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A revised geoscientific model for FORGE Utah EGS Laboratory

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ABSTRACT

An improved geoscientific model has been developed for the FORGE Utah site from synthesis of numerous independent datasets, including new geological, geophysical, and geochemical surveys, plus drilling and logging of the new deep vertical well 58-32 to 7536 ft (2248 m) depth. The stratigraphy consists of two broad rock types comprising basin fill sediments and crystalline basement rocks; the latter is mostly made of Miocene granitoids that will host the proposed EGS reservoir. The contact between these rock types forms an inclined plane, which dips ~20° west and which likely represents a large-scale detachment fault. The other mappable faults have small displacements. Among these faults, the Opal Mound fault is important because it forms a barrier to westward horizontal hydrothermal fluid flow from Roosevelt Hot Springs. The new vertical test well (58-32) penetrated the basement contact 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 having northeast-southwest orientations with near vertical dips. This is consistent with the northeast-southwest direction of maximum horizontal stress determined from geological observations. Permeability measurements range 6 to 30 microdarcies, and such low values are consistent with very low fluxes of soil CO_2 over the FORGE site. These data confirm the suitability of the FORGE Utah site for development of an underground EGS laboratory.

1. INTRODUCTION

In support of the effort by the DOE to establish an EGS laboratory in the western USA, a large amount of new geoscientific data has been collected from the FORGE Utah site near Milford, Utah. These data were obtained from surface surveys, including detailed geological mapping, regional gravity, 3D seismic reflection, and soil gas geochemistry. New data sets were also obtained from the logging and testing of well 58-32. This is a new vertical well that was drilled to 7536 ft in order to prove the characteristics of the proposed EGS reservoir, including lithology, structure, temperature, permeability, and stress regime. An overview of these results is reported below, with focus on the key attributes that are critical for establishing a successful FORGE EGS laboratory.

The FORGE Utah site is located 350 km south of Salt Lake City and 16 km north northeast of Milford, Utah, in an unpopulated area that is predominantly used for renewable energy, including wind, solar, and geothermal generation (Fig. 1). The site lies 5 km west-northwest of the Blundell geothermal power plant, which produces 35 MWe from flash and binary units.

The FORGE Utah site has been the subject of many investigations in the last 40 years as summarized in recent reports (e.g., Allis et al, 2016; Hardwick et al., 2016; Simmons et al., 2016). Much of this work was conducted in support of the exploration and development of the Roosevelt Hot Springs KGRA. However, Roosevelt Hot Springs represents only a small part of a large area associated with anomalous heat flow (e.g. Allis et al., 2015; Allis et al., 2016), and the area to the west of the Opal Mound fault has long attracted interest in terms of EGS research and development (e.g. East, 1981; Goff and Decker, 1983).

2. GEOLOGIC SETTING

The FORGE Utah 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, 2018; 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

The basement rocks are dominated by Miocene age granitic rocks, which make up the core of the Mineral Mountains (e.g. Capuano and Cole, 1982; Nielson et al., 1986; Coleman and Walker, 1992; Coleman et al., 1997; Simmons et al., 2016). These igneous units, along with the localized eruption of rhyolite that form Bailey ridge and Little Bearskin mountain (Fig. 1), represent a semi-continuous record of magmatism that spans 25 to 0.5 Ma, (Lipman et al., 1978; Coleman and Walker, 1992; Moore and Nielson, 1994; Coleman et al., 1997). Quartz, plagioclase, K-feldspar, biotite, clinopyroxene, hornblende, and magnetite-ilmenite make up the main igneous minerals (Nielson et al., 1986; Coleman and Walker, 1992; Fig. 1). These granitic plutons intruded rock containing tightly folded Precambrian gneiss (~1720 Ma) made of biotite, hornblende, K-feldspar, plagioclase, quartz, and sillimanite, which crops out in the western foothills of the Mineral Mountains (Nielson et al., 1986; Aleinikoff et al., 1987).

