Hotspot: The Snake River Geothermal Drilling Project—An Overview

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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, and an area with the highest calculated geothermal gradients. This makes the SRP one of the potentially highest producing geothermal districts in the United States. Elevated heat flow is typically highest along the margins of the topographic Snake River Plain and lowest along the axis of the plain, where thermal gradients are suppressed by the Snake River aquifer. Beneath this aquifer, however, thermal gradients rise again and may tap even higher heat flows associated with the intrusion of mafic magmas into a geophysically-imaged mid-crustal sill complex. The primary goal of this project is to evaluate geothermal potential in three distinct settings: (1) the high sub-aquifer geothermal gradient associated with the intrusion of mafic magmas and the release of crustal fluids from the associated wall rocks, (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 more traditional fault-bounded basin with thick sedimentary cover. All settings are found within the central or western Snake River Plain and represent previously untested targets for geothermal exploration. Our first drill site tests 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. Our second drill site assesses the geothermal potential of up-flow zones along a buried caldera margin, in an area of known geothermal potential (Twin Falls geothermal district). Further studies will include seismic reflection-refraction surveys, gravity-magnetic surveys, and downhole geophysical logs.

1. Introduction

The Snake River volcanic province overlies a thermal anomaly that extends deep into the mantle (e.g., Waite et al 2006; *Xue and Allen, 2010; James et al 2009; Obrebski et al 2010)* and represents one of the highest heat flow provinces in North America, and an area with the highest calculated geothermal gradients (*Blackwell 1980; Blackwell et al 1989, 1991, 1992; Blackwell and Richards 2004*). This makes the SRP one of the most under-developed and potentially highest producing geothermal districts in the United States. Elevated heat flow is typically highest along the margins of the topographic Snake River Plain and lowest along the axis of the plain, where thermal gradients are suppressed by the Snake River aquifer. Beneath this aquifer, however, thermal gradients rise again and may tap even higher heat flows associated with the intrusion of mafic magmas into a geophysically-imaged mid-crustal sill complex (*e.g., Peng and Humphreys 1998*).

Project Hotspot is an effort by an international group of investigators to understand this thermal system, its relationship to the volcanic and tectonic history of the Snake River volcanic province, and its relationship to the Yellowstone hotspot - the most active volcanic system in the continental United States. The Yellowstone Plateau volcanic field consists largely of rhyolite lavas and ignimbrites, with few mantle-derived basalts (*Christiansen 2001*). In contrast, the Snake River Plain (SRP), which appears to represent the track of the Yellowstone hotspot, consists of rhyolite caldera complexes that herald the onset of plume-related volcanism and basalts that are compositionally similar to ocean island basalts like Hawaii (*Pierce et al 2002*). The SRP preserves a record of volcanic activity that spans over 16 Ma and is still active today, with basalts as young as 200 ka in the west and 2 ka in the east. The SRP is unique because it is young and relatively undisturbed tectonically, and because it contains a complete record of volcanic activity associated with passage of the hotspot *(Shervais et al, 2006a).* The heat propagated by this hotspot drives high surface heat flows and numerous hot springs.

2. Geothermal Potential of Snake River Volcanic Province

Geothermal power has long been used in southern Idaho, but it has been confined almost exclusively to direct use applications such as space heating and aquaculture *(e.g., Sherman 1982; Mitchell et al 2003; Neely 1996; Fleischmann, 2006).* The Raft River site is the only commercial geothermal development used for power generation *(Nathenson et al 1980; Peterson et al 2004; Neely and Galinato 2007).* Nonetheless, 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*).

The Snake River Plain in southern Idaho represents the track of deep-seated mantle 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, and from rhyolites formed by the basalt, drives the high heatflow and geothermal gradients observed in deep drill holes from throughout the Snake River Plain (*Blackwell 1978, 1980, 1989; Brott et al 1976, 1978, 1981; Lewis and Young 1989*). Heat flow in the SRP tends to be high along the margins of the plain (80-100 mW/m^2-s) and low when measured in shallow drill holes along the axis of the plain (20-30 mW/m^2-s). However, 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 discrepancy 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. This aquifer varies in thickness from <100 m to >450 m in the eastern-most SRP. Thermal gradients through the aquifer are static until the base of the aquifer is reached, then rise quickly at deeper levels in the crust (*e.g., Blackwell 1989; Blackwell et al 1992; Smith 2004*). Below the aquifer along the axis of the plain, heat flow values are comparable to heat flow values along the margins of the plain or higher (75-110 mW/m^2-s; *Blackwell 1989*). Bottom hole temperatures for wells along the margins of the plain near Twin Falls are typically around 30-60ºC at 400-600 m depth (*Baker and Castelin 1990*) and as high as 120ºC at 2800 m depth in the axial region of the plain (*Blackwell 1989)*.

