First Results from HOTSPOT: The Snake River Plain Scientific Drilling Project, Idaho, U.S.A.

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Abstract

HOTSPOT is an international collaborative effort to understand the volcanic history of the Snake River Plain (SRP). The SRP overlies a thermal anomaly, the Yellowstone-Snake River hotspot, that is thought to represent a deep-seated mantle plume under North America. The primary goal of this project is to document the volcanic and stratigraphic history of the SRP, which represents the surface expression of this hotspot, and to understand how it affected the evolution of continental crust and mantle. An additional goal is to evaluate the geothermal potential of southern Idaho.

Project HOTSPOT has completed three drill holes. (1) The Kimama site is located along the central volcanic axis of the SRP; our goal here was to sample a long-term record of basaltic volcanism in the wake of the SRP hotspot. (2) The Kimberly site is located near the margin of the plain; our goal here was to sample a record of high-temperature rhyolite volcanism associated with the underlying plume. This site was chosen to form a nominally continuous record of volcanism when paired with the Kimama site. (3) The Mountain Home site is located in the western plain; our goal here was to sample the Pliocene-Pleistocene transition in lake sediments at this site and to sample older basalts that underlie the sediments.

We report here on our initial results for each site, and on some of the geophysical logging studies carried out as part of this project.

Introduction

Mantle plumes are thought to play a crucial role in the Earth's thermal and tectonic evolution. They have long been implicated in the rifting and breakup of continents, and plume-derived melts play a significant role in the creation and modification of the continental crust and mantle lithosphere (DePaolo and Manga, 2003; DePaolo and Weis, 2007). Much of our understanding of mantle plumes comes from plume tracks in oceanic lithosphere, but oceanic lithosphere is recycled back into the mantle by subduction, and evidence for mantle plumes in the oceanic realm is destroyed. Thus, if we are to understand plume-related volcanism prior to 200 Ma, we must learn how plume-derived magmas inter-

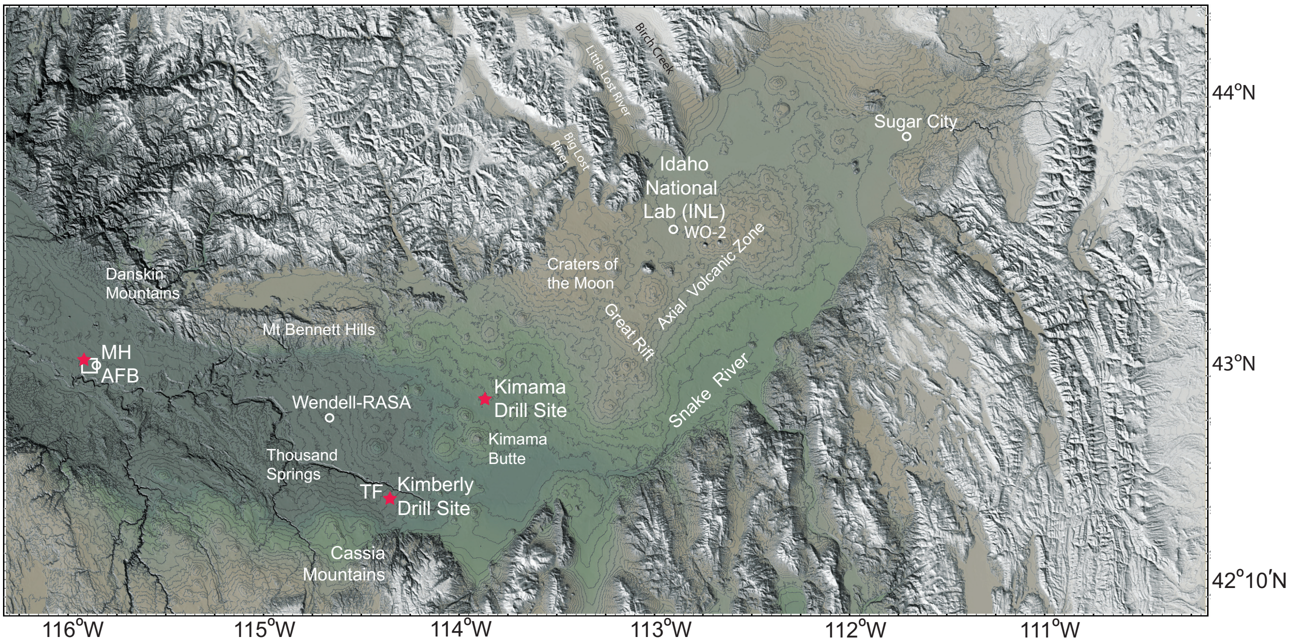

Figure 1. Shaded relief-topographic map of Snake River Plain derived from NASA 10-m DEM data and contoured at 30-m intervals. Red stars=new drill sites of this project; open circles=legacy drill sites discussed in text. TF=city of Twin Falls, MH AFB=Mountain Home Air Force Base.

act with continental lithosphere, and how this interaction affects the chemical and isotopic composition of lavas that erupt on the surface.

Hotspot volcanism in oceanic lithosphere has been the subject of studies by the International Continental Drilling Program (ICDP)—e.g., the Hawaii Drilling Project and the Reykjanes Drilling Project—and by the Integrated Ocean Drilling Program (IODP) and its predecessors (Neal et al., 1997; DePaolo et al., 2001; Elders et al., 2011). A variety of geochemical evidence from oceanic hotspots suggests that the source of volcanism involves mantle that is distinct from the shallowest upper mantle (DePaolo and Manga, 2003). Hotspot volcanism within continental lithosphere has not been studied in such detail, and it is undoubtedly more complex (Burov et al., 2007).