The basin fill consists of a layered sequence of sedimentary deposits that is more than 3000 m thick. From west to east, the surface of these deposits forms a catenary profile across the north Milford valley that backfills steep-sided valleys of the western Mineral Mountains. The surface in the vicinity of the FORGE site represents alluvial fan deposits whereas the very fine-grained lacustrine sediments to the west, in the central part of the north Milford valley, were deposited in the Pleistocene Lake Bonneville (Fig 1). Older alluvial deposits (0.5-1 Ma?) form the surface across the Roosevelt Hot Springs-Blundell production field, extending eastward beneath Bailey ridge (next to Bailey spring in Fig. 1), and the oldest deposits, dating back several million years, are restricted to a few isolated exposures. Beneath the surface, the most complete record of basin filling is preserved in the units penetrated by the Acord 1 well (Fig. 1), and the cuttings have been subject to new petrographic and X-ray analyses. Below about 1200 m depth down to the contact with the basement, the strata consist of volcaniclastic sandstones and gravels, lacustrine sediments, tuffaceous deposits, and localized flows of andesitic lavas. At shallower depths, calcareous lacustrine deposits made of siltstone and sandstone dominate. Mineralogically, most of the clasts are made of quartz, feldspar, and clays. Calcite and dolomite form micritic cements shallower than 1200 m depth, and anhydrite occurs sporadically through the stratigraphy.

2.2 Faults & Fault Systems

The Opal Mound fault extends for ~5 km in a north-northeast direction, branching in the northern most part. Most workers infer a 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 (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. The Negro Mag 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; this study).

The most significant fault structure also forms the unconformable contact between overlying basin fill and the underlying crystalline basement rock. This structure has been penetrated in wells west of the Opal Mound fault, including 9-1, 58-32 and Acord 1. These well data and the notably strong reflector in seismic reflection profiles strongly suggest the top of basement contact forms an inclined ramp, which dips ~20° west and intersects the surface near the Opal Mound fault. There is, however, little direct evidence of fault offset. 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 profiles, 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 spasm 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). The detachment fault(s) probably initiated as a moderate to steeply dipping plane(s) that rotated with extension in response to a rolling hinge associated with isostatic rebound of the footwall block (Wernicke and Axen, 1988; Buck, 1988; Coleman and Walker, 1994). After acquiring low angle orientations, however, slip along these structures greatly diminished.

In sum, there are four mappable faults and fault systems that can be traced to the surface or detected from drilling and seismic reflection. 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, and these probably root into the unnamed low angle detachment fault, which appears to have accommodated much of the extension (>10 km) in the late Miocene to form the North Milford valley. More recently, however, there seems to have been minimal regional fault movement, as reflected in the basin profile, and the absence of major fault scarps and faceted spurs along the Mineral Mountains range front.

