Hotspot: The Snake River Geothermal Drilling Project—Initial Report

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ABSTRACT

The Snake River volcanic province (SRP) overlies a thermal anomaly that extends deep into the mantle; it represents one of the highest heat flow provinces in North America. The primary goal of this project is to evaluate geothermal potential in three distinct settings: (1) Kimama site: inferred high sub-aquifer geothermal gradient associated with the intrusion of mafic magmas, (2) Kimberly site: a valley-margin setting where surface heat flow may be driven by the up-flow of hot fluids along buried caldera ring-fault complexes, and (3) Mountain Home site: a more traditional fault-bounded basin with thick sedimentary cover. The Kimama hole, on the axial volcanic zone, penetrated 1912 m of basalt with minor intercalated sediment; no rhyolite basement was encountered. Temperatures are isothermal through the aquifer (to 960 m), then rise steeply on a super-conductive gradient to an estimated bottom hole temperature of ~98°C. The Kimberly hole is on the inferred margin of a buried rhyolite eruptive center, penetrated rhyolite with intercalated basalt and sediment to a TD of 1958 m. Temperatures are isothermal at 55-60°C below 400 m, suggesting an immense passive geothermal resource. The Mountain Home hole is located above the margin of a buried gravity high in the western SRP. It penetrates a thick section of basalt and lacustrine sediment overlying altered basalt flows, hyaloclastites, and volcanic sediments, with a TD of 1821 m. Artesian flow of geothermal water from 1745 m depth documents a power-grade resource that is now being explored in more detail. In-depth studies continue at all three sites, complemented by high-resolution gravity, magnetic, and seismic surveys, and by downhole geophysical logging.

1. Introduction

Project Hotspot is an effort by an international group of investigators to understand Snake River volcanic province thermal system, its relationship to the volcanic and tectonic history of the Snake River volcanic province, and its relationship to the Yellowstone hotspot (Shervais et al., 2006a). The SRP preserves a record of volcanic activity that spans over 16 Ma and is active today, with basalts as young as 200 ka in the west and 2 ka in the east. The heat propagated by this hotspot drives high surface heat flows, numerous hot springs, and two passive geothermal districts (Boise and Twin Falls). The potential for power generation is significant, especially using binary generation systems that can exploit lower temperature resources (Sanyal and Butler, 2005; Neely and Galinato, 2007). Despite its well-known high heat flow, there have been few attempts to harness this heat for power generation.

Project Hotspot was conceived to explore heat distribution at depth within the Snake River volcanic province, and to determine the best ways to harness this resource. Preliminary reports on this project were published last year (Shervais et al., 2011; Potter et al., 2011; Sant et al., 2011; Kessler and Evans 2011; Twining and Bartholomay, 2011). Additional papers on specific aspects of this project are published in this volume (Armstrong et al., 2012; Delahunty et al., 2012; Nielson et al., 2012).

2. Project Hotspot: The Snake River Volcanic Province

The Snake River volcanic province in southern Idaho formed in response to movement of the continental lithosphere over a deep-seated mantle thermal anomaly (“hotspot”) that has thinned the lithosphere and fueled the intrusion of up to 10 km of hot basaltic magma into the lower and middle crust. The heat from these intrusions drives the high heat flow and geothermal gradients observed in deep drill holes from throughout the Snake River Plain (Blackwell, 1980, 1989; Brott et al., 1978, 1981; Lewis and Young, 1989).

Heat flow in shallow gradient holes is high along the margins of the plain (80-100 mW/m^2-s) and low along the axis of the plain (20-30 mW/m^2-s), which has led to suggestions that the volcanic axis is cooler than the margins of the plain, which is dominated by sediments. Previous deep drill holes (> 1 km) in the axial portion of the plain are characterized by high heat flows and high geothermal gradients below about 500 m depth (Blackwell, 1989). This contrast is caused by the Snake River aquifer – a massive aquifer system fed by the Lost River system north of Idaho Falls that extends under the plain and emerges at Thousand Springs, Idaho. Temperatures are isothermal through the aquifer, then rise on conductive or super conductive gradients at depth (e.g., Blackwell, 1989; Blackwell et al., 1992). Heat flow values along the axis of the plain calculated from sub-aquifer gradients are comparable to heat flow values along the margins of the plain or higher (75-110 mW/m^2-s; Blackwell 1989).