Project HOTSPOT is an effort by an international group of investigators to understand the long-term volcanic, tectonic, and thermal history of the Snake River volcanic province (Fig. 1) and its relationship to the Yellowstone hotspot, which sits above a sub-continental mantle plume (Shervais et al., 2006a). The SRP preserves a record of volcanic activity extending back to 16 Ma, and with basalts as recent as 200 ky in the western SRP graben, and as young as 2000 years at Craters of the Moon in the central SRP.

The central questions addressed by Project HOTSPOT are as follows: how do mantle hotspots interact with continental lithosphere, and how does this interaction affect the geochemical evolution of mantle-derived magmas and of the continental lithosphere?

Project HOTSPOT: The Snake River Volcanic Province

The Snake River volcanic province formed in response to movement of the continental lithosphere over the Yellowstone "mantle plume," which has thinned the lithosphere and fueled the intrusion of hot basaltic magma into the lower and middle crust, forming a sill complex up to 10 km thick. The onset of "hotspot"-related volcanism is generally marked by the eruption of large volumes of dry, high-temperature rhyolites as ignimbrites, lavas, and lava-like ignimbrites (Branney et al., 2008). The oldest rhyolites exposed (in western Idaho, eastern Oregon, and northern Nevada) are preceded by basalt; all of the younger rhyolites are overlain by up to a kilometer of "post-hotspot" basalts that erupted after the lithosphere moved to position southwest of the active plume source (Geist et al., 2002; Hughes et al., 2002; Shervais et al., 2005, 2006b).

Geologic mapping has documented widespread Quaternary volcanism throughout the central SRP (Shervais et al., 2005). Basaltic vents are dominant along the axial volcanic zone, forming a distinct topographic high that confines sediments and river drainages to topographic lows on the north and south (Fig. 1; Kauffman et al., 2005a, 2005b; Cooke et al., 2006a, 2006b; Matthews et al., 2006a, 2006b; Shervais et al., 2006c, 2006d). The basalt section thins northwest of Twin Falls, Idaho and becomes intercalated with fluvial and lacustrine sediments of the western SRP domain. For example, the Wendell-RASA well (342 m), which lies 40 km northwest of Twin Falls, has 122 m of Quaternary basalt (<400 ka) separated from older basalts (1.0–2.5 Ma) by 60 m of sediment; the older basalts are themselves underlain by more sediment (Whitehead and Lindholm, 1985).

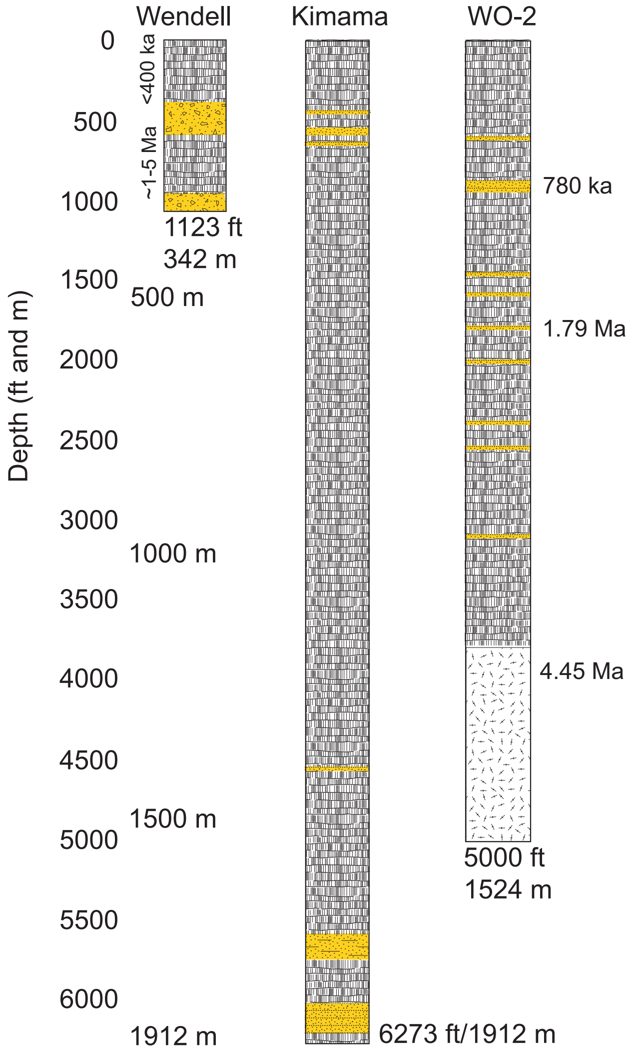

Figure 2. Lithologic log of the Kimama well compared to the Wendell-RASA well and WO-2 well at Idaho National Laboratory. See Fig. 1 for locations. Yellow stipple: sediment; white stipple: rhyolite; dark pattern: basalt.

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 (Shervais et al., 2005). This is in contrast to the 1500-m-deep WO-2 Idaho well site of the Idaho National Lab (INL), 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).