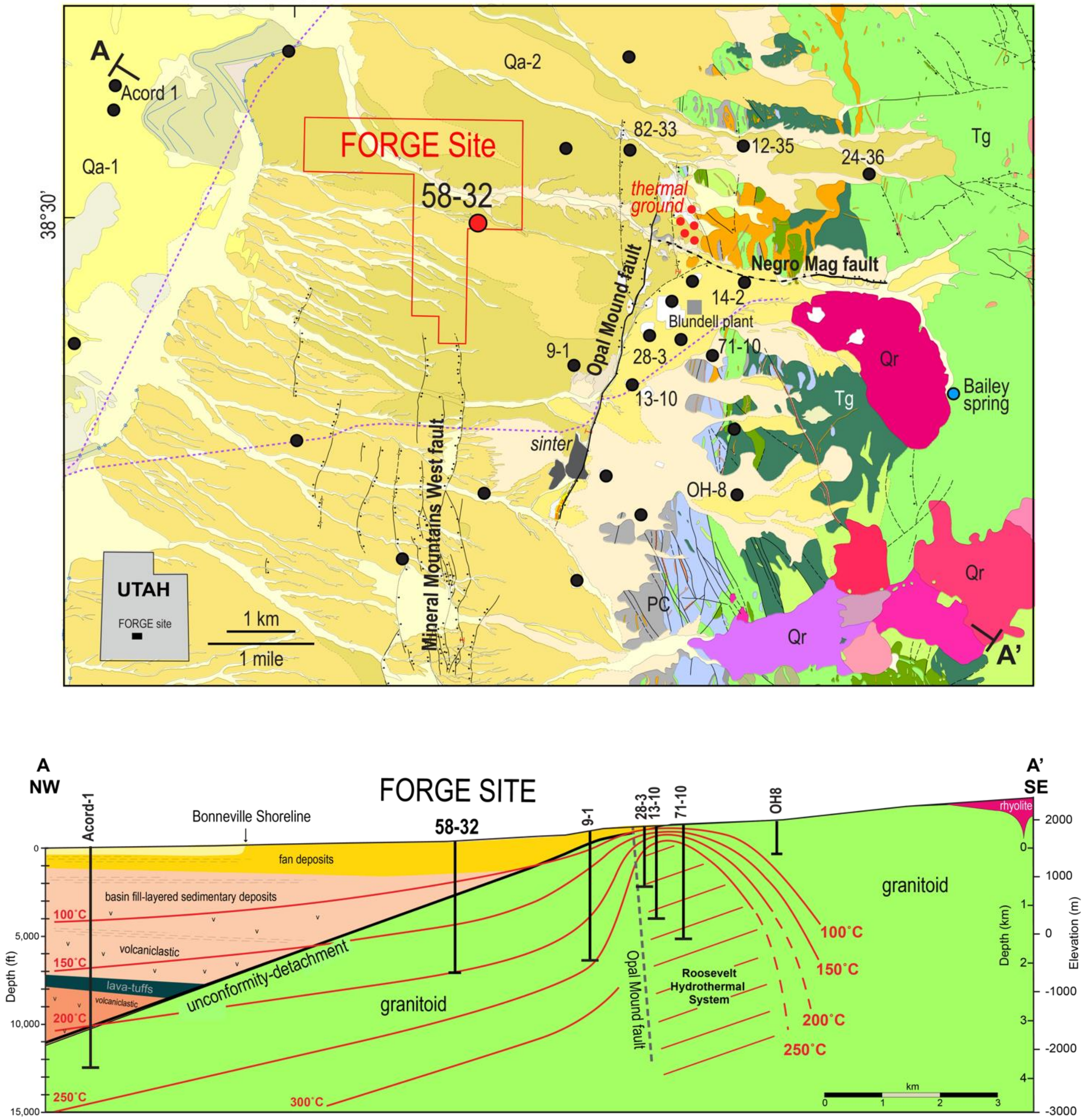

Figure 1. Geological map and cross section for the FORGE Utah site based on the integration of legacy reports, new field observations, seismic reflection profiles, and gravity data interpretation (Smith and Bruhn, 1984; Nielson et al., 1986; Smith et al., 1989; Sibbet and Nielson, 2017; this study). 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.

3. 58-32 TEST WELL

Well 58-32 was spudded on July 31, 2017 and was drilled vertically to 7536 ft (2298 m) depth in 57 days. The well penetrated layered alluvium deposits down to 3176 ft (968 m), where it crossed the contact with underlying crystalline basement rocks, which make up the rest of the stratigraphy to the bottom of the hole. Drill cuttings were collected every 10 ft and samples of core were collected from two intervals at 6800-6810.25 ft (2073-2076 m) and 7440-7452.15 ft (2268-2272 m). The cores were logged for their physical and lithologic properties, photographed, CT-scanned and plugged for mechanical testing. A complete suite of geophysical logs was run (2172-7536 ft), and the hole was then lined with 7-inch casing down to 7375 ft (2248 m). The FMI log is of particular interest, because apart from mapping fractures, it provides a continuous image of sedimentary and igneous rock textures. The last temperature log was run 37 days after the rig left the site. These activities will be described in later reports, and only the highlights are summarized below.