Our primary goal is to evaluate geothermal potential in three distinct settings (Figure 1): (1) the high sub-aquifer geothermal gradient associated with the intrusion of mafic magmas and the release of crustal fluids from the associated wall rocks, (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. We explore the use of surface geophysical studies, including gravity, magnetic, and seismic techniques, in identifying these resources, and to verify their application by drilling slimhole test wells that will be logged using conventional wireline geophysical logs and walk-away vertical seismic profiles.

3. Site Characterization and Selection

Extensive work in the Snake River volcanic province has documented the need for deep drill holes to assess subsurface conditions and understand thermal potential *(e.g., Embree et al 1978; Natheson et al 1980; Whitehead and Lindholm 1985; Lewis and Stone 1988; Shervais et al 1994; Geist et al 2002).* The complex volcanic stratigraphy, with density/velocity inversions and non-continuous layering, presents a challenge to traditional seismic surveys and requires a better understanding of the local stratigraphy and its seismic response in order to produce meaningful interpretations *(e.g., Bradford et al 2006).* These interpretations are aided by gravity and magnetic models that constrain overall crustal structure.

Our workplan calls for drilling three new intermediate depth (1.5-1.9 km) slim-hole exploration wells in the central and western Snake River Plain, in combination with high-resolution seismic, gravity and magnetic surveys (Figure 1). Borehole geophysical logs and vertical seismic profiles will acquired to further constrain the stratigraphy and the physical and seismic character of its components. These wells 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. Our criteria for selecting and evaluating these sites is discussed below.

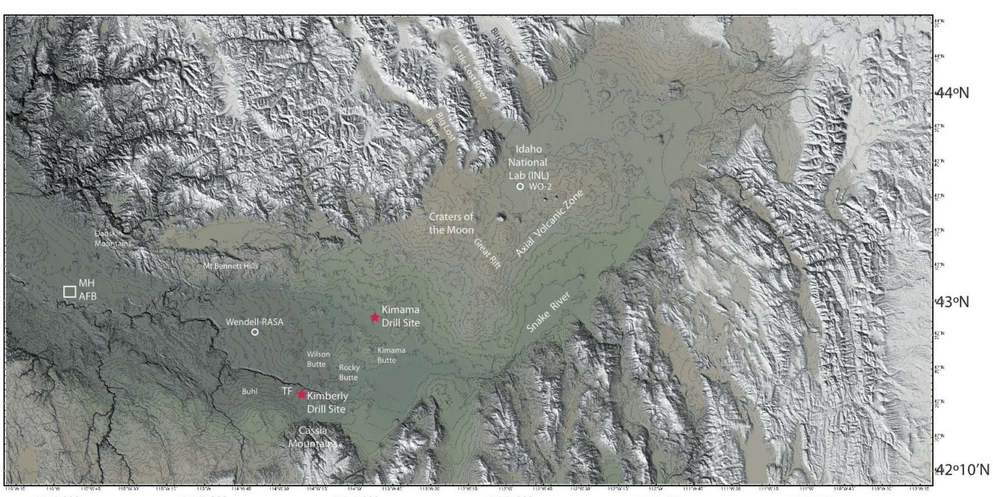

Figure 1. Shaded relief-topographic map of Snake River Plain derived from NASA 10m DEM data and contoured at 30m intervals. Red stars = new drill sites of this project; open circles = legacy drill sites.