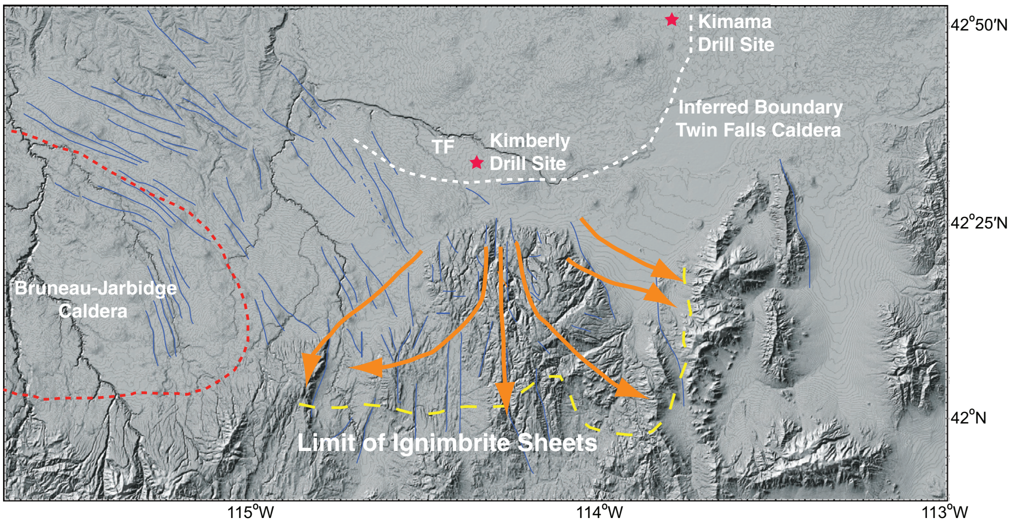

Figure 3. Shaded relief map of Twin Falls area, with 10-m contours calculated from NASA 10-m DEM data in GeoMapApp. Blue lines show mapped faults and lineaments mapped in 10-m data. Orange arrows show flow directions on ash flow tuff sheets in the Cassia Mountains, mapped by McCurry et al. (1996), with southern extent of sheets marked by long-dashed yellow line at the bottom. Bruneau-Jarbidge caldera marked by dashed red line. Southern margin of the Twin Falls caldera complex, inferred from regional Bouger gravity anomaly, shown with short-dashed white line. Drill sites marked with red stars; TF=city of Twin Falls.

One of the primary goals of Project HOTSPOT was acquisition of continuous core in the central SRP that documents the long-term volcanic and sedimentary record of hotspot passage, from the early rhyolitic volcanism (which marks arrival of the plume over a given location) to the later, post-plume basaltic volcanism (Shervais et al., 2006a). This record will be combined with existing core to the west and east to produce a four-dimensional (space and time) synthesis of mantle plume-continental lithosphere interaction. It is this plume-continental lithosphere interaction that leads to the eruption of early A-type rhyolites, rather than basalt, as the dominant volcanic signature of the subcontinental plume, in contrast to oceanic plumes. Basalts post-date the rhyolites and form after the locus of rhyolite volcanism has shifted to the northwest in response to the southwestward movement of the North American plate (Smith and Braille, 1994).

Another primary goal was recovery of a similar long-term record in the western SRP, including lacustrine sediments thought to span the Pliocene-Pleistocene transition, and the onset of North American glaciation (Shervais et al., 2006a). This paleo-climate goal targeted the lacustrine sedimentary record of “Lake Idaho,” a large long-lived lake that filled the western SRP graben during the Neogene.

In addition to these scientific goals, drilling was planned to validate new exploration techniques for geothermal resources and to document the existence of new geothermal resources in a setting that has no previous development of high-temperature geothermal prospects. Heat flow in shallow drill holes is high along the margins of the plain (80–100 mW m^{-2} s^{-1}) and low along the axis of the plain (20–30 mW m^{-2} s^{-1}). However, previous deep drillholes (>1 km) in the axial portion of the plain have high geothermal gradients similar to the margins of the plain below ~200–500 m depth (75–110 mW m^{-2} s^{-1}; Blackwell, 1989). This contrast between the shallow and deep parts of the axial portion of the plain is caused by the Snake River aquifer, a massive aquifer system that extends under the plain and emerges at Thousand Springs, Idaho.

An offset drilling strategy was employed, with our first hole drilled along the central volcanic axis (to capture the most complete record of basaltic volcanism), and our second hole drilled along the southern margin of the plain, where rhyolite is exposed beneath basalt in the Snake River Canyon (Fig. 1). This approach allowed us to drill almost 4 km of section at a significantly lower cost than a single continuous drill hole in the central SRP and to complete an additional 1.8 km drillhole in the western plain.

Preliminary Results

Drilling was completed between September 2010 and January 2012. In all, three deep holes were completed, collecting over 5.9 km of core for further study with better than 98% core recovery (Fig. 1). Geophysical studies carried out in conjunction with the drilling effort included (1) high-resolution gravity and magnetic surveys, (2) high-resolution shallow seismic surveys, and (3) borehole geophysical logs. The borehole data will be used to correlate the surface geophysical studies and extend the cored stratigraphy away from the drill sites.

Cores from all three sites were moved to the Core Laboratory of the Utah State University in Logan 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 (DIS) database.

1. Kimama – Continuous Basalt Core from the Axial Volcanic Zone

The Kimama drill site was set up to acquire a continuous record of basaltic volcanism along the central volcanic axis and to test the extent of geothermal resources beneath the Snake River aquifer. Elevated groundwater temperatures beneath the central volcanic axis (15°C–17°C) imply a significant flux of conductive heat flow from below (Potter et al., 2012).

