PROCEEDINGS, 44th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 11-13, 2019
SGP-TR-214

Conceptual Model for a Basalt-Related Geothermal System: Mountain Home AFB, Idaho, USA

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Keywords: Basaltic magmatism, sills, normal faults, hydrothermal breccias, clay alteration, gravity

ABSTRACT

We have been investigating the potential for commercial high-temperature geothermal development in the Snake River Plain (SRP) in Idaho. The SRP is a very large basaltic province that was formed following the passage of the Yellowstone mantle plume. Although the province is characterized by high heat flow in general, the presence of high-temperature geothermal systems within reasonable drilling depths will require relatively shallow magmatic heat sources. Several studies now relate the geometry of mafic heat sources to the rates of magma supply versus tectonic extension. High extension with respect to magma supply results in feeder dikes and rapid magma ascent to the surface whereas high magma supply with respect to extension produces sills or plutons that have sufficient residence time to be an effective heat source. Mountain Home Air Force Base (MHAFB) is located on the southern margin of a gravity and magnetic high that is associated with a large layered sill complex. The initial geothermal drilling (MH-1) at MHAFB in 1986 reached a depth of 1342 m, and continuous core was collected below a depth of 305 m. The maximum temperature measured was 93˚C at a depth of 1207 m, the maximum depth to which the temperature log was run. In 2012, we cored hole MH-2 to a depth of 1821 m 4 km away from MH-1 and measured a maximum temperature of 150º C. Analysis of the geologic data from these holes shows that the hydrothermal activity is hosted by a normal fault zone associated with extension over the top of the sill complex.

1. INTRODUCTION

The Snake River Plain (SRP) in Idaho (Fig. 1) is a large basaltic province associated with the passage of the Yellowstone mantle plume, and it is part of the largest heat flow anomaly in the USA (Blackwell and Richards, 2004). The eastern SRP represents the track of the Yellowstone hotspot – a deep-seated mantle plume that has remained relatively fixed in space as the North American plate moved to the southwest (Smith et al., 2009). As the plate moved over the plume, large silicic caldera complexes formed. As the magma chambers beneath these calderas solidified and were able to sustain brittle fracturing, basaltic magmas were able to reach the surface and form the extensive lava flows that define the surface geology of the SRP.

High-resolution seismic imaging carried out over several decades has established the presence of a mid-crustal sill complex at 10-20 km depth (Smith et al., 2009). Basalt geochemistry shows that this sill complex comprises a series of layered magma chambers, which evolved by fractional crystallization and magma recharge, and fed surface eruptions (Shervais et al., 2006; Jean et al., 2013). Geologic mapping and deep drill holes constrain the thickness and distribution of surface basalt flows. Taken together, these data document a magma flux of ~10^4-10^5 km^3/Ma under the eastern and central SRP, with little or no extension perpendicular to its boundaries (Payne et al., 2012). Resurgent basalt volcanism (<800 ka, and as young as 2100 years BP) formed long after the plume passed, driven by back-flow of plume material to the west. These resurgent basalts are also plume-derived, and postulated to result from delamination of subcontinental lithospheric mantle (Shervais and Vetter, 2009).

2. MOUNTAIN HOME GEOTHERMAL SYSTEM

The geothermal system at the MHAFB (Fig. 1) represents a blind high-temperature geothermal system that is not associated with any mapped faults or surface geothermal manifestations. Initial investigations of the resource were prompted by elevated geothermal gradient estimates (65ºC/km) determined from a wildcat oil well (Bostic 1A, 2949 m) drilled in 1973 at a location 20 km southeast of the town of Mountain Home (Figure 1). A deep (1342 m depth) geothermal exploratory well (MH-1) was drilled in 1986 (Lewis and Stone, 1988) as part of an effort to assess resources at MHAFB. A temperature of 93ºC logged at a depth of 1207 m, and an estimated thermal gradient of 69ºC/km, suggested that temperatures at depths in of 1500–1800 m are high enough to support binary cycle power generation.