3.1 Rock Types and Mineralogy

The upper interval of layered alluvium (0-3176 ft; 0-968 m) consists of poorly sorted and poorly lithified sands and gravels made of quartz and feldspar eroded from the plutonic rocks in the Mineral Mountains. The upper two-thirds probably resembles fan deposits on the surface. Between 2172 (662 m) and 3176 ft (968 m), the horizontally bedded sediments are interspersed with distinctive cobble to boulder sized clasts that are clearly visible in the FMI log, correlating stratigraphically and texturally with late Tertiary deposits exposed on the surface. These deeper strata likely accumulated near the subsiding base of a very tall and steep range front, representing a depositional setting unlike anything seen along the western edge of the Mineral Mountains today.

The lower interval (3176-7536 ft; 968-2298 m) consists of plutonic igneous rocks, very similar to those exposed in the Mineral Mountains. Based on thin section and X-ray diffraction analyses of cuttings and cores, plagioclase, K-feldspar, and quartz are the dominant minerals, with minor amounts of biotite, hornblende, clinopyroxene, apatite, titanite, zircon, and magnetite-ilmenite (Fig. 2). The proportions of minerals were used to classify the igneous rock types, according to the IUGS scheme, as monzodiorite, quartz monzodiorite, monzonite, quartz monzonite, and granite, plus minor granodiorite and diorite. Illite and chlorite are the main clay minerals, but they constitute <5% of the rock. Other secondary minerals include carbonate and anhydrite, and factures in the cored intervals are locally lined with chlorite or epidote.

The only other notable lithology encountered during drilling occupies a 20 ft interval beneath the basement contact. It comprises a fine grained rhyolitic rock, with quartz (resorbed) and sanidine phenocrysts and spherulites, set in a devitrified groundmass. Thin sections reveal evidence of shearing, brecciation and cementation by quartz, and of hydrothermal veining filled in paragenetic order with chalcedony, quartz, kaolinite, and late calcite. This rock appears to be the product of high-level to surficial magmatic and hydrothermal activity.

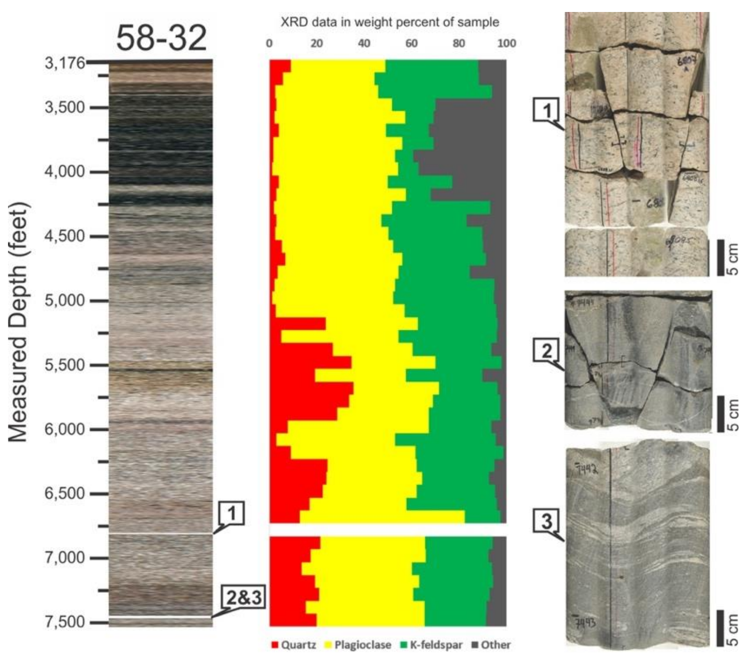

Figure 2. Rock types and mineralogy of units penetrated by well 58-32 from 3176 (968 m) to 7536 ft (2298 m). The left image shows the chipboard and the color variation in crystalline plutonic rocks with depth. The center image shows the proportions of quartz, plagioclase, and K-feldspar determined from quantitative x-ray diffraction of drill cuttings. The right image shows photographs of core segments taken from depth intervals labeled 1, 2 and 3 on the chipboard. The steeply dipping fractures in drill core 1 appear to have a natural origin, but there is less certainty about the fractures in drill core 2, which might have been induced by drilling. The light and dark banding in drill core 3 is a characteristic feature that occurs sporadically through the basement rocks as indicated by the FMI log.