Lindholm (1996) used potential field, resistivity, and well data to infer a basalt thickness of 1.2–1.4 km in the axial volcanic zone (Fig. 1). The topographic axial volcanic high is apparently mirrored by a keel of basalt that runs from the central plain to the eastern plain, and thins toward the margins and the ends. The hole was spudded into late Pleistocene basalts around 174 ky in age and was anticipated to encounter rhyolite between 1.2 km and 1.4 km depth. The plan was to continue drilling a few hundred meters into underlying rhyolite to allow correlation with the Kimberly drill site; however, the results of drilling forced changes to this plan.

Drilling at Kimama was completed between September 2010 and January 2011 with a final depth of 1912 m. An original target depth (TD) of ~1500 m for this site was based on an expected depth of ~1200 m to the basalt-rhyolite contact. However, no basalt-rhyolite contact was recovered, and budget constraints prevented further deepening of the hole. Borehole logging was carried out through the drillstring by a U.S. Geological Survey team (Twining and Barthomay, 2011). Cased (i.e., through drillstring) and open hole logging were carried out in the deepest parts of the Kimana hole. Open hole logging was carried out by the ICDP Operational Support Group in June–July 2011 in the upper sections.

The Kimama section consists almost entirely of basalt, with thin intercalations of loess-like sediment in the upper 200 m of the hole, and with somewhat thicker intercalated beds of fluvial gravels, sands, and silts in the lower 300 m (Fig. 2). Very thin silt intercalations are scattered throughout the intervening depths. Potter et al. (2011) have documented 557 basalt flow units in this section, based on natural gamma logs, neutron logs, and the recovered core, with a total thickness of 1803 m. Preliminary geochemical studies and paleomagnetic results suggest at least thirty flow groups representing distinct time periods, and magma batches are present, with the oldest lavas ~6 Ma in age (Bradshaw et al., 2012; Champion and Duncan, 2012; Potter et al., 2012).

The thickness of basalt plus intercalated sediment in the Kimama drillhole (1912 m) is almost 70% more than in the WO-2 drillhole at the Idaho National Laboratory, about 90 km to the northeast. It is also over five times greater than the section sampled by the Wendell-RASA drillhole (Fig. 2). This large thickness of basalt was completely unexpected, and its existence suggests the presence of a deep, possibly fault-controlled accommodation space.

The electrical resistivity (ER) maps are thought to define the depth to water-saturated basalt—generally interpreted to represent the base of the younger Quaternary basalts, excluding older Pliocene basalts which have limited porosity (Lindholm, 1996). Our data suggest that the ER measurements most likely correspond to the base of the Snake River aquifer. Below the aquifer, basalt porosity is sealed by authigenic mineralization that restricts permeability (Morse and McCurry, 2002). Based on these ER maps, the depth to base of the aquifer at the Kimama site was estimated to be ~850 m. However, thermal gradient logs of the Kimama drillhole document a near-isothermal gradient from the top of the aquifer to ~980 m depth, which is now interpreted to reflect the true base of the aquifer (Nielson et al., 2012). This is almost twice the documented thickness of the Snake River aquifer in other locales.

Temperatures (15°C–17°C) within this thick aquifer are elevated relative to groundwater temperatures farther east and along the margins of the plain (~9°C). However, even this modest temperature increase must reflect a significant flux of heat from lower in the crust (Blackwell, 1989), which is consistent with the thermal gradient of ~75°C–80°C per

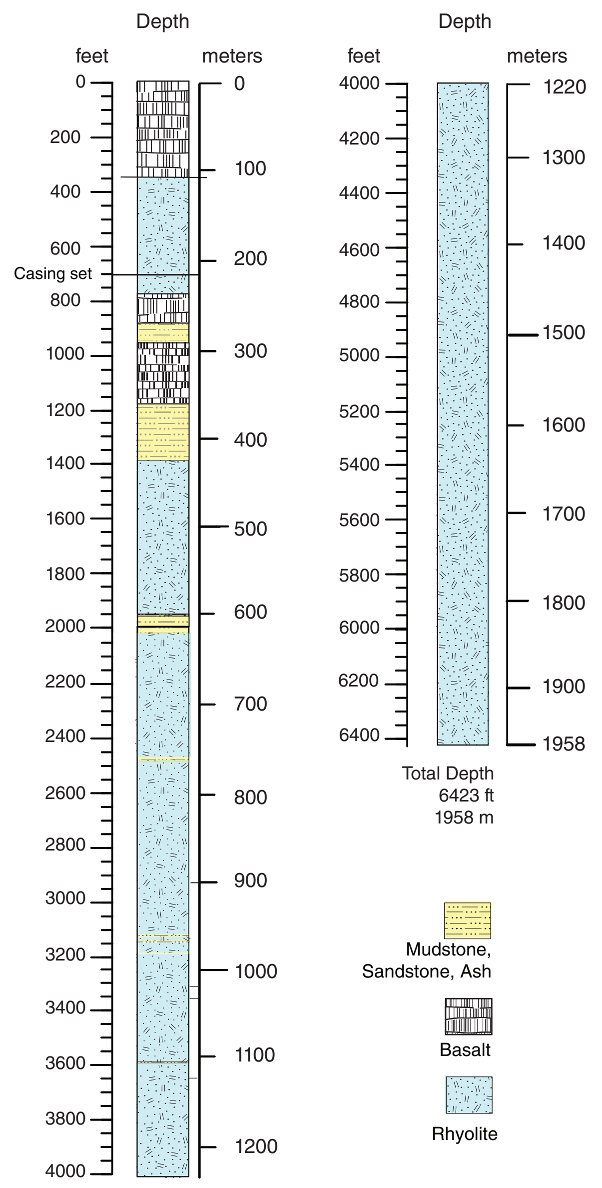

Figure 4. Lithologic log of the Kimberly well.

km below the aquifer, and a bottom hole temperature of ~98°C (Nielson et al., 2012).