The primary goal of Project Hotspot is to evaluate the geothermal potential in three distinct settings (Figure 1): (1) the high sub-aquifer geothermal gradient associated with the intrusion and crystallization of mafic magmas; (2) the valley-margin settings where surface heat flow may be driven by the up-flow of hot fluids along buried caldera ring-fault complexes; and (3) a sedimentary basin adjacent to range-front faults in a large complex graben. The first two settings are found within the central Snake River Plain and represent previously untested targets for geothermal exploration. The third setting is found within the western SRP graben. We also apply surface geophysical studies, including gravity, magnetic, and seismic techniques, in identifying these resources, and to verify their application by drilling slimhole test wells that were logged using conventional wireline geophysical logs and walk-away vertical seismic profiles.

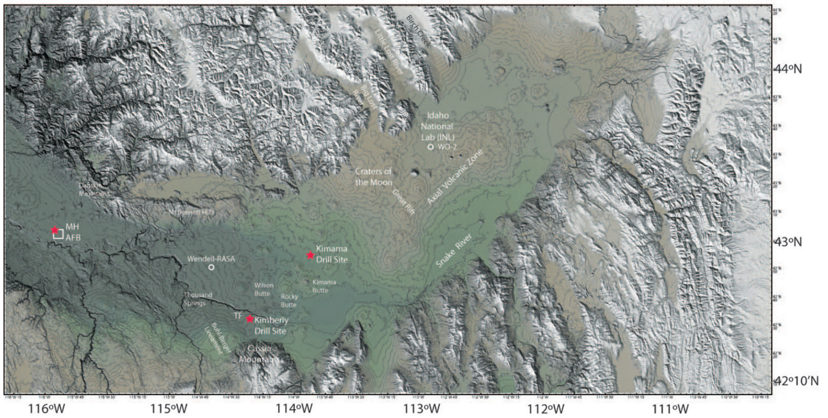

Figure 1. Shaded relief-topographic map of Snake River Plain derived from NASA 10m DEM data and contoured at 30m intervals. Red stars = new drill sites of this project; open circles = legacy drill sites discussed in text.

3. Results

Project Hotspot began drilling at its first site in September 2010, and completed drilling at its final site in January 2012 (Figure 1). In all, three deep holes were completed, collecting over 5.9 km of core for further study. High-resolution seismic, gravity and magnetic surveys were carried out in conjunction with the drilling effort. Borehole geophysical logs and vertical seismic profiles were acquired at each site to further constrain the stratigraphy and the physical and seismic character of its components. The borehole data will be used to validate the surface and geophysical studies, which will further constrain the extent and quality of the geothermal resources in this region.

Core from all three sites was moved to the USU Core Laboratory for processing, which includes high-resolution photographs, high resolution image scans of whole round core sections, and detailed lithologic and structural logging. All data are entered into ICDP's Drilling Information System database and will be transferred to the National Geothermal Database when complete.

3.1 Kimama — Elevated Heat Flux Under the Volcanic Axis

The primary goal of the Kimama drill site was to test the extent of geothermal resources along the axis of the plain, beneath the Snake River aquifer, in an area where elevated groundwater temperatures imply a significant flux of conductive or advective heat flow from below (Shervais et al., 2011). The use of shallow temperature gradient drill holes to define a thermal anomaly is not a meaningful test in this situation because of the refrigeration effect of the massive shallow groundwater flow.