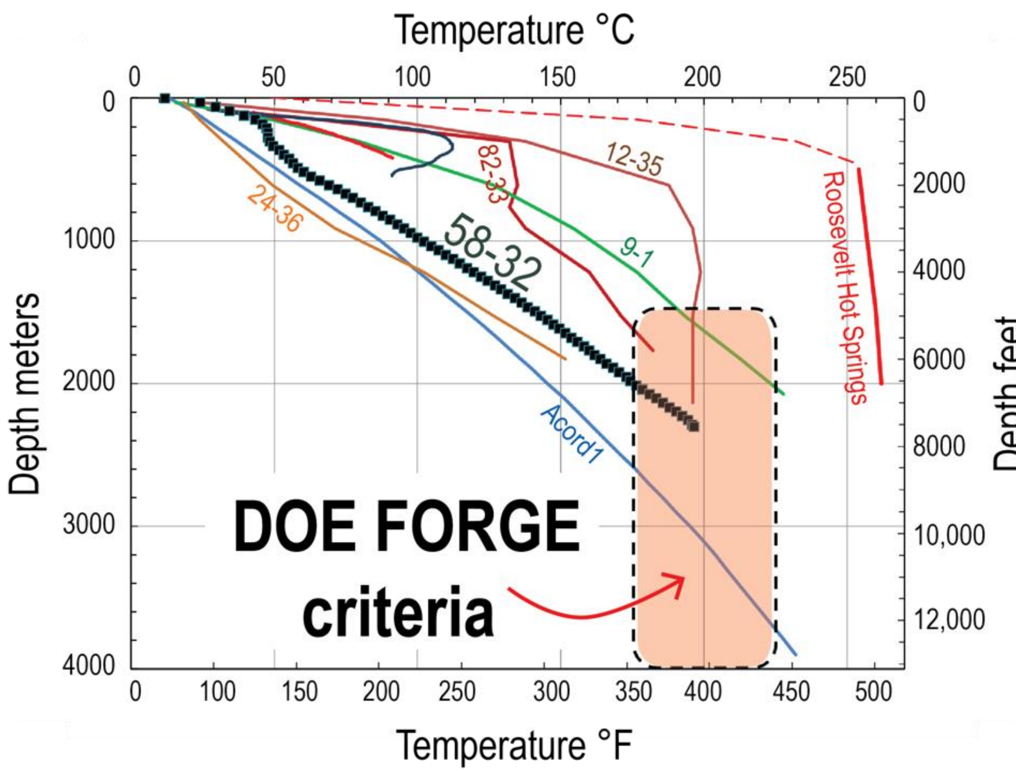

Figure 3. Temperature profiles for 58-32 and surrounding wells.