2. Kimberly – The Basalt-Rhyolite Transition and Plume-Driven Rhyolite Volcanism

The primary goal of the Kimberly drillhole was to core the lower portion of the composite basalt-rhyolite section that characterizes the central and eastern SRP. A section exposed in the Snake River Canyon documents about 100 m of basalt overlying rhyolite 6.25 Ma old (Shervais et al., 2005). Regional Bouguer gravity anomalies and mapped flow directions in ignimbrites exposed south of Kimberly in the Cassia Mountains suggest that this site lies on the southern margin of the Twin Falls eruptive complex, an immense Yellowstone-scale rhyolite eruptive center inferred to underlie the central SRP north of Twin Falls (Fig. 3). The Kimberly site was selected to lie just outside the margin of this eruptive center, so that core would capture proximal rhyolite ashflows.

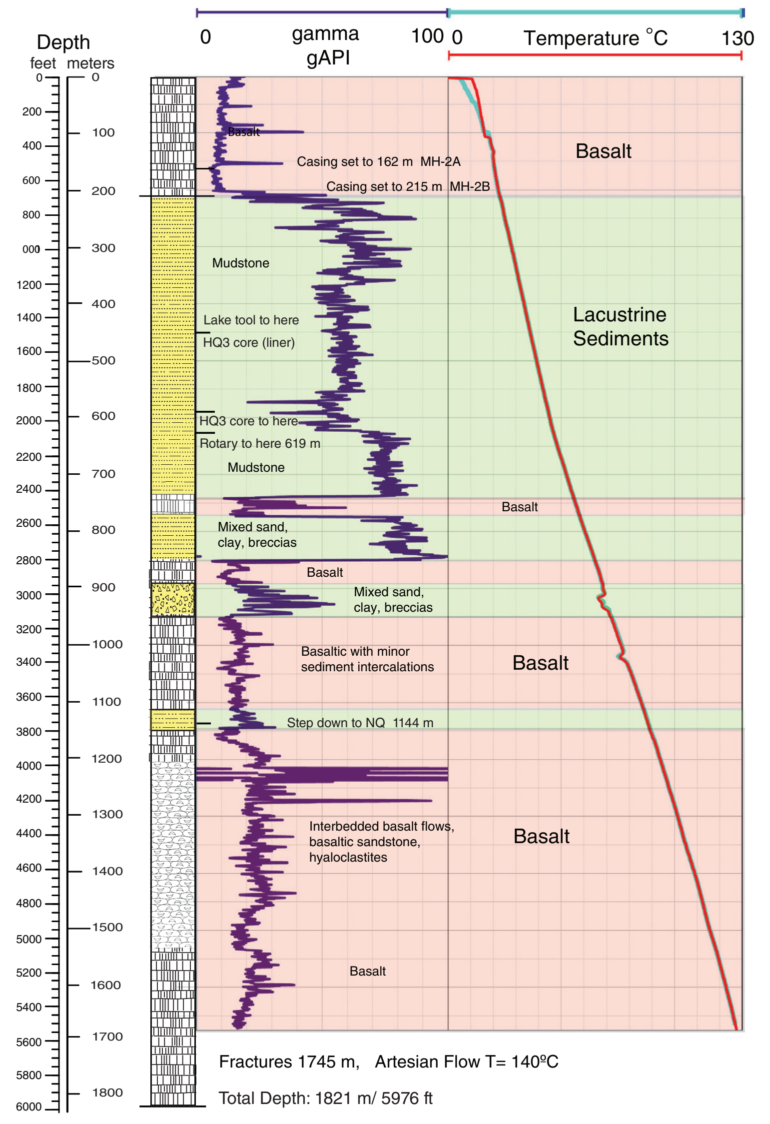

Figure 5. Lithologic column for the Mountain Home, Idaho drill core.

An additional goal was to assess the geothermal potential of up-flow zones along a buried caldera margin. 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; Lewis and Young, 1989; Baker and Castelin, 1990). Geothermal wells in the Twin Falls Groundwater Management Area range in temperature from around 30°C to 72°C.

Kimberly drilling was completed between January 2011 and June 2011; it reached a total depth of 1958 m (uppermost 214 m not cored; similar section exposed in the nearby Snake River Canyon). This deep hole is dominated by massive rhyolite lava and welded ashflow tuffs, with basalt/sediment intercalations at 241 m to 424 m depth, and thin altered ash interbeds around 610 m depth (Fig. 4). The lower 900 m (from 1050 m to 1958 m) has no apparent flow contacts and may represent a single, thick welded ashflow tuff. There is no indication of granophyric textures that would suggest an intrusive origin, even in the deepest recovered core.

Temperature measurements, made while drilling with the Drilling, Observation and Sampling of the Earths Continental Crust (DOSECC) core barrel temperature tool, and wireline temperature logging document a cool water aquifer in the upper 400 m of the Kimberly drillhole, underlain by an immense, 55°C–60°C water aquifer extending from 400 m to TD at 1958 m (Nielson et al., 2012).

