PROCEEDINGS, 49th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2024
SGP-TR-227

The interplay of impermeable crystalline basement rocks, tectonic fracturing, and magmatic intrusion in the development of geothermal resources at Utah FORGE and Roosevelt Hot Springs

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Keywords: Utah FORGE, Roosevelt Hot Springs, heat transfer, helium isotopes, magnetotelluric resistivity, geology

ABSTRACT

The geothermal reservoirs at Roosevelt Hot Springs and Utah FORGE EGS share common host rocks comprising Oligocene-Miocene granitoids and Precambrian gneiss representing end-member conditions of convective and conductive heat flow that formed within a large-scale magmatic geothermal system. Native state convective heat transfer at Roosevelt Hot Springs of 60-70 MW, equating to heat loss of 3-7 W/m^2, is restricted east of the Opal Mound fault over ~10 km^2, whereas to the west conductive heat flow ranges 100-200 mW/m^2 over >50 km^2 as expressed by linear temperature gradients measured in Utah FORGE wells.

The magnetotelluric resistivity structure shows that the crystalline basement, which hosts geothermal reservoirs, is thick and likely extends to 15 km depth, covering an area >400 km^2 and a volume >8000 km^3. Judging from the modeled very high resistivity, it is also impermeable except for a narrow N-S trending corridor (1-2 km wide) of elevated conductivity extending to >10 km depth directly beneath Roosevelt Hot Springs. A separate subvertical pipe-like zone of enhanced electrical conductivity extends continuously to >20 km depth to the northwest of Utah FORGE that supplies mantle helium into the shallow groundwater regime in the center of the Milford valley.

The endowment of anomalous thermal energy within conductively heated basement rock is estimated to be 2.5E+17 kJ which is equivalent to >400 km^3 of just solidified felsic magma. This is consistent with the large mantle helium anomaly (1.9 to 2.6 R/Ra) which includes both Roosevelt Hot Springs and the Milford valley groundwaters and covers >200 km^2. That a zone of partial melt currently exist beneath 10 km depth is indicated by reduced seismic shear velocities at mid crustal depths, otherwise the geometry and distribution of any sort of magma body is difficult to resolve. A felsic magmatic composition is also consistent with the 0.9 to 0.5 Ma eruption of rhyolite in the Mineral Mountains, and this suggests that silicic magmatism has been semicontinuous for almost 10^6 years.

Overall, the thick impermeable nature of the crystalline basement rock beneath the east side of the Milford valley and forming the core of the Mineral Mountains impedes ascent of magma and bifurcates the flow of deep-sourced helium to the surface. As a result, convective hydrothermal heat transfer is strongly localized within a narrow corridor of highly fractured rock, whereas a much larger volume of rock is heated directly and conductively by magmatic intrusion stimulated by mafic underplating.

1. INTRODUCTION

The juxtaposition of two distinct types of geothermal resource that includes the Utah FORGE EGS project and the Roosevelt Hot Springs hydrothermal system has few comparable analogs. The two resources sit side by side and are separated by the Opal Mound fault a relatively minor structural feature that divides a convective heat flow setting to the east from the conductive heat flow setting to the west (Allis et al., 2019). As the two resources share the same non-porous crystalline host rocks, the presence and absence of structurally controlled permeability has played a fundamental role in their respective development. A separate genetic factor is the source of heat, which has long been attributed to magmatic activity based on the eruption of rhyolite flow dome complexes between 0.9 and 0.5 Ma (Lipman et al., 1978; Nielsen et al., 1986) and detection of mantle helium in produced geothermal fluids at Roosevelt Hot Springs (Welhan et al., 1988; Kennedy and van Soest, 2007; Simmons et al., 2021).

While investigations in the late 1970s to early 1980s suggested the thermal anomaly was widespread, it was only with the drilling of Utah FORGE that the areal extent of hot impermeable conditions in the basement rocks was confirmed (Allis et al., 2019). With temperatures of >200°C having been penetrated at <3 km depth, success has been achieved in the cost-effective testing of EGS technologies (Moore et al., 2023). The real value of such findings, however, are reflected in the efforts to realize commercial scale EGS production at the nearby Cape Station project where drilling commenced in 2023 (https://fervoenergy.com/fervos-year-in-review/).

