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Mantle Helium in Cold Ground Water in the North Milford Valley and the Implications for Additional Geothermal Resources near Roosevelt Hot Springs and Utah FORGE

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ABSTRACT

The endowment of geothermal energy at Roosevelt Hot Spring and the Utah FORGE site have been associated with magmatic heat, mainly on the basis of 0.9 to 0.5 Ma rhyolites occurring in the Mineral Mountains and mantle helium isotope signatures in produced geothermal fluids. Here we report another major manifestation of magmatic activity in the form of a large mantle helium anomaly covering greater than 200 km^2 that occurs in cold groundwaters sampled from shallow groundwater wells in the center of the North Milford valley. There are three aspects of this work that are worth highlighting. First, the extent of the mantle helium anomaly is exceptional and greatly exceeds the dimensions of the known geothermal resources based on what can be deduced from surface geology, heat flow, and deep drilling. Second, the mantle helium anomaly is offset from the center of maximum heat flow, which encircles the region encompassing the Utah FORGE site and Roosevelt Hot Springs. Third, the uniformity of the isotopic ratios between 1.9 and 2.6 R/Ra overlaps that measured at Roosevelt Hot Springs, and this suggests 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. These findings suggest the potential for additional geothermal resources in the North Milford Valley.

1. INTRODUCTION

The Utah FORGE EGS site is situated in southwestern Utah, within the North Milford valley and adjacent to the Roosevelt Hot Springs hydrothermal system. Since the 1970s, a large amount of geoscientific data about the project area and surrounding setting have been obtained during geothermal development first at Roosevelt Hot Springs and later at the Utah FORGE site (e.g., Allis and Moore, 2019). Among the many relevant findings were the recognition of a mantle He isotope signature in the high temperature geothermal fluids from Roosevelt Hot Springs (Whelan et al., 1988) and a shallow subsurface hydrothermal outflow plume hosted in an alluvial aquifer that drains towards the center of the valley (Vuataz and Goff, 1987; Kirby et al., 2019). The mantle He isotope signature has been and remains evidence of a magmatic heat source, whereas the shallow outflow plume affects groundwater quality making it non-potable. In 2015, as part of a separate study, we detected mantle He in samples of cold groundwater obtained from several shallow wells near the center of the valley. Since then, we have surveyed and sampled additional groundwater wells, plus natural springs, and production wells at Roosevelt Hot Springs. In this brief report, we summarize the results of this work which provide a clearer picture of the spatial pattern relating to a large mantle He anomaly hosted in cold groundwaters and the relationship to the outflow plume originating from the Roosevelt Hot Springs. We also discuss the implications in terms of the potential for additional geothermal resources in the region.

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 North Milford valley, in association with a broad geothermal anomaly with elevated heat flow covering ~100 km^2. (Allis et al., 2019). These resources lie within a large geologically complex region that is situated inside the southeast margin of the Basin and Range province near the western edge of the Colorado Plateau (e.g., Dickinson, 2006; Wannamaker et al., 2008). Hydrothermal activity is widespread across this region, and Roosevelt Hot Springs is one of three producing geothermal fields, including Cove Fort-Sulphurdale, and Thermo Hot Springs, which are associated with young extensional faults, centers of Quaternary basalt-rhyolite magmatism, and high regional heat flow (e.g., Simmons et al., 2019).

The North 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. The strata exposed in the San Francisco Mountains is made of Neoproterozoic and Paleozoic clastic and carbonate units and Tertiary volcanic-plutonic rocks, whereas the Mineral Mountains is cored by a large Oligocene-Miocene age plutonic complex (Nielson et al., 1986; Coleman and Walker, 1992; Kirby, 2019).