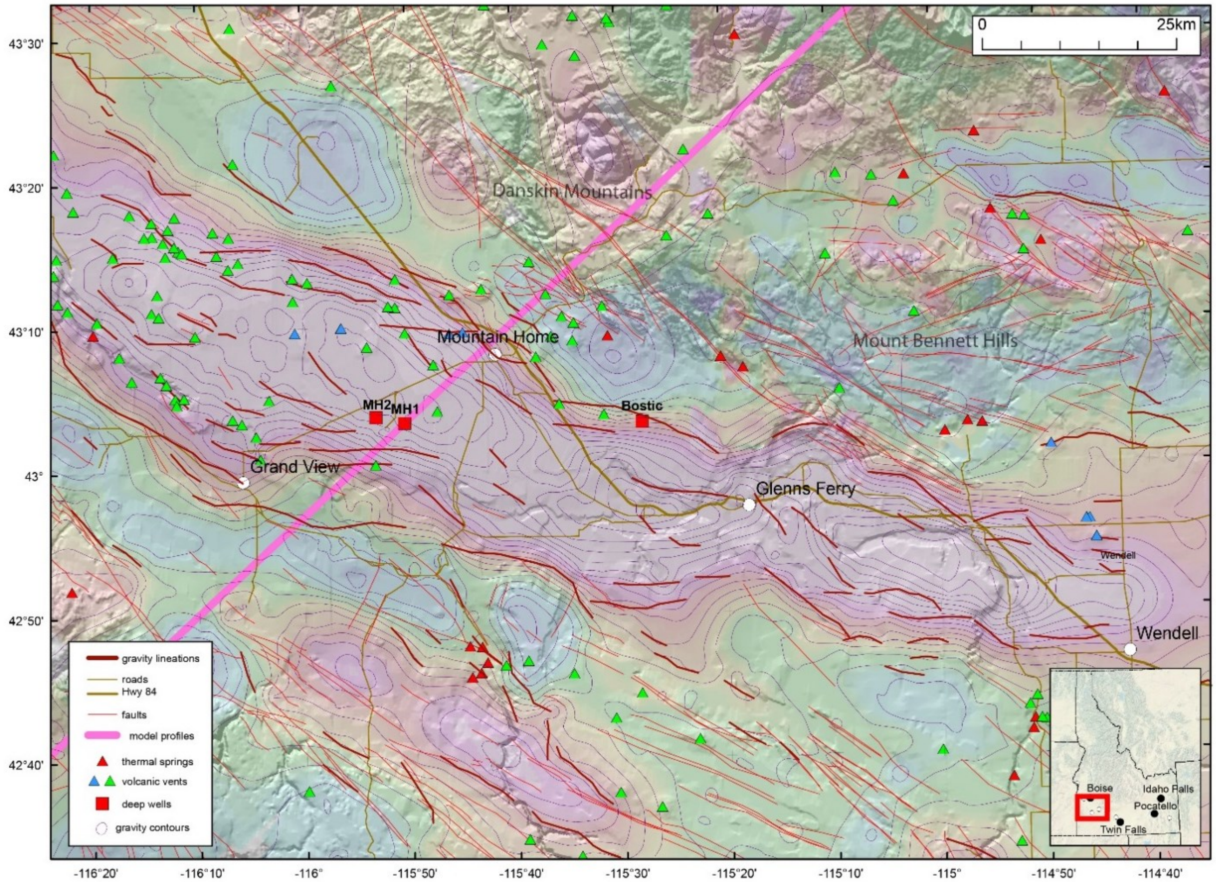

Figure 1. Colored residual isostatic gravity and shaded topographic relief map of the western SRP showing volcanic vents, thermal springs, and deep drill holes. Also shown are geophysically-inferred structural features (gravity lineations) based on maximum horizontal gradients of residual isostatic gravity. Geophysical grids are superimposed on a topographic base map (after Glen et al., 2017, Fig. 3). Wells MH-1 and MH-2 were drilled at MHAFB.

In 2012, MH-2 was cored to a depth of 1821 m (Delahunty et al., 2012; Nielson et al., 2012). The hole was drilled through basalt flows to a depth of 200 m where it encountered lacustrine sediments that were present to a depth of 740 m. The top of the sediments were 76 m deeper than the equivalent horizon encountered in MH-1. The bottom of these sediments showed indications of hydrothermal alteration that led us to postulate that relatively impermeable lake beds form the seal on the hydrothermal system (Nielson et al., 2015). Below the lake section, MH-2 encountered sediments, basaltic flows and hyaloclastites before it intersected hydrothermal fluids at a depth of 1745 m. The fluids were intersected within a fault zone, and core shows the presence of hydrothermal brecciation with associated calcite and minor amounts of quartz, pyrite and chalcopyrite (Nielson et al., 2012; Nielson and Shervais, 2014). More detailed analysis of fluid inclusions (Atkinson, 2015) demonstrated past boiling conditions with maximum temperatures of 340ºC.

The sequence of low-permeability lake sediments that overlie the geothermal system at Mountain Home likely helped to maintain the resource by insulating the reservoir, preventing upward migration of the thermal fluids, and inhibiting mixing with cold meteoric water that could degrade the resource (Shervais et al., 2016).

Kessler et al. (2017) conducted a comprehensive structural analysis of the lower part of MH-2 that included the fault zone that hosts the hydrothermal fluids. They concluded that the zone hosting the hydrothermal fluid has normal offset, a strike of 300º and a dip of approximately 80º to the NE (Nielson et al., 2018). Walker and Wheeler (2016) have studied clay mineralogy in MH-2 below the lake beds. Smectite is pervasive in the core indicating hydrothermal alteration; however, in a zone from 1708 to 1793 m, corrensite is present consistent with prograde alteration. However, smectite again is the dominant clay mineral from 1793 m to TD. The significance of the return to smectite below 1793 m is that the borehole penetrated a cooler regime that we interpret as the footwall of the fault zone that controls the hydrothermal fluid flow. From the structural and alteration evidence, we postulate that the geothermal system is hosted by a graben structure and MH-2 intersected a bounding fault of that structure and then continued into a lower thermal regime to the southwest.