Geologic mapping documents widespread Quaternary volcanism throughout the central SRP (Shervais et al., 2005). Basaltic vents occur both along the margins of the plain and near its center, but young volcanic vents are dominant within the axial volcanic zone, forming a distinct topographic high that confines sediments to troughs on the north and south (Kauffman et al, 2005a, 2005b; Shervais et al, 2006c, 2006d; Cooke et al, 2006a, 2006b; Matthews et al., 2006a, 2006b; Cooke, 1999; Matthews, 2000; Hobson, 2009; DeRaps, 2009). Northwest of Twin Falls the basalt flows thin out and become intercalated with fluvial and lacustrine sediments of the western SRP domain. This is well-documented in the Wendell-RASA well (342 m), which has 122 m of young Quaternary basalt (<400 ka) separated from older basalts deeper in the well by 60 m of sediment (Whitehead and Lindholm, 1985; Jean et al, submitted). The older basalts (1.0-2.5 Ma) are themselves underlain by more sediment. Basalt flows also thin towards the margins of the plain, where they may sit directly on rhyolite or on sediment horizons that rest on rhyolite. This is in contrast to the 1500 m deep WO-2 well at the INL site, which contains ~1200 m of basalt with minor intercalated sediments on top of 300 m of rhyolite, with no intervening sediments and no major sediment horizons within the basalt (Morgan, 1990; Hackett et al., 2002; William Hackett, unpublished well log).

Drilling commenced at Kimama in September 2010 and was completed in January 2011. Final depth of the drill hole was 1912 m (6273 feet). The cored section consists almost entirely of massive basalt flows with a few thin sedimentary intercalations. Our target depth for this site was 1500 m, based on an inferred depth to the basalt-rhyolite contact of ~1200 m. Because we did not encounter the basalt-rhyolite contact at 1500 m, drilling continued to 19112 m. Lithology continued to be dominated by massive basalt flows, with two thick horizons of sediment near the bottom of hole, including river gravels indicating a former stream channel.; no rhyolite was recovered. Borehole logging was carried out through the drill string by the USGS in October-November 2010 (Twining and Barthomay 2011) and by Century Geophysics in late January 2011. Open hole logging was carried out by the ICDP Operational Support Group in June-July 2011.

The Kimama site was chosen because it sits on an axial volcanic zone that is defined by high topography to the east and by electrical resistivity (ER) maps that define a buried keel of basalt underlying the topographic high. The ER maps are thought to define the depth to saturated basalt – generally interpreted to represent the base of the younger Quaternary basalts, and excluding older Pliocene basalts which have limited porosity (e.g., Lindholm 1996). A more nuanced interpretation suggests that the ER measurements most likely corresponds to the base of the Snake River aquifer, which is sealed by authigenic mineralization of the older basalts that seals off permeability (e.g., Morse and McCurry 2002). Based on these ER maps, the depth to base of the aquifer at the Kimama site was estimated to be be ~850 m (2800 feet).

A lithologic log of the Kimama drill hole shows that it consists almost entirely of basalt, with thin intercalations of loess-like sediment in the upper 200 m of the hole, and somewhat thicker beds of fluvial gravels, sands, and silts in the lower 300 m of the hole (figure 2). Very thin silt intercalations are scattered through intervening depths. Potter et al., (2011) have documented 557 basalt flow units in this section, based on gamma logs, neutron logs, and the recovered core, with a measured total thickness of 1803 m (5915 feet). Contrary to expectations, we did not encounter rhyolite basement.

The thickness of basalt plus intercalated sediment in the Kimama drill hole (1912 m) is almost 70% thicker than in the WO-2 drill hole at the Idaho National Laboratory, about 90 km to the NE. It is also over 5 times greater than the section sampled by the Wendell-RASA drill hole (figure 2). The immense thickness of basalt was unexpected, even along the axial volcanic high, and suggests the formation of a deep accommodation space in the central SRP where the western SRP graben intersects the down-warped eastern plain.