This paper deals with the interplay of impermeable crystalline basement rocks, tectonic fracturing, and magmatic intrusion in the development of geothermal resources at Utah FORGE and Roosevelt Hot Springs. It builds on understanding of the thermal structure and heat flow (Allis et al., 2019), the helium isotope patterns occurring in cold ground waters (Simmons and Kirby, 2023), and the magnetotelluric (MT) resistivity model (Wannamaker et al., 2021). A distinctive feature is the impermeable nature of the crystalline basement rocks, which has induced conductive heat flow and apparently suppressed ascent of deep-seated magmas.

2. GEOLOGICAL SETTING

Geothermal resources associated with the Utah FORGE site and Roosevelt Hot Springs are located beneath gently sloping alluvial cover, on the east side of the Milford valley (Figure 1), and they are associated with a heat flow anomaly covering ~100 km^2 (Allis et al., 2019). The valley is part of a large geologically complex region that is situated inside the southeast margin of the Basin and Range province (Wannamaker et al., 2008; Simmons et al. 2019), where hydrothermal activity is widespread but scattered, and associated with young extensional faults and Quaternary volcanism (e.g., Simmons et al., 2019).

The Milford valley represents the northern extension of the Escalante desert, with an axis that runs north-south that is bounded to the west by the San Francisco Mountains and to the east by the Mineral Mountains. Seismic reflection and gravity profiles show that the valley occupies an asymmetric rift basin floored by relatively dense basement rocks that form a strong seismic reflector (Smith and Bruhn, 1984; Miller et al. 2019; Hardwick et al., 2019). These same basement rocks form the large Oligocene-Miocene age plutonic complex exposed in the Mineral Mountains (Nielson et al., 1986; Coleman and Walker, 1992; Kirby, 2019). Furthermore, the basement contact with overlying basin-fill represents a rotated normal fault that accommodated much of the local tectonic extension between 10 and 8 Ma (Bartley, 2019). Separately, the Mineral Mountains host several discrete Pleistocene (0.9-0.5 Ma) volcanic centers (1–15 km^2) that mainly comprise rhyolite flow dome complexes (Lipman et al., 1978; Kirby, 2019). For example, the Bailey Ridge flow which is made of obsidian and rhyolitic pyroclastic deposits lies 2–5 km east of Roosevelt Hot Springs. This localized magmatic activity is part of a belt of predominantly mafic volcanism the extends across southwestern Utah (Best et al., 1980).

The Opal Mound and Mag Lee faults are relatively short length (<10 km) structures that intersect at an orthogonal angle and appear to bound the Roosevelt Hot Springs geothermal reservoir (Nielson et al., 1986; Bartley, 2019; Knudsen et al., 2019; Allis et al., 2019). Both faults have what appear to be small vertical offsets of 10-15 m based on topographic expression, and both are believed to dip steeply. The Mineral Mountains West fault system is the only other young fault system known, comprising a series of normal fault segments with small offsets that extends southward from the Utah FORGE site. Regional natural seismicity is sporadic and dispersed, and representative of the western fringe of the Intermountain seismic belt, which runs north-south along the eastern edge of the Basin and Range (Pankow et al., 2009). Locally, it includes relatively frequent swarms just east of Roosevelt Hot Springs beneath the western foothills of the Mineral Mountains (Mesimeri et al., 2021).

Geothermal activity is expressed on the surface at Roosevelt Hot Springs, which is a high-temperature hydrothermal system that is entirely hosted in fractured basement rocks (Capuano and Cole, 1982; Nielson et al., 1986; Allis et al., 2019; Simmons et al., 2021). Hydrothermal upflow covers ~10 km^2 and corresponds to convective heat transfer of 60-70 MW. This is equivalent to a concentrated heat flow of 3-7 W/m^2 that contrasts with the larger adjoining region lying mostly to the west of the Opal Mound fault and covering >100 km^2 where anomalous conductive heat transfer ranging 100 to 180 mW/m^2 predominates (Figure 2; Allis et al., 2019). Such a sharp partitioning of large heat flow domains can be attributed to differences in basement rock permeability. Beneath the Utah FORGE site, the measured geotherm in deep wells is ~70°C/km, and the isotherms dip gently to the northwest (Allis et al., 2019).