Explored geothermal systems in basaltic terrains are associated with areas having a high magma budget (Nielson et al., 2017; Karson et al., 2015). There have been limited observations of the heat sources for basalt-related systems, but we believe that they are either sheeted dike complexes or sills. The hydrothermal brecciation in MH-2 leads us to postulate the proximity of intrusive rocks, and we set up a tentative model based on the volume and geometry of a high-level sill exposed at the western margin of the SRP (Graveyard

Point). This sill had original dimensions that we estimate as 5 km x 3 km and a thickness of 200 m. Numerical models of thermal evolution during sill injection show that a single sill emplaced at a depth of about 2 km will result in heating of the surrounding rocks to over 300ºC after 20,000 years (Nielson and Shervais 2014; Nielson et al., 2017); multiple sill injections will result in the continuous accumulation of heat as the ambient temperature of the host rocks is raised with each injection.

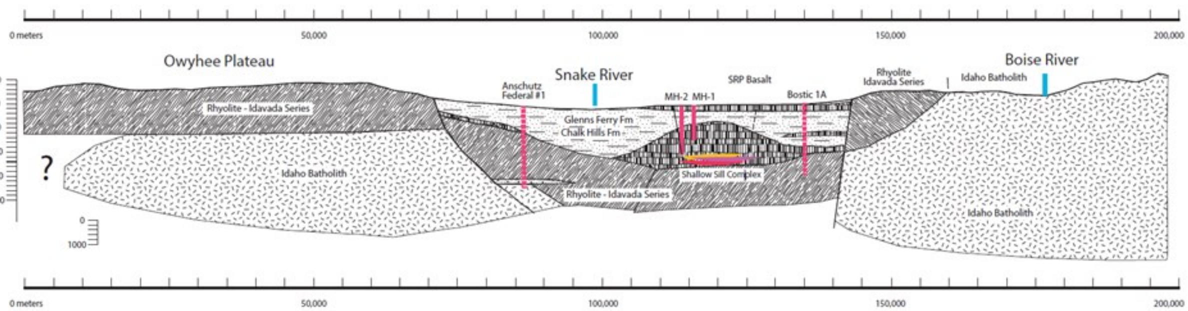

Figure 2. Conceptual model along NE-SW profile across the SRP extending through the MHAFB. Profile location is shown as the pink line on Figure 1.

3. GEOPHYSICS

A regional potential field model was developed for the western SRP based on high-resolution gravity data collected across the plain (Glen et al., 2017). The dominant feature along the profile is a prominent gravity high that extends nearly the full length of the western SRP (Fig. 1). This high is primarily modeled as a dense mafic root and sill complex intruded into the lower and middle crust and a high-density block in the upper crust consisting largely of a thick section of mafic lavas and sills. Both wells (MH-1 and MH-2) drilled at the MHAFB are located over the gravity high (Fig. 1) and extend into basalts interpreted to mark the top of the high-density block. However, neither of these holes intersected dikes or sills.

Due to the large density contrast of the mafic intrusive complex with respect to surrounding silicic volcanic and granitic basement rocks, gravity offers a particularly well-suited method for characterizing the sill compex and aiding with the interpretation of the subsurface. Figure 2 is an interpreted cross section along the profile line shown in Figure 1. Note that this line passes through MH-1, but MH-2, Anschutz Federal #1 and Bostic 1A are projected onto the section to provide geologic control. As shown in Fig 2, the geothermal system is interpreted to be located in a thick section of basalt flows that are underlain by sills. The sills are inferred from the high fluid inclusion temperatures and presence of hydrothermal breccias; although they are not present in core from MH-1 or MH-2. The permeability is controlled by faults that appear to represent a graben with steep dips to the NE as evidenced by the geologic relationships in MH-1 and MH-2.

4. CONCLUSIONS

The most recent magmatic activity in the Snake River Plain is basaltic and related to post-caldera forming stages associated with the Yellowstone mantle plume. In areas of high magma budget where the volume of magma generation exceeds the tectonic accommodation space, sill complexes can form and serve as the heat source for geothermal circulation. Although the SRP is not presently magmatically active, voluminous flows younger than 200 ka have been documented.

Our conceptual model involves the high heat flow of the SRP that is produced by lower- and mid-crustal sill complexes, and associated with this regional foundation, are areas of high-level (~2 km) intrusives that generate hydrothermal circulation at depths that can be exploited. The primary heat source for the drillable resource has been modeled as a sill complex (Nielson et al., 2017). This high-level activity also feeds young (~200ka) volcanism north and west of Mountain Home (see vents shown in Figure 1).

We believe that exploitable geothermal resources in the overall high heat flow province are associated with shallow sill complexes that occasionally erupted to feed recent flows, but principally served as high-level magma reservoirs that power hydrothermal circulation.

ACKNOWLEDGEMENTS-

This paper was supported in part by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Geothermal Technologies Office (GTO) through award DE-EE0006733 to Utah State University and with support from the U. S. Geological Survey's Energy Program.

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