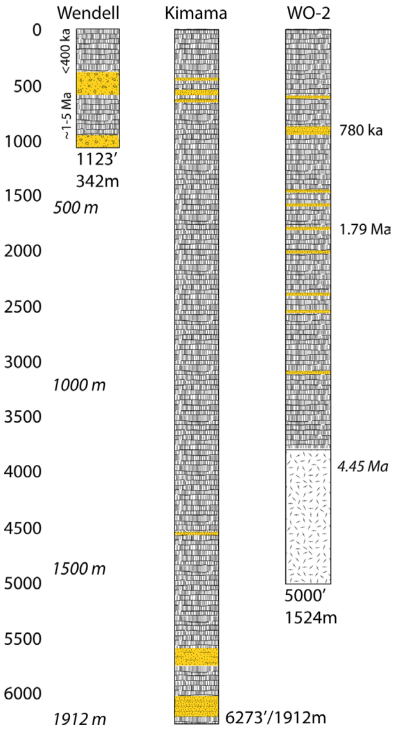

Figure 2. Lithologic log of the Kimama well compared to Wendell-RASA well and WO-2 well at Idaho National Laboratory. See figure 1 for locations.

Thermal logs of the Kimama drill hole document a near isothermal gradient from the top of the aquifer to 960 m depth, with a sharp rise to a conductive gradient below that depth, which is interpreted to reflect the base of the aquifer (Nielson et al., 2012). This is nearly twice the documented thickness of the Snake River aquifer in other locales (maximum 550 m thick). Temperatures within the aquifer here (15-17°C) are elevated relative to groundwater temperatures farther east, and along the margins of the plain (~9°C), which must reflect an enormous flux of heat from lower in the crust (e.g., Blackwell, 1989). The thermal gradient below the aquifer is ~80°C per km, and projects to a bottom hole temperature of ~98°C (Nielson et al, 2012). This confirms the existence of high subaquifer thermal gradients and the potential for power generation beneath the axial volcanic zone.

3.2 Kimberly — Up-flow Along a Buried Caldera Margin

The primary goal of the Kimberly drill hole was to assess the geothermal potential of up-flow zones along a buried caldera margin. The Twin Falls area hosts a large number of shallow geothermal wells, so it has a documented geothermal potential and is well-characterized stratigraphically (Street and deTar, 1987; Lewis and Young, 1989; Baker and Castelin, 1990). The Kimberly drill site lies south of the Snake River where groundwater flow is dominated by water that originates in the Cassia Mountains to the south, and penetrates deeply into the crust where it is heated before upwelling in the Twin Falls low-temperature geothermal district (Street and deTar, 1987; Baker and Castelin, 1990). Geothermal wells in the Twin Falls Groundwater Management Area range in temperature from around 30°C to 72°C, with the highest temperature occurring along the Buhl-Berger lineament.

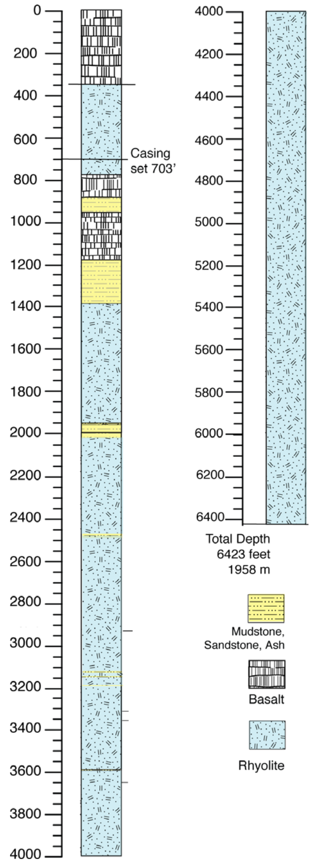

Figure 3. Lithologic log of the Kimberly well.