3. Mountain Home – Basalts and Lacustrine Sediments of the Western SRP

Basaltic volcanism in the western SRP occurred early in the history of the hotspot and continued throughout the Neogene, with basalts as young as 200 ky that erupted across a wide area (Shervais et al., 2005). A major goal of our project in the western plain was to capture a record of the older basalts and the lacustrine sediments which overlie them (Lewis and Stone, 1988). Sampling of the Neogene lacustrine deposits will test hypotheses for changes in moisture transport to inland North America from the Pacific initiation of Northern Hemisphere glaciation, and examine the response of the Great Basin hydrological system to the Pliocene climatic optimum. The lacustrine record will also allow us to infer the chronology of biotic recovery in the post-eruption intervals following some of the largest explosive volcanic eruptions known. Finally, this core will allow us to resolve late Neogene records of biotic and landscape evolution in response to tectonic and magmatic processes related to SRP-Yellowstone hotspot evolution, and to develop a reference section for regional biostratigraphy.

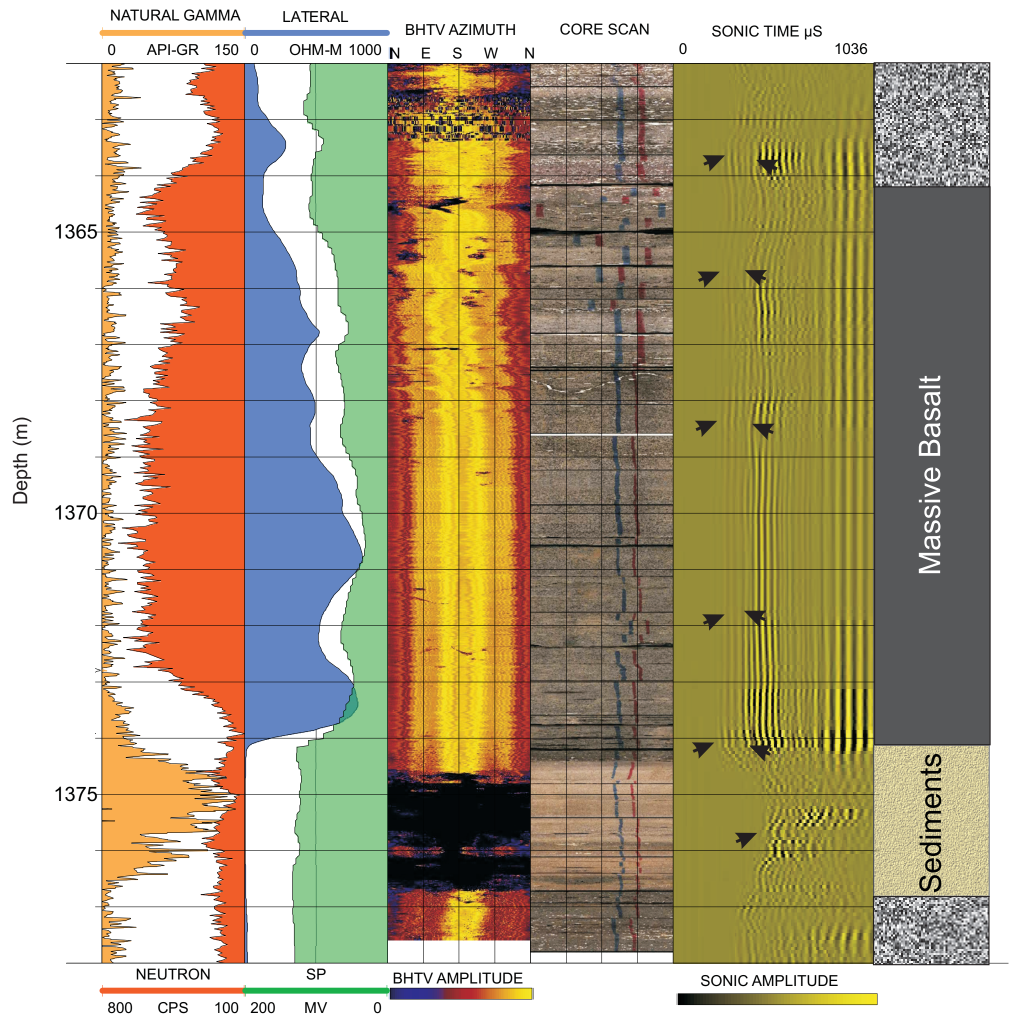

Figure 6. Comparison of geophysical and core scan logs through a massive basalt flow, 1362–1378 m in the Kimama 1B borehole. The logs shown are the observed natural gamma radioactivity (in counts per second, CPS), the returning scattered neutron response (in reversed counts per second), the lateral electrical resistivity log (linear scale in Ω–m), and the Spontaneous Potential (SP) log (in reversed mV). The borehole televiewer (BHTV) amplitudes are normalized, and black indicates lost signal; the BHTV log has been rotated to align with geographic north. The unwrapped core scans are from RGB images; these have not been oriented. In the sonic log display the arrivals of the P- and S-waves are highlighted by right and left pointing arrows, respectively.