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; Smith et al. 1989; Miller et al. 2019; Hardwick et al., 2019). Deep drilling on the east side of the valley reveals the basement is mostly made of Oligocene-Miocene granitoids that include rafts of Precambrian gneiss (Nielson et al., 1986; Coleman and Walker, 1992; Kirby, 2019; Jones et al., 2019; Moore et al., 2021). The basement contact with overlying basin-fill represents a rotated normal fault that accommodated much of the local tectonic extension between 10 and 6 Ma (Bartley, 2019).

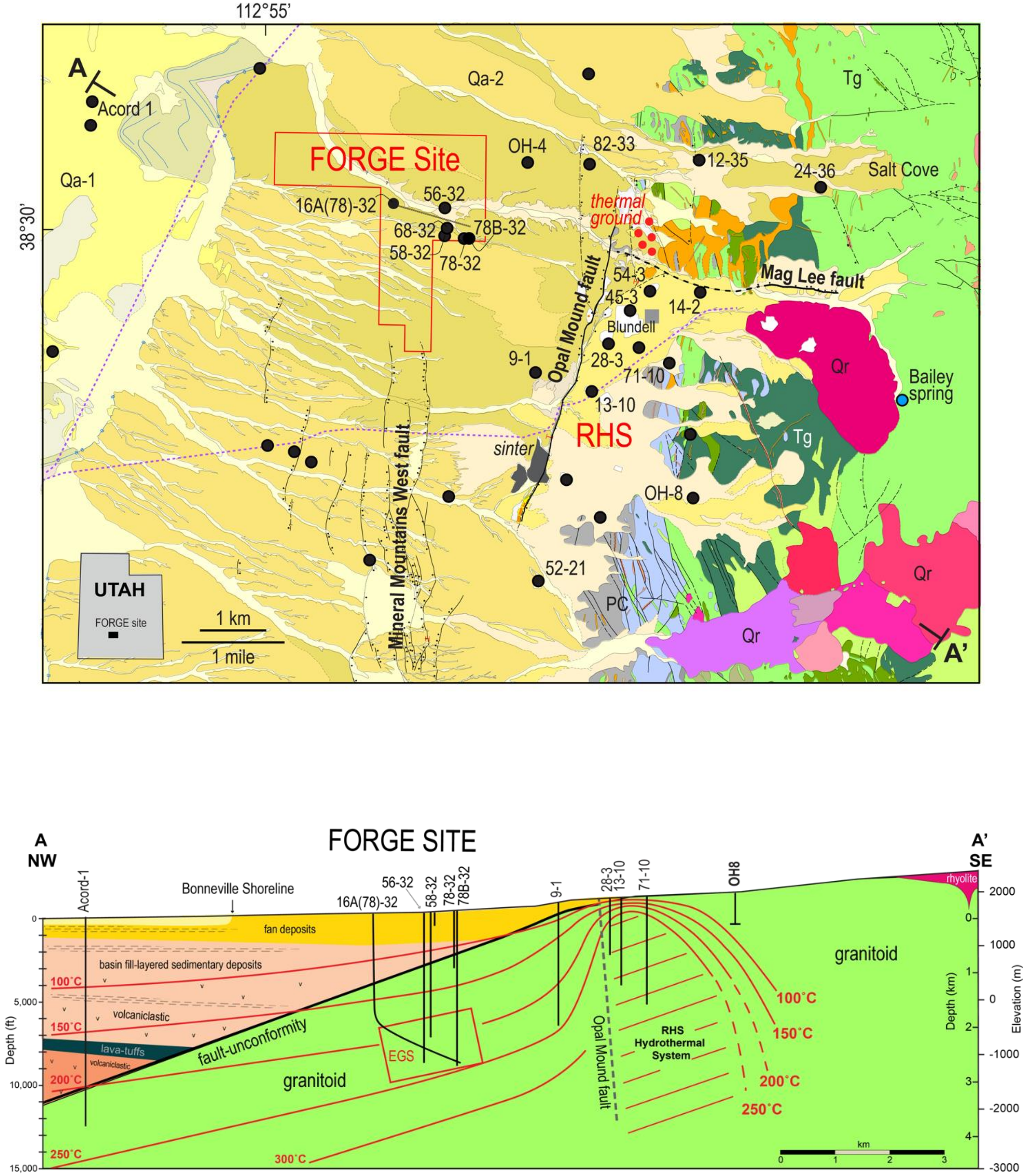

Figure 1: Geologic map and cross section of the Utah FORGE site, Roosevelt Hot Springs (RHS) and surrounding area (modified from Nielson et al. 1986 and Kirby, 2019). The thermal structure is interpreted from well measurements (Allis et al., 2019), and the red box denotes the location of the EGS test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

Infilling the valley is a layered sequence of sedimentary and volcanic deposits (>3000 m), which from youngest (Recent) to oldest (Tertiary) consist of unconsolidated alluvial sand, gravel, and clay, calcareous lacustrine siltstones and sandstones, volcaniclastic sandstones and gravels, tuffaceous deposits, and localized flows of andesitic lavas as revealed in deep wells (Jones et al., 2019). Across the valley from west to east through the Utah FORGE site, the surface of these deposits forms a continuous gently curving catenary profile. The shallow groundwater aquifers are hosted in a sequence of sands, gravels, and clays, deposited by coalescing alluvial fans and lacustrine sediments (Kirby et al., 2019; Knudsen et al., 2019). The hydraulic gradient follows topography towards the center of the valley and from south to north down the middle of the valley along the mostly dry Beaver River channel where occasional flow is controlled up stream by the release of dammed water during high-runoff events.