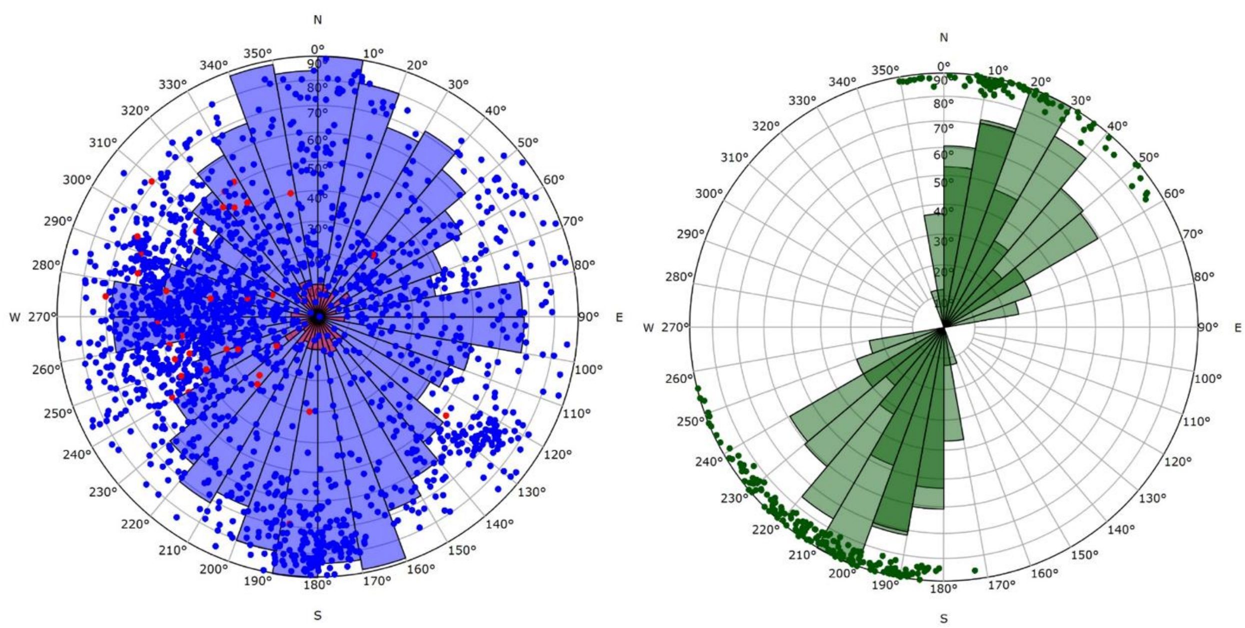

Figure 4. The stereonet projections of fracture patterns in 58-32 interpreted from the FMI log. The left image shows the azimuth and dip (upper pole orientations) of ~2000 natural fractures in crystalline basement rocks (blue=conductive part resistive; red= continuous fracture). The right image shows the azimuth and dip (upper pole orientations) of fractures induced by drilling, reflecting the orientation of regional maximum horizontal stress.