Drilling commenced in January 2011 and was completed in June 2011, with a 6 week hiatus in March-April. The Kimberly well was completed at a total depth 1958 m (6423 feet). Our original target depth for this hole was 1830 m (6000 feet), but after drilling to 1912 m at site #1 (Kimama) this was revised to 1500 m (5000 feet). We were able to exceed our original target depth by setting casing to 214 m (703 feet) with an air-rotary drill rig used for water well installation, without recovering core. Most of the uncored section is exposed in the nearby Snake River canyon.

Lithology of the Kimberly drill hole is dominated by massive rhyolite welded tuff flows, with two basalt-sediment intercalations at 241 m to 424 m (790 to 1391 feet) depth, and thin altered ash interbeds around 610 m (2000 feet) depth. The lower 900 m (from 1050 m to 1958 m) has no apparent flow contacts and may represent a single, large welded ash flow tuff. Even at the bottom of the hole, there was no indication of textures that would suggest an intrusive origin — the lowest core is welded ash flow tuff. Core below about 500 m depth exhibits propyllitic or argillic alteration (chlorite, sulfides, ±epidote), which indicates hydrothermal circulation.

Temperature logs of the Kimberly drill hole and temperature measurements made while drilling with the DOSECC core barrel temperature tool document a cool water aquifer in the upper 400 m, underlain by an immense warm water aquifer, 55°C to 60°C, from 400 m to TD at 1958 m depth (Nielson et al, 2012). While these temperatures are too low to support power generation, they document an extensive passive geothermal resource that has not been tapped by existing shallow (<700 m deep) wells.

3.3 Mountain Home — Geothermal Potential of the Western SRP

The western SRP has a long history of passive geothermal space heating applications, especially within the city of Boise (e.g., Brown et al., 1980; Neely 1996). Previous wells (MH-1, Bostic 1-A) document elevated temperatures at depth that are close to those needed to sustain geothermal development (Lewis and Stone 1988; Arney 1982; Arney et al., 1982, 1984). A prominent Bouguer gravity anomaly beneath the Mountain Home area (Shervais et al., 2011; Armstrong et al., 2012) extends into the Boise area, where it has been shown to represent an uplifted horst block in the subsurface (Wood, 1994). The primary science goal of the Mountain Home drill core is to assess the geothermal potential under Mountain Home AFB; an extended discussion of this site is presented in Armstrong et al. (2012).

Drilling operations commenced at Mountain Home in July 2011. At 599 m (1967 ft) the HQ drill rods became stuck, and after several days of trying to free them, the decision was made to abandon the hole, and to drill a new hole offset 7 m (20 ft) from the first. The second hole at this site was begun in September 2011 and completed in January 2012. Borehole logging was completed in January 2012, with temperature and gamma logs taken with the drill string in place; open hole logging was restricted to the 1200 m of the drill hole (NQ section) because sediments in the upper part of the hole are unstable and it was deemed to risky to remove the HQ rods and PQ-size casing at this time. A 2⅜″ liner has been placed in the hole for long term temperature monitoring.

Lithology of the Mountain Home site consists of an upper basalt unit with minor interbedded sediments 0-215 m (0-705 ft), overlying interbedded sands and clays, with minor gravels and thin basalt layers from 215-850 m (705-2800 ft). From 850 m to 1250 m (2800-4100 ft) basalt horizons alternate with sandstone, gravels, and volcanic ash. Below 1250 m the section consists of basalt flows, basalt hyaloclastites, and basaltic sands that are compact and well-indurated, but less dense than massive basalt.

At 1745 m (5726 ft) a fracture system was encountered with artesian flow of geothermal fluids (Nielson et al., 2012; Armstrong et al., 2012). Temperature readings with the DOSECC BHT tool indicated temperatures of ~150°C when the geothermal zone was encountered; later temperature logging indicates temperatures of ~135-140°C (Nielson et al., 2012).

Chemical analysis of the geothermal waters shows that they are sulfate-rich, indicative of volcanic waters, and have a high pH (9.6), consistent with interaction with altered basalt (Lachmar et al., 2012). Calculated equilibrium temperatures are 140-150°C (Giggenbach, 1988, 1997), consistent with the measured temperatures in the geothermal zone.