The Mineral Mountains host several discrete Pleistocene volcanic centers (1–15 km^2) that comprise basaltic cones and rhyolite flow dome complexes, the latter of which erupted 0.9–0.5 Ma (Lipman et al., 1978; Kirby, 2019). Of these, the prominent Bailey Ridge flow includes obsidian and rhyolitic pyroclastic deposits, which lies 2–5 km east of Roosevelt Hot Springs. This localized magmatic activity is part of a belt of scattered volcanism the extends from northern Arizona up through southwestern Utah (Best et al., 1980; Valentine et al., 2021).

Evidence of geologically young faulting is restricted to just three structures. The Opal Mound and Mag Lee faults are relatively short length structures that intersect at an orthogonal angle and appear to form the boundaries of the Roosevelt Hot Springs geothermal reservoir, whereas the Mineral Mountains West fault system comprises a series of parallel north-south trending, normal fault segments with small offsets that extends southward from the Utah FORGE site for ~ 25 km (Fig. 1). No other modern faults have been identified in the vicinity of Roosevelt Hot Springs and the Utah FORGE site. Regional natural seismicity occurs sporadically and notably includes the swarm activity just east of Roosevelt Hot Springs beneath the western foothills of the Mineral Mountains (Mesimeri et al., 2021), and a swarm of events near the town of Milford (Whidden et al., 2023). This regionally dispersed style of seismic activity lies on 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).

3. GROUNDWATER COMPOSITIONS

The groundwater composition data that we interpret are presented in a series of graphs, showing the relative proportions of chloride, bicarbonate and sulfate (Fig. 2), stable isotopes (Fig. 3), and He and Ne isotopes (Fig. 4). The spatial relations are shown in plan view in Figure 5. These data were acquired from sampling shallow groundwater wells (100-650 ft depth) with water levels that range from 10 to 350 ft. depth below the surface (https://gdr.openei.org/submissions/1139).