3.1 Kimama – Elevated Heat Flux Under the Volcanic Axis

The primary goal of the Kimama drill site is 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 (*e.g., Smith, 2004; Smith et al, 2002, submitted*). 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 in the central SRP northeast of Twin Falls has been carried out over the last decade by the lead author and his students, and by personnel of the Idaho Geological Survey, resulting in the publication of several geologic maps at 1/24000 or 1/100,000 scales *(Kauffman et al, 2005a, 2005b; Shervais et al, 2006c, 2006d; Cooke et al, 2006a, 2006b; Matthews et al., 2006a, 2006b)* and unpublished thesis maps *(Cooke, 1999; Matthews, 2000; Hobson, 2009; DeRaps, 2009)*. This mapping ties into published mapping by the US Geological Survey in the Craters of the Moon 1/100,000 sheet *(Kuntz et al 2007)* and into unpublished mapping by our east of longitude 114ºW; the results of this work have summarized by *Shervais et al. (2005*).

The principal result from the geologic mapping is to show that Quaternary volcanism is widespread throughout the central SRP, with young vents occurring both along the margins of the plain and near its center (Figure 2), but young volcanic vents are dominant within the axial volcanic zone. While some vents with similar ages may align parallel to the NS-trending volcanic rift zones defined by *Kuntz (1992; Kuntz et al 2002),* other young vents are as likely to define other alignments. These trends are often highlighted on regional magnetic maps, since basalts with similar ages will commonly have the same magnetic polarity, resulting in striped magnetic alignments (Figure 3A).

Northwest of Twin Falls, vents become less common and the basalt flows thin out and become intercalated with fluvial and lacustrine sediments. 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)*. The older basalts (1.0-4.5 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)*.

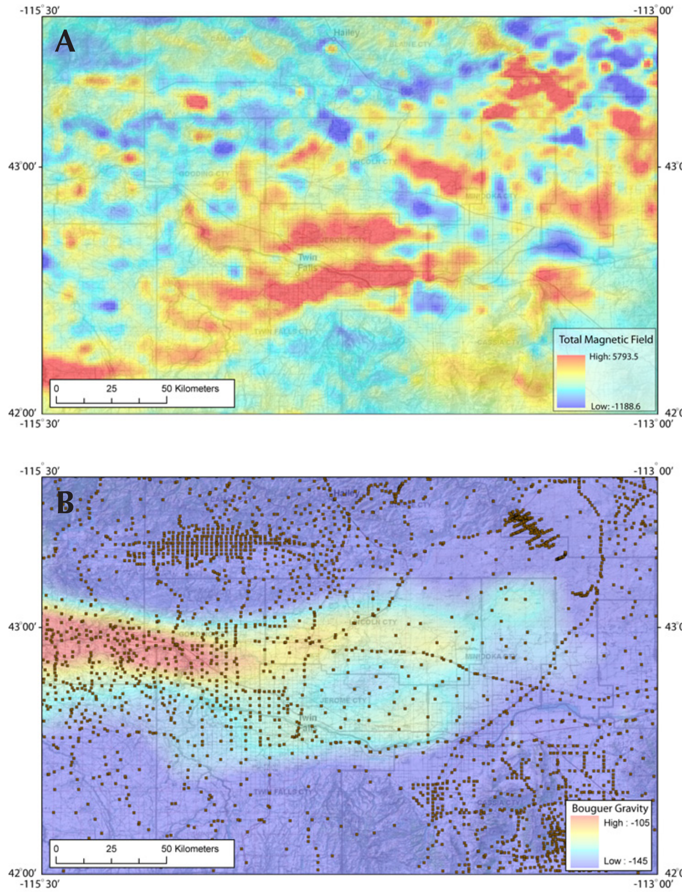

Figure 3. Magnetic (A) and Bouguer Gravity (B) maps of central and western Snake River Plain. Magnetic lineaments may represent concentrations of similarly aged basalts. Gravity high in west is continuation of western SRP horst block; oval gravity anomaly in east may represent outline of the Twin Falls eruptive complex.

The concentration of young Quaternary volcanism along the Axial Volcanic Zone, and the nexus of volcanic rift zones, which trend NNW and EW, makes this region a high priority for geothermal exploration *(Shervais et al 2005, 2006a, 2006b)*. Vent concentrations are highest between the Great Rift and the Twin Falls-Shoshone area (Figure 2), so our model suggests that this region, centered around our Kimama drill site, is more likely to encounter high temperature resources at depth than areas lying farther west; the Great Rift itself lies within Craters of the Moon National Monument, and is off-limits to exploration.