The basement rocks that host the Roosevelt Hot Springs and the Utah FORGE reservoirs are largely made of coarsely crystalline granitoids that range from granite to diorite in composition. The minerals comprise tight interlocking grains of quartz, plagioclase, K-feldspar, biotite, clinopyroxene, hornblende, and magnetite-ilmenite (Jones et al., 2019). These granitoids were emplaced 26 to 17 Ma and intruded into tightly folded Precambrian gneiss (Coleman and Walker, 1992). The gneiss is mineralogically similar, being made of biotite, hornblende, K-feldspar, plagioclase, and quartz, with minor to trace occurrences of sillimanite. Although laboratory and field testing indicate rock permeabilities are in the range of 1s-100s micro-darcy, the development of a small population of secondary minerals mainly associated with granitoids provide evidence of stronger permeability in the geologic past. These minerals are made of epidote, actinolite, carbonate, and clays, and they appear to mainly occupy fracture fillings. Some chlorite-smectite lined structures contain traces of halite, a highly soluble salt that provisionally may have contributed to sharp increases in the TDS concentrations of flow back waters during the stimulation of well 16A(78)-32 (Jones et al., 2023).

3. MANTLE HELIUM ANOMALY

Mantle helium was first detected in Roosevelt Hot Springs production fluids over 35 years ago, providing diagnostic evidence of a magmatic heat source in the area (Welhan et al., 1988). In 2015, as part of a regional survey of thermal waters, mantle helium was detected in cold groundwaters produced from shallow wells west of the Utah FORGE site. Follow up measurements have proven the existence of a large mantle helium anomaly covering >200 km^2 that occurs mostly towards the center of the Milford valley (Figure 2; Simmons and Kirby, 2023). Its extent surpasses the dimensions of many known geothermal resources, and most of the anomaly also appears to be offset from the center of maximum heat flow, which encircles the region encompassing the Utah FORGE site and Roosevelt Hot Springs. Furthermore, the concentration of helium in groundwaters, which strongly correlates with the $^{4}He/^{20}Ne$ ratio, exceeds the value of air saturated water by more than two orders of magnitude. The patterns of the $^{4}He/^{20}Ne$ ratio thus imply there are separate pathways of helium ascent, which is consistent with the MT resistivity structure described below.

An important characteristic is the uniformity of the helium isotope ratios, which hover between 1.9 and 2.6 R/Ra and bracket the values measured at Roosevelt Hot Springs. This strong coherence suggests that the helium originated from a common magmatic source in the form of a felsic melt body similar in composition to the rhyolite that erupted over 500,000 years ago in the Mineral Mountains. These values are distinct from helium isotope ratios measured in basaltic lavas elsewhere in SW Utah, which range from 4.6 to 6.7 R/Ra (e.g., Dodson et al., 1998). Nevertheless, the intrusion of such mafic magma is believed to be the most likely means by which mantle helium was introduced into the lower crust. Associated heating subsequently induced partial melting that also liberated radiogenic ^{4}He which accounts for the lowering of mantle sourced R/Ra values across the Milford valley.