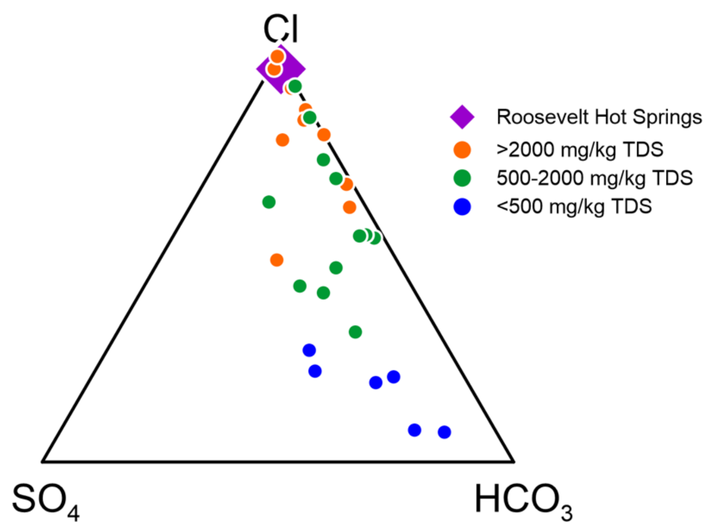

Figure 2: Trilinear plot showing the relative concentrations of chloride, bicarbonate, and sulfate in groundwaters and hydrothermal waters produced from Roosevelt Hot Springs.

Figures 2 and 3 show the variable nature of groundwater compositions, containing from <500 to >4000 mg/kg TDS. The most dilute waters with <500 mg/kg TDS are relatively rich in bicarbonate (100-150 mg/kg) with subordinate chloride (10-70 mg/kg) and sulfate (10-90 mg/kg), and these waters occur in the southwestern and northeastern part of the study area. The oxygen and hydrogen isotope compositions range widely but form an array that parallels and lies just to the left of the global meteoric water line (Fig. 3).

At the other end of the compositional spectrum are the saline groundwaters with >2000 mg/kg TDS, which are rich in chloride (900-2400 mg/kg Cl) with subordinate bicarbonate (10-840 mg/kg) and subordinate sulfate (<5 to 500 mg/kg). These waters are compositionally similar to the produced reservoir waters at Roosevelt Hot Springs, which are also chloride-rich with TDS >5000 mg/kg (Simmons et al., 2021). High concentrations of B and Li along with relatively tight clustering of hydrogen isotope compositions, having enriched oxygen isotopes ratios, provide evidence of a shared common origin in the form of a shallow outflow plume originating from Roosevelt Hot Springs (Vuataz and Goff, 1987; Kirby et al., 2019). This plume follows the hydraulic gradient basin-ward in a westerly to northwesterly direction, and along this flow path, modest in-mixing and dilution occur. Tentatively, the most distal expression of the plume occurs in the northern part of the valley (Fig. 5).

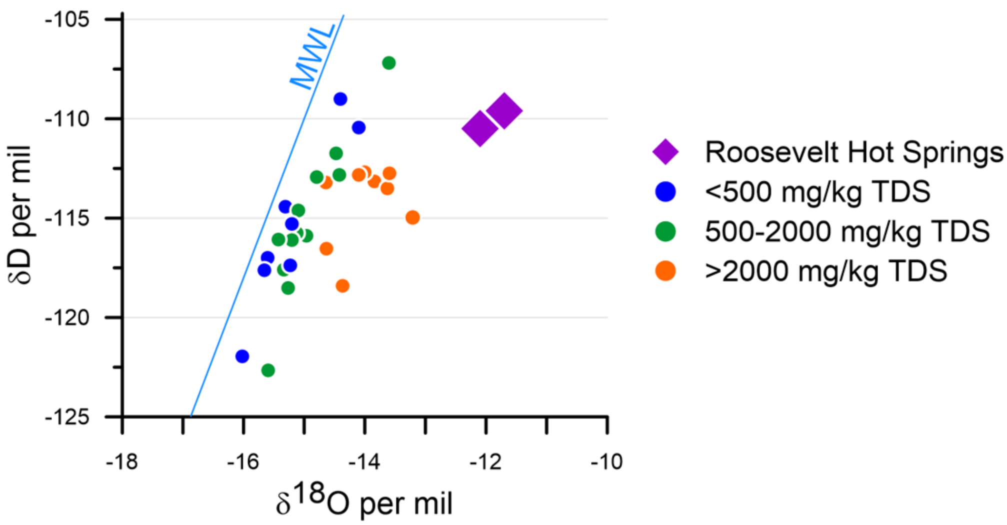

Figure 3: Stable isotope compositions of groundwaters and hydrothermal waters produced from Roosevelt Hot Springs. The global meteoric water line (MWL, Craig, 1961) is shown for reference.