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) logs that define a buried keel of basalt underlying the topographic high. The ER logs define the depth to saturated basalt – generally interpreted to represent the base of the younger Quaternary basalts, and excluding

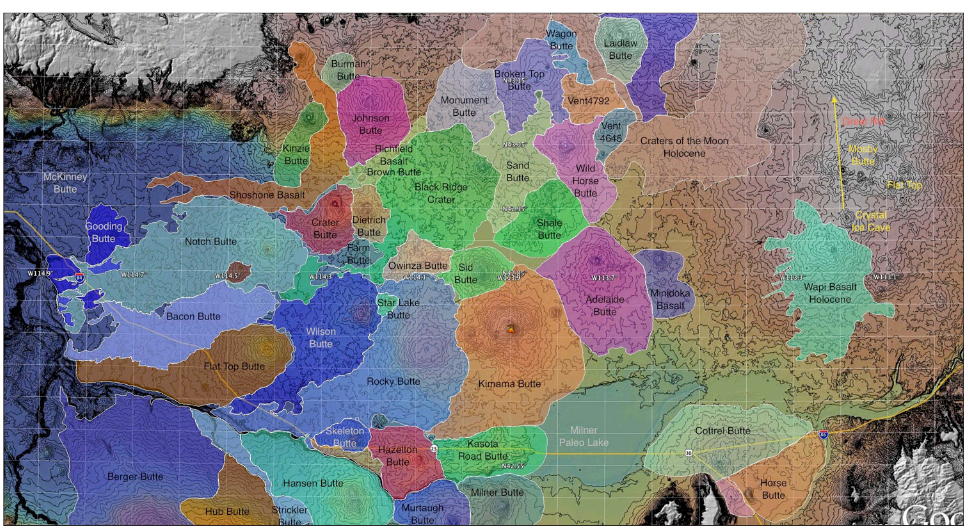

Figure 2. Partial compilation of basaltic vents in the central Snake River Plain. Note clustering of vents along the Axial Volcanic Zone (AVZ). Vents range in age from ~4 Ma to as young as 2000 years.

older Pliocene basalts which have limited porosity (*e.g., Lindholm 1996*). Based on these ER logs and nearby wells, the depth to base of Pleistocene basalt at the Kimama site is about 850 m (2800 feet). For comparison, the WO-2 borehole on the Idaho National Laboratory (INL) site is located on the same ER depth contour, and sampled 1200 m (3900 feet) of basalt. The basalt thickness estimated from ER measurements most likely corresponds very approximately 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*). The Wendell-RASA borehole, situated near the 500 m ER depth contour, encountered 335 m (1100 feet) of basalt plus sediment, but did not encounter rhyolite basement.

Detailed assessments of groundwater temperatures and flow paths beneath the Idaho National Lab and adjacent areas *(Smith 2004, Smith et al 2002, McLing et al 2002)* show that the base of the Snake River aquifer varies from 200 m to 500 m depth, based on the inflection depth of groundwater temperatures in deep wells, which change from isothermal within the aquifer to conductive below the aquifer. Thick portions of the aquifer correspond to massive inputs of cold water from (1) the combined Snake River-Henrys Fork River drainages and (2) the Centennial Mountains, including the Big Lost River, Little Lost River, and Birch Creek drainages.

This flux of cold water is concentrated in groundwater plumes that follow the southern and northern margins of the Snake River Plain, paralleling flow of the Snake River (in the south) and the Little Wood River (in the north), and skirting the thick axis of basalt volcanism that underlies the central volcanic axis of the plain. Goundwater temperatures form a linear high along the central axis of the Snake River Plain that corresponds with both the axial topographic high and the axial volcanic keel (*Smith 2004; Smith et al, 2002, McLing et al 2002*). The elevated groundwater temperatures are especially remarkable in light of the massive flow of cold water documented by deep wells and by cold springs that emerge from the aquifer west of Twin Falls. The conceptual model for this process is shown in Figure 4, taken from *Smith (2004),* which depicts a longitudinal profile along the axis of the central and eastern SRP. Cold water enters the system from the surrounding mountains, fed by major river systems from the north, east and southeast. This plume of cold water is gradually heated from below by the high plume-derived heat flux, which is focused under the axis of the plain (Figure 4). The axial heat flux is enhanced by the intrusion of the mid-crustal sill complex, which advects heat into the middle crust as magma, and continuously releases latent heat of fusion as the sills cool and crystallize (*Shervais et al 2006b*).