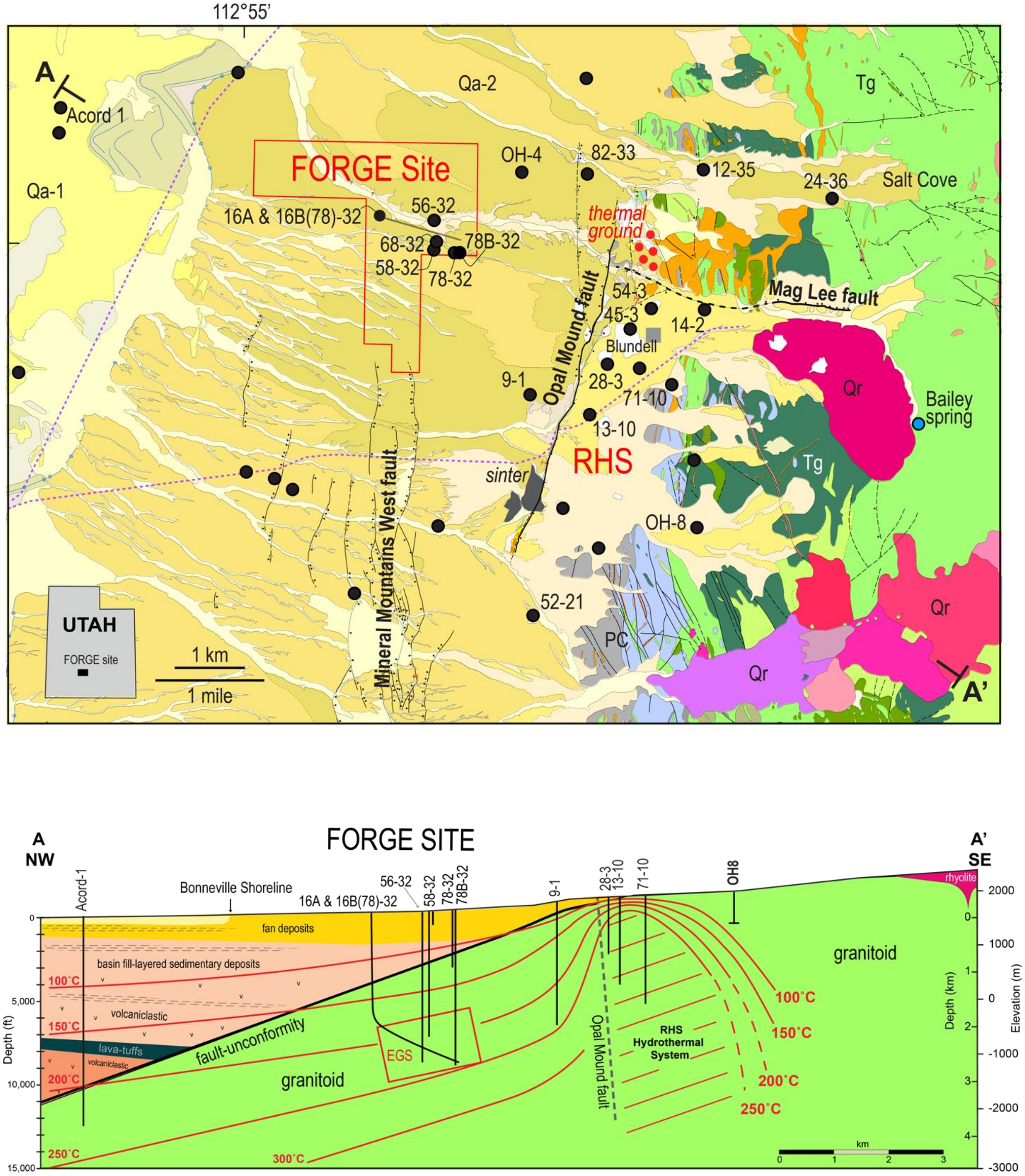

Figure 1: Geologic map and cross section of the Utah FORGE site, Roosevelt Hot Springs (RHS) and surrounding area (modified from Nielson et al. 1986 and Kirby, 2019). The thermal structure is interpreted from well measurements (Allis et al., 2019), and the red box denotes the location of the EGS test reservoir.

4. MT RESISTIVITY STRUCTURE

Plan and cross-sectional views of the MT resistivity structure are shown to illuminate the nature of the deeper crust (Figure 3), and these images are products of the most recent model inversion, which were executed to help filter the effects of the Kern River pipeline (https://gdr.openei.org/submissions/1578). The images show that from the surface to <5 km depth, the domains of strong conductance (<1.5 $\log_{10}\Omega m$) represent the basin fill strata, whereas the domain of strongest resistance represent crystalline basement rock, including the granitoid and gneiss exposed in the core of the Mineral Mountains. In both plan and cross section view, this strongly resistive feature (>3.75 $\log_{10}\Omega m$) forms a coherent mass >8000 km^3 that extends westward beneath the Milford valley to at least 15 km depth. On the eastern side, this resistor is bisected by a narrow corridor representing a slightly more conductive zone (1.5-3 $\log_{10}\Omega m$) that underlies Roosevelt Hot Springs well 45-3 and Bailey spring. Wannamaker et al. (2021) identified this feature as an ascent pathway for hydrothermal fluids and magmatic intrusion. In the vicinity beneath LWM, a shallow groundwater well, a subvertical pipe-like zone of enhanced electrical conductivity (1.0-1.5 $\log_{10}\Omega m$) extends continuously to >20 km depth, and this too was identified as a separate potential ascent pathway for deeply derived helium (Wannamaker et al., 2021), which is possibly accompanied by advective heat transfer. A third pipe-like zone of enhanced electrical conductivity occurs directly north of Utah FORGE, forming an elongate ENE trending feature that intersects the Cove Fort basaltic volcanic center to the east. This zone merges with the root to the upflow zone beneath Roosevelt Hot Springs, connecting through to the highly conductive region at 35-40 km depth that is associated with a zone of mafic melt below the base of the crust (Wannamaker et al., 2008; 2021). Unclear from the MT model is where felsic partial melts might be accumulating, and it is inferred that the resistivity contrast is too diffuse to provide clear demarcation.