Intermediate to the high and low TDS groundwaters contain 500-2000 mg/kg TDS. These waters are predominantly chloride-rich (150-800 mg/kg), with variable bicarbonate (50-400 mg/kg) and lower sulfate (<5 to 120 mg/kg). The oxygen and hydrogen isotope compositions of these intermediate TDS groundwaters range widely forming an array that overlaps and parallels the low TDS groundwaters (Fig. 3). Interestingly, the compositional range of isotopic data for three closely spaced samples separated about 5 km apart span the full range of $\delta^{18}O$ and δD values. Such complexity is attributed to the variability in the isotopic compositions of meteoric recharge falling over the valley bounding ranges and subsequent flow towards the middle of the basin.

4. HELIUM ISOTOPE DATA

Copper tubes sealed with refrigeration-type clamps were used to collect samples of dissolved noble gases from groundwater and geothermal wells. Helium isotope ($^3He/^4He$) analyses were performed at the Dissolved Gas Laboratory at the University of Utah. The resulting data were corrected for atmosphere contamination using the $^4He/^{20}Ne$ value of air and reported in R/Ra notation where R=$^3He/^4He$ sample and Ra=$^3He/^4He$ atmosphere. The concentrations of helium in groundwater samples range for 10^{-9} to 10^{-6} mol/kg and show a strong positive correlation with $^4He/^{20}Ne$ values. The lowest concentrations of helium were found in the low TDS groundwaters, plotting close to the composition of air saturated water (ASW) in Figure 5. The only outliers are two repeat low TDS samples with R/Ra of 0.26 to 0.49 and $^4He/^{20}Ne$ of 0.50 and 1.28 from the 600 ft. deep groundwater well at Milford.

The highest concentrations of helium (10^{-6} mol/kg), with $^4He/^{20}Ne$ ratios of 30 to 40, were measured in the Roosevelt Hot Springs produced geothermal waters (Simmons et al., 2021). The R/Ra values of 2.10 to 2.19 are very similar to previous measurements (Whelan et al., 1988), and provide unequivocal evidence of a component of mantle helium and a magmatic heat source (e.g., Whelan et al., 1988; Kennedy and van Soest, 2007).

Another sample with high concentration of helium (10^{-6} mol/kg), having a $^4He/^{20}Ne$ of >120, was measured in an intermediate TDS groundwater obtained from a 500 ft. deep groundwater well in the southwest part of Milford Valley (Figure 5). With an R/Ra value of 1.88, this sample is slightly lower than the He isotope ratio for Roosevelt Hot Springs, and the trends in Figure 4 show that it has very strong coherence with the other intermediate TDS waters, which range from 2.0 to 2.5 in R/Ra and from 10 to 40 in $^4He/^{20}Ne$. Only one intermediate TDS sample lies outside this group, with an R/Ra value of 0.12, and it comes from the 200 ft. deep well on the far southwestern edge of the study area.

The high TDS groundwaters are similar in helium isotope composition to both Roosevelt Hot Springs geothermal fluids and the intermediate TDS groundwaters with values of 2.1 to 2.6 R/Ra. The $^4He/^{20}Ne$ values, however, are lower, ranging from 0.45 to 25, which spans the range of results between Roosevelt Hot Springs and the low TDS groundwaters plotting near ASW. The lower $^4He/^{20}Ne$ values are consistent with lower dissolved helium concentrations of between 10^{-9} and 10^{-8} mol/kg, occurring in high TDS groundwaters proximal to Roosevelt Hot Springs, and they are interpreted to reflect the effects of steam loss in the boiling upflow zone of Roosevelt Hot Springs followed by dilution as thermal waters cool and disperse basin-ward in the outflow plume.