Drilling operations at Mountain Home were completed between July 2011 and January 2012. A first hole was abandoned at 599 m depth because of drilling problems, but a second hole offset 7 m from the first hole successfully reached a final depth of 1821 m. Borehole logging was first carried out in January 2012 to a depth of 1690 m, prior to final deepening of the hole. Temperature and natural gamma-ray logs were recorded within the drill-string; open hole logging was restricted to the lower 1200 m of the drillhole because sediments in the upper part of the hole were too unstable to remove the casing before the plug-and-abandon process. A second logging campaign in November 2012 attempted additional logging to the final TD of 1821 m, but temperatures in the lower 200 m exceeded the stability limits on the tools. However, open hole logging with a high-T borehole televiewer was successful between 1200 m and 1600 m.

The Mountain Home drill section consists of an upper basalt unit with minor interbedded sediments at 0–215 m, overlying interbedded sands and clays, with minor gravels and thin basalt layers at 215–850 m. From 850 m to 1250 m, 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 (Fig. 5).

A fracture system was encountered at 1745 m with artesian flow of geothermal fluids (Nielson et al., 2012). Temperature readings with the bottom hole temperature (BHT) tool indicated temperatures ~150°C when the geothermal zone was encountered; later temperature logging indicates temperatures of ~135°–140°C, possibly as the result of downward flow of cold water (Nielson et al., 2012). Chemical analysis of the geothermal waters shows that they are sulfate-rich, indicative of steam-heated 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 measured temperatures in the geothermal zone.

Geophysical Logging

An ambitious borehole geophysics program was implemented to support the geological interpretations and to provide additional information on modern-day tectonic regimes in the SRP. The logs obtained include total natural γ–radiation (including some spectral γ logging for U, Th, and K contents), neutron hydrogen index, γ–γ density, resistivity, magnetic susceptibility and full vector magnetic field, 4-arm caliper (i.e., dipmeter), full waveform sonic, and ultrasonic borehole televiewer imaging (Schmitt et al., 2012).

The neutron and γ–γ density logs employ radioactive sources. As such, and in the interest of minimizing any risk they would be lost in the open hole, both of these were run in the drillstring. While this precludes accurate quantitative assessment of density or hydrogen index, it does provide useful semi-quantitative comparisons for purposes of mapping the lithology. Figure 6 compares a variety of different logs through a massive basalt flow between 1362 m and 1378 m in the Kimama 1B borehole. Through this zone, the lithologies are simplified into three categories of sediment interbeds, seen as the reddish tinged layer between 1374.5 m and 1376.5 m, the low porosity massive basalt above 1374.5 m to 1364 m, and a more porous basalt with precipitate-filled vesicles (above 1364 m and also below 1376.5 m). The latter lithology is related to the top of the flows where porosity can exist from both rubble and vesiculation. The interbedded sediment consists of mostly loess deposits laid down in periods between subsequent flows.

The neutron response is primarily sensitive to the density of hydrogen nuclei in the surrounding fluids, clays, and hydrous alteration products. As such, and somewhat unexpectedly, the relative neutron log intensity could indicate individual basalt flows primarily because of porosity and clay content differences between the dense massive basalt and the rubbly and sediment-containing flow tops. This is apparent in the neutron log of Fig. 6, where high returning neutron fluxes (indicative of low H content) correlate well with the massive basalt, particularly above 1373 m. This signal decays towards the top of the flow where the higher porosity can contain more fluids and possibly hydrous minerals. The sediment layer, too, has higher porosity, and it contains clay minerals that produce a low neutron response.

Natural γ-ray radiation is produced by the decay of various isotopes of uranium, thorium, and potassium. The concentration of these elements is typically low in basalt except for horizons of "Craters of the Moon"-type evolved basalts with high K_2O (>1 wt%; Potter et al., 2011). Spectral γ-logging through the thick rhyolites at Kimberly, however, gave K_2O concentrations of 2.5–3.5 wt% that contributes to a relatively high total response often in excess of 200 API (American Petroleum Institute) units. In the basalt sections, the natural γ-ray log was usually, but not always, a strong indicator of sediment intercalations. This is also seen in Fig. 6 where the natural radioactivity is low everywhere except for the sediment layer.

The electrical resistivity, measured by the lateral log (Fig. 6), is high in the massive basalts due to their low porosity and lack of conductive minerals. The lateral log resistivity mirrors the neutron responses to some degree. The sediments are much more conductive.

The borehole televiewer image quality also correlates well with the lithology. The signal is lost due to washing of the borehole during the coring operations through the softer sediments. Images through massive basalt and rhyolite are mostly featureless except for fractures that appear mostly to be filled by precipitates in the core (Fig. 7). Vesicles near the tops of the basalt flows are more apparent.

The full-waveform acoustic log also displays interesting correlations with the lithology through this section. In Fig. 6, the arrivals of the P- and S-waves are highlighted by the right and left pointing arrows, respectively. Traveltimes are short within massive basalt, indicative of a high sonic log velocity. Strong S-waves also appear throughout the massive basalt. A possible existence of split shear waves (e.g., the section between 1374 m and 1372 m) could indicate stress-induced seismic anisotropy around the borehole. Only the P-wave first arrival is seen within the sediment layer, and no clear S-wave can be unambiguously interpreted through the sediments.

