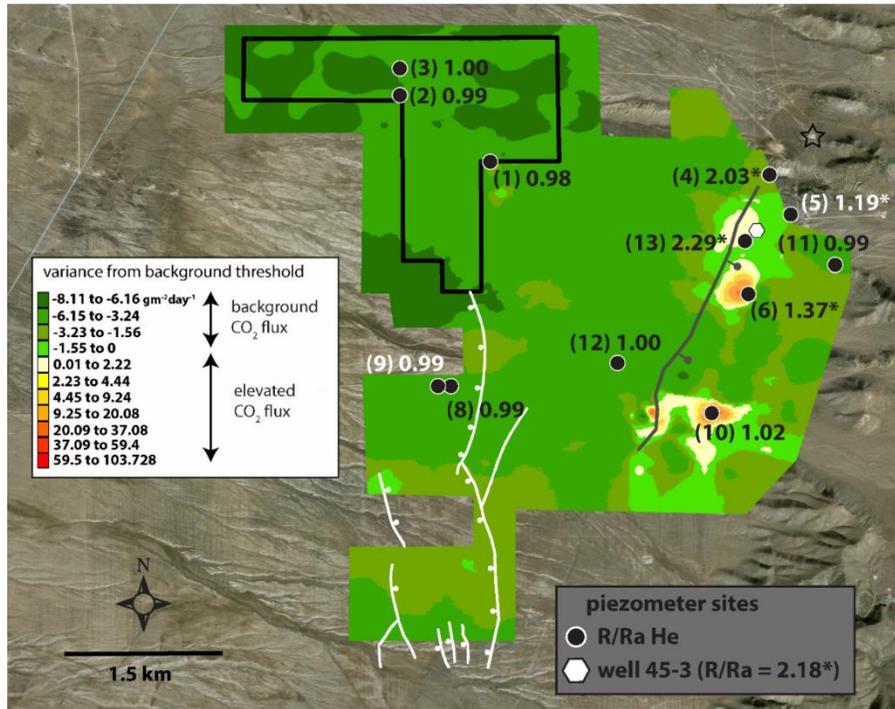
A helium isotope soil gas survey was performed in fall 2017, using diffusion samplers that were deployed in piezometers (2-3' long and 1" diameter stainless steel tubes) which had been dug with an auger tool and backfilled with compacted soil. The results show that the only sites having R/Ra values >1, indicating a component of mantle helium, are located east of the Opal Mound fault correlating with the strongest CO<sub>2</sub> fluxes (Fig. 7). All of the other samples, including those collected in the vicinity of the FORGE site, have values of 0.98 to 1.00 R/Ra representing air. Overall, these surveys confirm the absence of detectable hydrothermal upflow beneath the FORGE site.

## 7. SUMMARY

A large multidisciplinary geoscientific dataset has been acquired at the Utah FORGE site, including the drilling, logging, and testing of a vertical test well to 7536 ft (2298 m) depth. 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<sup>3</sup>). 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 Great Basin that is tectonically quiet, consistent with long term monitoring of seismic activity (e.g., Pankow et al. 2017).

## 8. ACKNOWLEDGMENTS

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**Figure 7. Integrated results of soil gas surveys showing CO<sub>2</sub> flux patterns and spot analyses of helium isotope ratios. Asterisks indicate He isotope values that have been corrected for air contamination.**

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