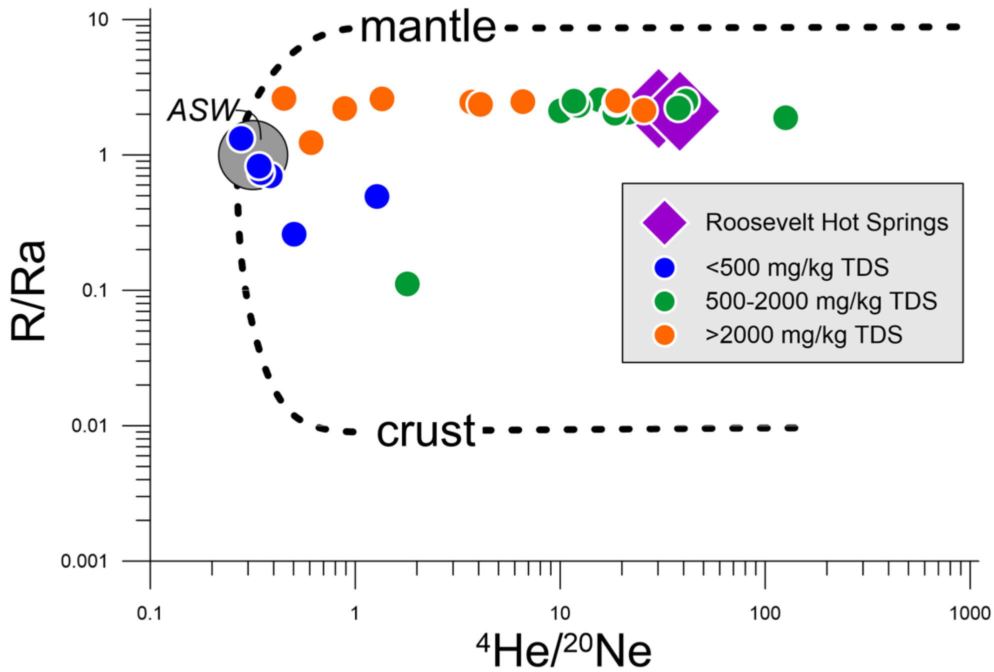

Figure 4: Helium isotope (R/Ra c) and $^{4}He/^{20}Ne$ compositions of groundwaters and hydrothermal waters produced from Roosevelt Hot Springs.