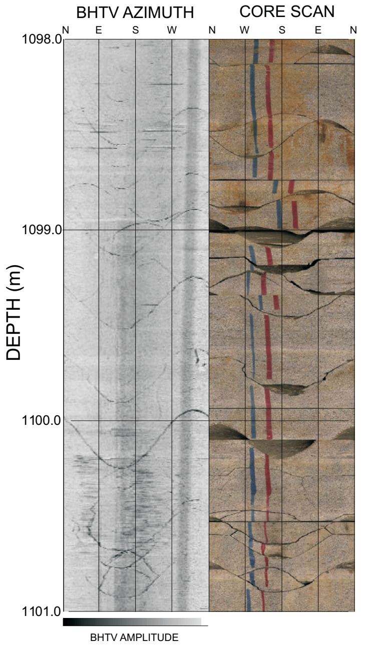

Figure 7. Examples of BHTV and core images from the Kimama 2A corehole. Comparison of ultrasonic borehole televiewer images through naturally fractured rhyolite with the corresponding unwrapped core scans. The core scans have been oriented based on the televiewer images. Note that the core image mirrors that of the televiewer.

Figure 6 is just one example of the logging data obtained. The Kimberly logging campaign was the most extensive carried out and is a rare, if not unique, set of geophysical logs through a thick sequence of rhyolitic ignimbrites. The relative uniformity of the thick rhyolite sequence provided for a high quality borehole and consequently exceptional borehole televiewer images. Comparisons between the core and televiewer images allow the former to be oriented, greatly supporting stress and fracture related studies. In addition, numerous drilling-induced fractures indicating the horizontal principal stress directions were observed.

High-resolution surface and borehole seismic data were acquired in order to provide additional structural information in the immediate vicinity of each of the three boreholes. These typically included (when possible), 2-D seismic profiles crossing near the borehole as well as closely spaced (2-m) zero-offset and walk-a-way vertical seismic profile (VSP) data.

The results of the processed VSP from Kimama (Fig. 8) display strong seismic reflectors associated with the sediment interbeds and prove that substantial seismic energy in fact does transmit through the basalts. Lack of proper seismic images within basalt flows is due to scattering effects in the near surface.

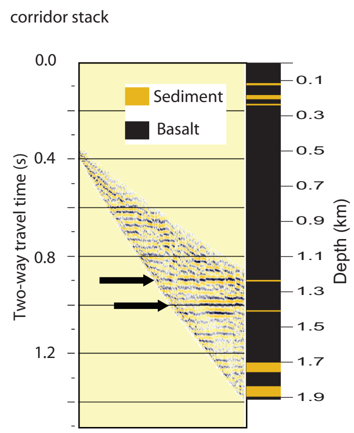

Figure 8. Processed vertical seismic profile from the Kimama 1B borehole. Two strong reflectors associated with sediment interbeds at 900 m and just below 1000 m depth are highlighted by arrows.

Summary and Conclusions

The Kimama and Kimberly core holes were selected to produce a composite section through volcanic crust in the central SRP that replicated a slice through time and the eruptive history of the plain in this location. We succeeded in this goal—basalts near the bottom of the Kimama core hole are ~6 Ma in age, while rhyolite lava overlain by basalt in the uppermost Kimberly core hole has been dated at 6.25 Ma (Shoshone Falls rhyolite; Bonnichsen et al., 2008). Basalts in the Kimama hole are at least 50% thicker than anticipated, and they preserve a remarkable record of essentially contin-uous mafic volcanism within the Axial Volcanic Zone. The occurrence of clastic fluvial sediments at ~1800 m depth in Kimama shows that during its earliest history, the Axial Volcanic Zone was not a topographic high but a basin with a through-going drainage system. The repeated occurrence of highly evolved “Craters of the Moon”-type lavas in the Kimama hole at three depth horizons in the well shows that these highly evolved flows form repeatedly during evolution of volcanic province, not just towards the end of volcanism.

The Kimberly core hole is notable because it documents the intercalation of basalt and rhyolite immediately after the initial phase of rhyolite volcanism, and because it reveals the occurrence of massive rhyolite ignimbrites that may be up to 900 m thick. The Mountain Home well confirms the occurrence of an older basaltic basement, which underlies Pliocene-Pleistocene paleo-lake sediments that are over 600 m thick. Comparison with dated sections exposed in outcrop suggests that the lower basalts are 6–8 Ma in age, while basalts that overlie the paleo-lake sediments are less than 2 Ma. Geochemical and paleomagnetic studies are just beginning on the Kimberly and Mountain Home core samples.

Drilling and geophysical surveys have been largely completed, and we are currently evaluating the results. The Kimama well, completed at 1912 m, samples an aquifer that is twice as deep as the next deepest part of the aquifer (960 m vs. 500 m at the INL site), suppressing the thermal gradient. Nonetheless, a temperature gradient of 80°C km^{-1} underlies the aquifer, reflecting a deep buried resource that may be tapped where the aquifer is thinner. The Kimberly well (1958 m) taps a warm water aquifer at 55°C–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) in-tersected a 135°C–140°C (or higher) geothermal resource with artesian flow to the surface. Combined with data from older explora-tion efforts, this documents a significant electric-grade geothermal resource that lies outside existing geothermal resource areas.

The central questions addressed by Project HOTSPOT—how mantle hotspots interact with continental lithosphere, and how this interaction affects the geochemical evolution of mantle-derived magmas and of the continental lithosphere—must await completion of the geochemical and isotopic studies before they can be answered. However, the excellent core recovery achieved (>98% of cored intervals) has provided the HOTSPOT Science Team with the material it needs to address this question, and the geophysical campaign places these results within the broader context of stratigraphic and tectonic evolution.

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