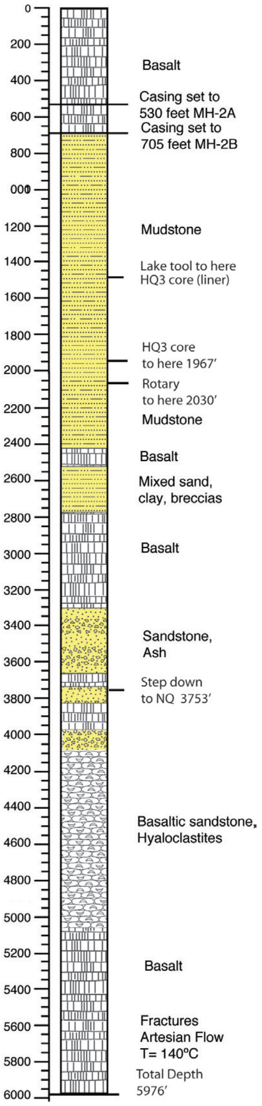

Figure 4. Lithologic log of the Mountain Home AFB well MH-2.

The difference in stratigraphy between the MH-1 well (Lewis and Stone, 1988) and Bostic 1A well (Arney et al., 1984) is best explained by their positions relative to the inferred basement high, with MH-1 bottoming on top of the inferred horst block (but near its southern margin) and Bostic 1A traversing a thick section of sediments and volcanic flows filling the small graben that lies north of the horst block, and south of the Danskin Mountains. There may in fact be vertical upflow zones along both the northern and southern margins of this inferred horst block, explaining the elevated bottom hole temperatures found in both wells (Lewis and Stone, 1988; Arney et al., 1982, 1984).

4. Summary and Conclusions

Young active volcanic regions with high heat flow offer significant geothermal energy potential, and many of these areas have not been explored for their economic potential. This project focuses on undeveloped "greenfield" region noted for its high heat flow and the common development of low-temperature passive geothermal, but which has not been developed for electrical generation. Our goals are [1] to identify new geothermal resources in the undeveloped Snake River Plain region; or failing that [2] to characterize the thermal regime at depth in such a way as to further exploration goals in more focused efforts; and [3] to document specific exploration methods and protocols that can be used effectively in these terranes. These include slimhole drilling with bottom hole temperature tool (Neilson et al., 2012), high resolution seismic surveys, vertical seismic profiles of the wells, and high-resolution gravity and magnetic surveys.

We use a combination of traditional geologic tools (geologic mapping, petrologic studies, and geochemical investigations of core and surface samples) and geophysical techniques (high-resolution active source seismic reflection-refraction surveys, detailed ground-based gravity and magnetic surveys), along with relatively deep test wells that allow us to document the underlying stratigraphy (ground truth), geothermal gradients below the surface aquifers, fracture densities, and hydraulic conductivities.

Drilling and geophysical surveys have been largely completed and we are currently evaluating the results. The Kimama well, competed at 1912 m (6275 ft), samples an aquifer that is twice as deep as the next deepest part of the aquifer, and three times thicker than normal (960 m; 3150 ft), suppressing the thermal gradient. Nonetheless, a temperature gradient of 75-80°C/km underlies the aquifer, reflecting a deep buried resource that may be tapped where the aquifer is thinner. The Kimberly well (1958 m, 6424 ft) taps a warm water aquifer at 55-60°C that is too cool for power generation but may represent an immense passive resource (Nielson et al., 2012). Finally, the Mountain Home well (1821 m; 5974 feet) intersected a 135-140ºC (or higher) geothermal resource with artesian flow to the surface. Combined with data from older exploration efforts, our work documents a significant electric-grade geothermal resource that lies outside existing geothermal resource areas, and may herald a new greenfield development in southern Idaho.

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