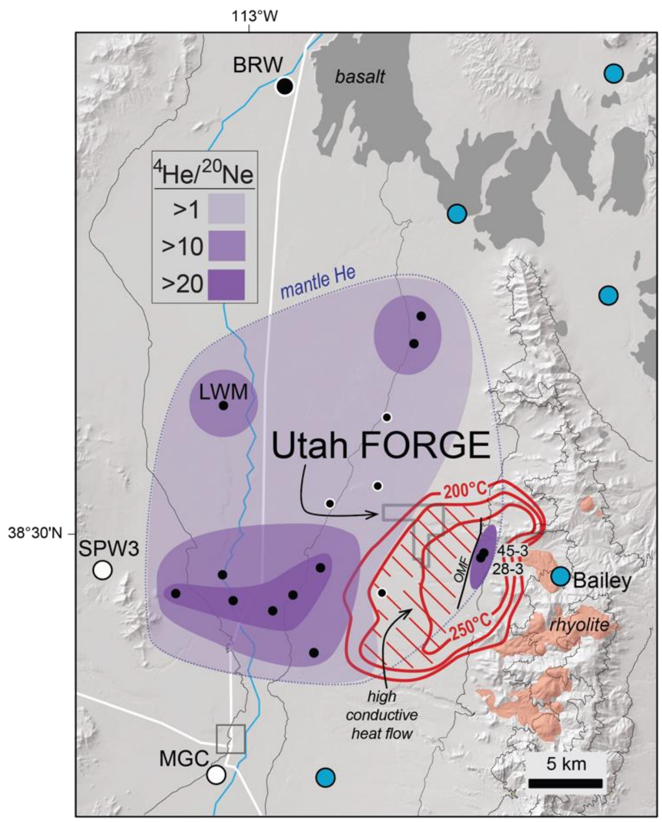

Figure 2: Plan view of the cold groundwater mantle helium anomaly shown bounded by $^4He/^3He$ values >1.8 R/Ra (lavender filled region) in the Milford valley. The red contours demarcate the isotherms at 3 km depth related to the geothermal anomaly that encloses Utah FORGE and Roosevelt Hot Springs (Allis et al., 2019). Black filled circles represent shallow groundwater wells, except for 45-3 and 28-3, which are geothermal production wells. Rhyolite flow dome centers are shown in pink, and outlying basalt lava flows are shown in dark grey.