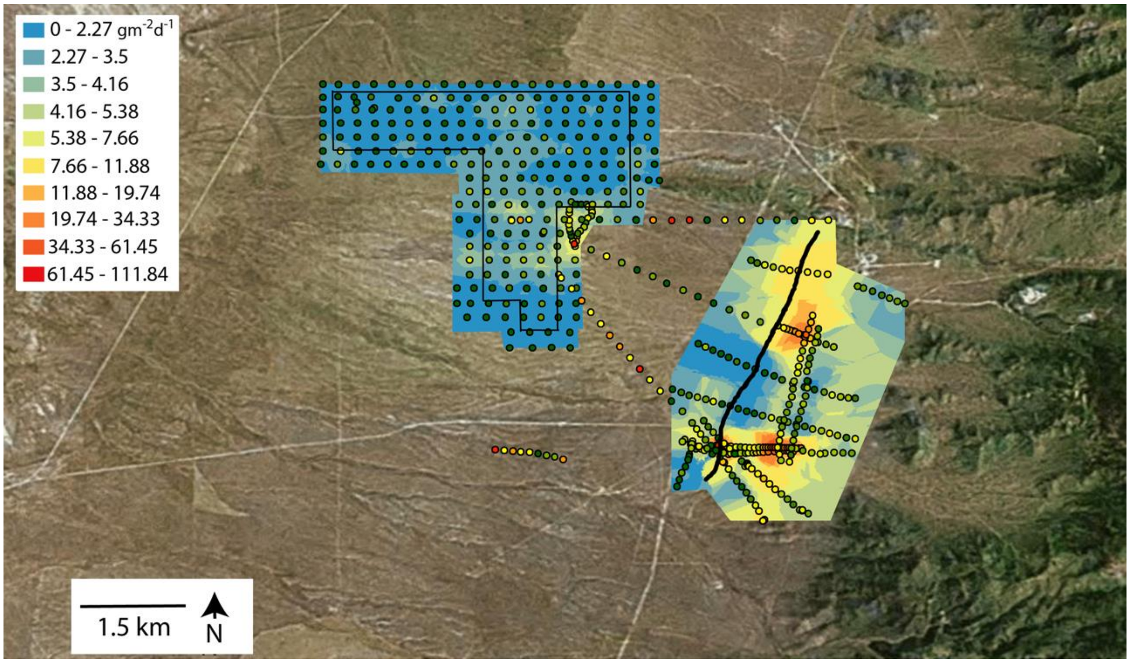

Figure 5. Soil CO_2 survey stations and fluxes measured June, 2017 over the FORGE site and east of the Opal Mound fault (bold black line). Most of the measurements produced values below the statistically determined background threshold of 7.66 grams/m^{2}day. Anomalous fluxes are limited to areas of hydrothermal activity east of the Opal Mound fault and associated with the Roosevelt Hot Springs hydrothermal system.

3.2 Temperature Survey

A wireline temperature survey was run 37 days after the completion of all well testing, and the resulting profile is compared to others from nearby wells in Figure 3. The maximum temperature of 197°C was measured at the bottom of the hole, and the linear profile (below 1700 ft, 518 m depth) indicates a conductive gradient of 73°C/km. Further information about this and other temperature data are described in Allis et al. (2018).

3.3 Fractures, Stress Regime and Permeability

An FMI log was run from 2172 ft to TD at 7536 ft. Approximately 2000 natural fractures, most restricted to the basement rocks (>3176 ft depth), were identified. 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°) 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 dips to the southeast and northwest. These patterns strongly resemble the spacings and orientations of fractures in granitic rocks in the Mineral Mountains, especially those occurring east of Roosevelt Hot Springs. They are also different from the factures and joint patterns occurring in young rhyolite flows, and this suggests that most of the fractures in granitic rocks formed before 0.5-0.8 Ma.

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 the orientation of σ_{Hmax} determined from geological observations to the east. Well testing suggests permeabilities of the granite near the bottom of the hole are approximately 30 microdarcies, consistent with a measurement of 6 microdarcies that was acquired on core plugs at EGI. These values indicate that the proposed EGS reservoir has very low natural permeability.

4. SOIL GAS SURVEY

As a check on the possible existence of cryptic hydrothermal flow within and around the FORGE site, a CO_2 soil gas survey was performed in June, 2017. Diffuse flux measurements were made using a PP Systems EGM-4 or EGM-5 portable carbon dioxide analyzer. For each measurement, the sensor was in contact with the ground for ~5 minutes, and the resulting values were extrapolated to give fluxes in grams/m^{2}day. Over 700 individual measurements were acquired from sample stations spaced 0.1 mi (160 m) apart. About a third of the stations were concentrated around the FORGE site (271 stations). The remaining stations were laid out along transects crossing the Opal Mound fault and aligned north-south through the Roosevelt Hot Springs production field (463 stations). The results are shown in Figure 4, and from statistical analysis, a background flux of 7.66 grams/m^{2}day was derived. Most of the measurements around the FORGE site are below this background threshold. By contrast, anomalously high CO_2 fluxes, greatly exceeding the threshold value, are measured in the vicinity of Roosevelt Hot Springs and east of the Opal Mound. Five carbon isotope measurements were obtained on a small set of soil gas samples that were collected into Tedlar bags and analyzed using a Thermo Fisher Delta Ray Isotope Ratio Infrared Spectrometer (IRIS). The results gave $\delta^{13}C$ values of -10 to -12 per mil, which suggest a biogenic source associated with desert vegetation. Overall, the results confirm the absence of detectable hydrothermal upflow beneath the FORGE site. Instead and as expected, hydrothermal activity is restricted to the east side of the Opal Mound fault where anomalously high CO_2 fluxes were detected.

5. SUMMARY

The acquisition of large multidisciplinary geoscientific datasets, including the drilling of a vertical test well to 7536 ft (2298 m) depth, confirm the suitability of the FORGE Utah site for development of an underground EGS laboratory. 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 (>50 km^3). The reservoir rocks are also fractured, but they lack connectivity to support natural flow of water. The geological record indicates that the FORGE Utah site is located in a part of the Great Basin that is tectonically quiet, consistent with long term monitoring of seismic activity (Pankow et al. 2017).

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