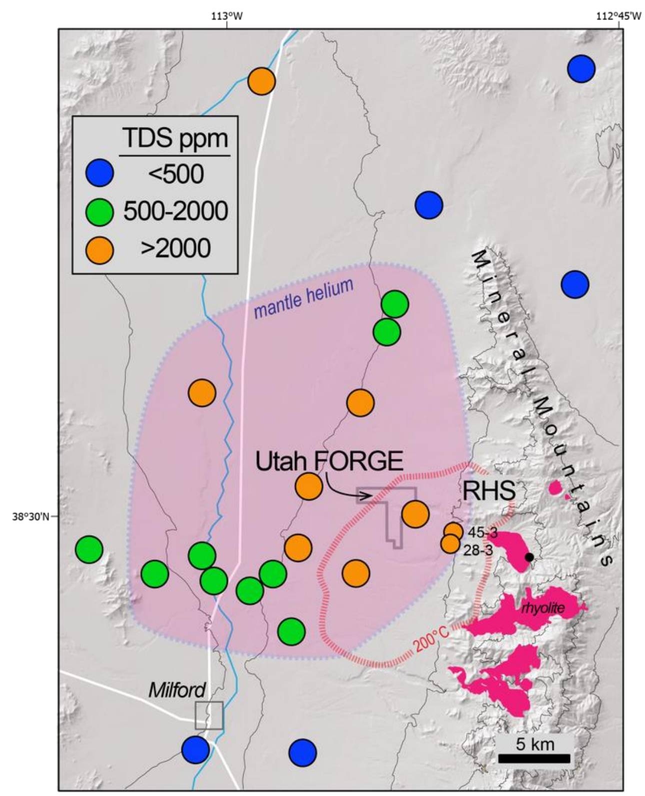

Figure 4: Plan view of the pink filled mantle helium isotope anomaly bounded by >1.8 R/Ra in the North Milford valley in relation to the thermal anomaly outlined by the 200°C isotherm at 3 km depth (Allis et al., 2019), and rhyolite flow dome centers in the Mineral Mountains.

5. DISCUSSION AND CONCLUSIONS

There are three aspects of this work that are worth highlighting. First, the extent of the mantle helium anomaly is exceptional and greatly exceeds the dimensions of the known geothermal resources and covers ~270 km^2 as shown in Figure 5. A survey of helium in soil gases over the Utah FORGE site (Rahilly et al., 2019), however, shows no evidence of mantle He, and it is plausible that hot dry crystalline rock forming the EGS reservoir is impermeable to the upflow of deep sourced helium. Accordingly, and limiting the mantle He anomaly to occurrences in groundwater wells west of Utah FORGE, the areal extent covers ~200 km^2, which remains surprisingly large.

Second, the mantle helium anomaly is offset from the center of maximum heat flow based on interpretation of the deep thermal structure, which is localized in the zone encircling Utah FORGE and Roosevelt Hot Springs (Fig. 5). On this basis, one might be compelled to argue that the mantle helium anomaly is the product of long-lived hydrothermal outflow, but this does not explain how the anomaly is most strongly manifest in intermediate TDS groundwaters rather than high TDS groundwaters, as described above. Consequently, separate paths of deep upflow are likely. The provisional results of the regional 3D resistivity model derived from the interpretation of a magneto-telluric survey, show the existence of conductive volumes of rock extending to >15 km depth in the middle of the North Milford valley which might mark such flow paths (Wannamaker et al., 2021). This is the subject of further investigation.

Third, the uniformity of the isotopic ratios for Roosevelt Hot Springs hydrothermal fluids and cold groundwaters in the North Milford valley suggests a common shared magmatic origin, which we infer to be a deep crustal intrusion. Furthermore, this range of values of 1.9 to 2.6 R/Ra is distinct from helium isotope ratios measured in basaltic lavas elsewhere in SW Utah, that range from 4.5 to 7.5 R/Ra (Graham and Reid, 1996; Dodson et al., 1998). Nevertheless, deep sourced mafic magma seems to be the most likely means by which mantle helium was introduced into the crust. The predominance of felsic volcanism in the Mineral Mountains supports the possibility that ascent of mafic magma induced partial melting and crustal assimilation. In this way the addition of radiogenic ^4He could account for the lowering of mantle sourced R/Ra values across the North Milford valley.

In sum, we interpret that the North Milford valley mantle He anomaly derives from a deep felsic pluton. Based on a back of the envelope calculation of stored heat, we estimate the volume of such a pluton to be at least 200 to 300 km^3, however, the geometry and distribution of such a melt body (or melt bodies) remains unknown. In addition, the exact mechanism by which mantle helium ascends and becomes incorporated in cold groundwaters is unclear, but it seems likely that at least part of the flow path was accompanied by the transfer of heat as seen at Roosevelt Hot Springs. Provisionally, mantle He in the cold groundwaters is sourced via one or more separate flow paths which transect the crust west of Utah FORGE. The presence of such a prominent widespread geochemical feature of deep-seated magmatic origin suggests the potential of additional undiscovered geothermal resources in the North Milford valley.

5. ACKNOWLEDGEMENTS

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