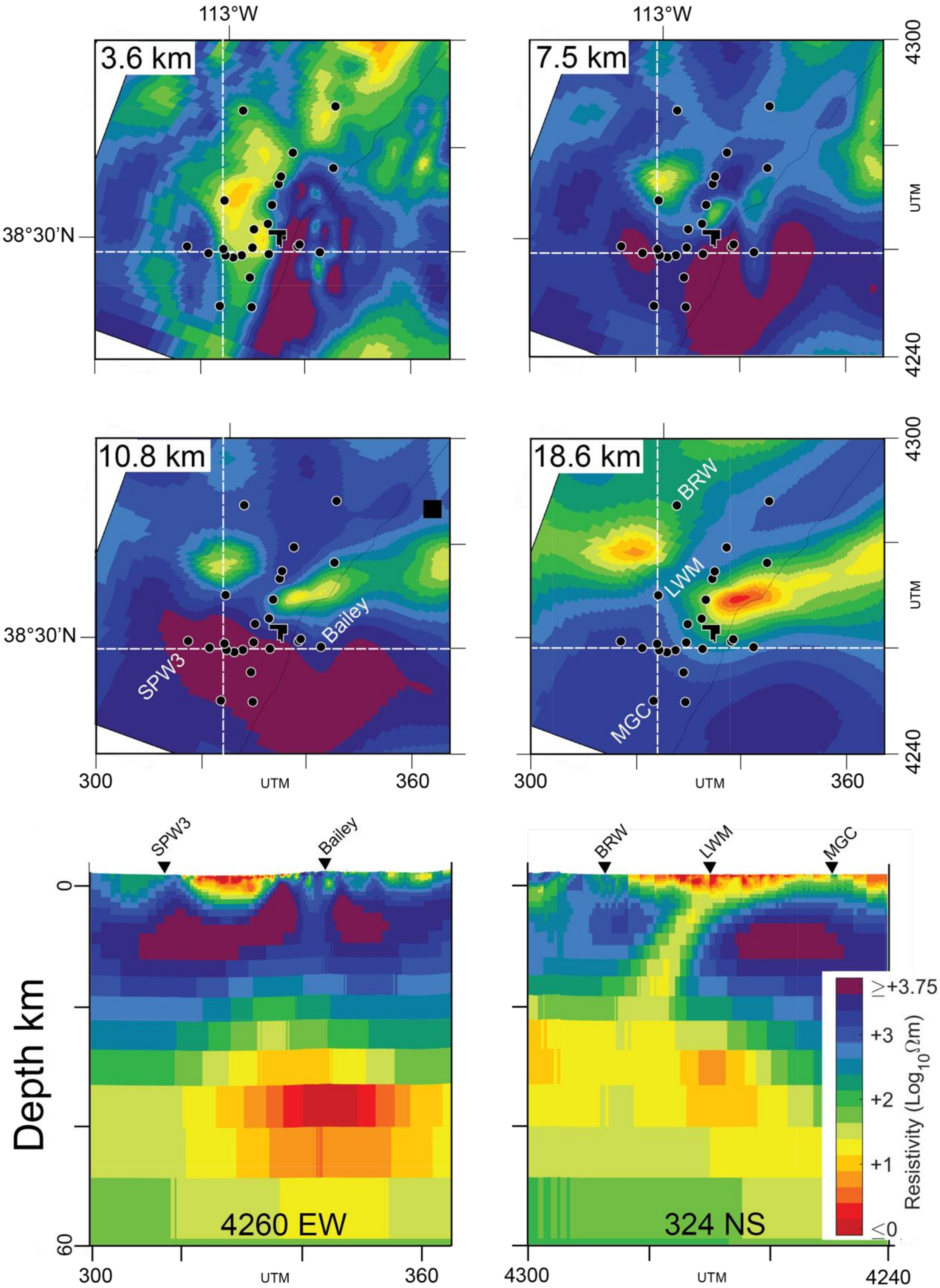

Figure 3: Plan (top four images) and cross section (bottom two images) views showing change in MT resistivity structure with increasing depth following Wannamaker et al. (2021) and based on recent modeled inversion.

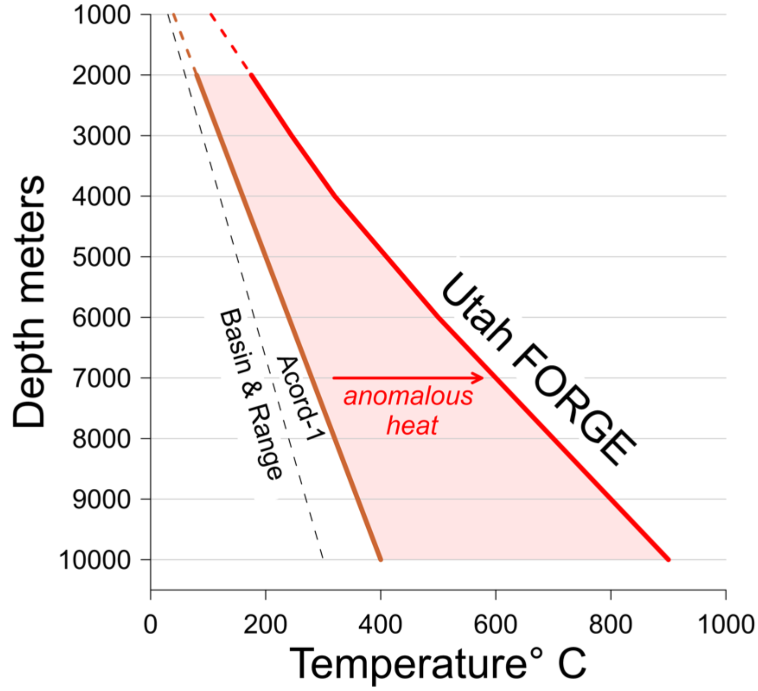

Figure 4: Geotherms based on interpretations of deep well measurements beneath and near Utah FORGE (Allis et al., 2019). The anomalous heat is calculated (2.5E+17 kJ) and used to estimate the volume of recently solidified felsic magma.

5. SOLIDIFIED MELT VOLUME

The volume of recently solidified felsic magma can be estimated based on a calculation of anomalous stored heat in the hot granitic basement rock west of the Opal Mound fault, which requires rock density, the specific heat of granite, and the difference in regional background and Utah FORGE temperature gradients. The calculation is limited to the column of hot dry rock having high conductive heat flow that is inscribed by the 225°C isotherm at 3 km depth, covering ~30 km^2 and extending to 10 km depth (Figure 4). The resulting value for anomalous stored heat (2.5E+17 kJ) represents a summation of values calculated for 1000 m depth intervals from 2000 to 10,000 m, which is equivalent to >400 km^3 of recently solidified granite. The volume estimate is conservative as it excludes the heat flow associated with hydrothermal activity at Roosevelt Hot Springs east of the Opal Mound fault. Notably, the volume of new granite is large in comparison to the roughly 6 km^3 of rhyolite exposed in the Mineral Mountains (Figure 2). If this granitic melt body formed a sill 2 km thick, it would have an aerial extent comparable to the mantle helium anomaly outlined in Figure 2. Separately, regions of low seismic velocity between 5 and 15 km depth have been interpreted as an effect of partial melting (Robinson and Iyer, 1981; Wells et al., 2022). As heat transfer via conduction is slow compared to convection, the location of melt is expected to be concentrated in the vicinity of the strongest part of the thermal anomaly.

6. DISCUSSION AND CONCLUSIONS

High geothermal heat flow and the infiltration of mantle sourced helium into the shallow groundwater system over a large region are interpreted as products of semi-continuous magmatism over the last 10^6 years. The absence of eruptions in the last several hundred thousand years indicates magmas stall out before rising to shallow crustal levels. Conceptually, mafic magma intrudes the lower crust, which induces partial melting. The resulting felsic magma forms a continuous medium that occupies the interstices of a crystal mush, diluting the original mantle helium signature through incorporation of about three times as much radiogenic helium. Additionally, it forms the magmatic parent to eruptions of rhyolite in the Mineral Mountains. The zone of partial melt is poorly defined, but likely hugs the base of the granitoid-gneiss resistor and almost certainly controls the homogenization of the helium isotope ratios.

At Roosevelt Hot Springs, coupled transport of heat and deeply derived helium through to the surface is carried by hydrothermal fluids via a narrow structural corridor of interconnected fractures that bisects the granitic basement rock. In the center of the Milford valley, by contrast, a pipe-shaped conduit, which transects the lower and upper crust into the deep part of the sediment filled-basin, provides a separate pathway for helium ascent which infiltrates the cold groundwater regime. Based on the zonation of $^4He/^{20}Ne$ values (Figure 2), it appears likely that within the basin-fill strata pathways of helium ascent split into subzones of upflow that maybe be structurally controlled having an E-W orientation. Thus, two distinct end-member fluid flow regimes have developed, representing coupled and decoupled heat and mass transfer. Critically, the development of a hydrothermal convection cell beneath Roosevelt Hot Springs appears entirely dependent on concentrated tectonic fracturing to form a connected permeable slot extending several kilometers depth. Unfortunately, not much is known about how or when it formed are even of the fine scale attributes other than what can be deduced from the record of geothermal production (e.g., Simmons et al., 2021).

Overall, the thick impermeable nature of the crystalline basement rock beneath the east side of the Milford valley and forming the core of the Mineral Mountains impedes ascent of magma and bifurcates the flow of deep-sourced helium to the surface. As a result, convective hydrothermal heat transfer is strongly localized within a narrow corridor of highly fractured rock, whereas a much larger volume of rock is heated directly and conductively by magmatic intrusion. By blocking the rise of buoyant magma, the impermeable basement trapped thermal energy released by crystallizing mafic melt at mid to deep crustal levels to facilitate partial melting and to form a thick thermal aureole that is endowed with a large quantity of magmatic heat.

5. ACKNOWLEDGEMENTS

This work is sponsored by the U.S. Department of Energy, Energy Efficiency and Renewable Energy (EERE) Geothermal Technologies Office projects DE-EE0007080 and DE-EE0007604.

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