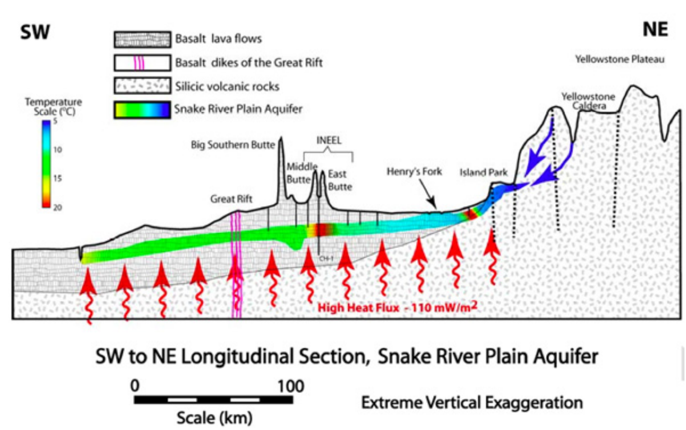

Figure 4. Conceptual model for heating of ground water along central axis of SRP, from Smith (2004).

We selected the Kimama site for several reasons, based on the analysis above. First, it sits within the an area that has a high concentration of Quaternary volcanic vents. Second, it sits on the Axial Volcanic Zone where heat from the underlying mantle plume and sill complex should be highest. Third, it sits above the elongated plume of warm ground water defined by *Smith (2004),* which shows that this heat is being advected to the surface. Finally, as shown in the following section, it appears to sit above the eastern margin of a buried caldera complex, which may provide enhanced pathways for heat transport along its ring fracture system. Our selected location is about 40 km west of the Great Rift – a volcanically active rift zone with anomalous crust that has likely been affected by hydrothermal circulation *(Kuntz et al 1982).* Note that the Great Rift lies within Craters of the Moon National Monument, and is off-limits to development.

3.2 Kimberly – Up-Flow along a Buried Caldera Margin

The primary goal of the Kimberly drill hole is to assess the geothermal potential of up-flow zones along a buried caldera margin. The large number of shallow geothermal wells in the Twin Falls area makes this area one of the best characterized stratigraphically, and a prime location to explore for higher temperature resources at depth (*Street and deTar, 1987; Lewis and Young, 1989; Baker and Castelin, 1990*). The drill site lies south of the Snake River where groundwater flow is dominated by water that originates in the 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 30ºC to 72ºC, with the highest temperature occurring along the Buhl-Berger lineament. High temperatures are also found in the Kimberly area (up to 55ºC) near our drill site (*Baker and Castelin, 1990).*

Stratigraphy in the Twin Falls area is well-defined by exposed sections and by well data that extend to depths of 700 mbs. The oldest volcanic rocks in region are ash flow tuffs and pyroclastic deposits of the Idavada Group (*circa* 10-12 Ma); these have been subdivided into more detailed local units, but may be conveniently grouped together here for discussion *(e.g., Street and DeTar 1987; McCurry et al, 1996; Bonnichsen et al 2008).* These are commonly overlain by fine-grained lacustrine sediments (mudstone, shale, siltstone) that are generally correlated with the Glenns Ferry Formation (*Street and DeTar 1987)*.

Overlying this in places is the Twin Falls rhyolite, also known as the Shoshone Falls rhyolite, a circa 6.5 Ma lava flow that is exposed in the Snake River Canyon from Shoshone Falls in the east to west of the Perrine Bridge in Twin Falls (*Bonnichsen et al 2008)*. The Twin Falls rhyolite lava flow varies from zero to 150 m thick. Where it is exposed in the Snake River Canyon north of Twin Falls, the upper surface is an exhumed paleo-flow top marked by ogives and ramp structures. We interpret this unit to represent a post-caldera rhyolite flow erupted from ring fractures along a caldera margin that is now buried by younger basalt flows. Similar caldera-margin lavas are well-known in other eruptive centers, most notably the Yellowstone caldera *(e.g., Christiansen, 2001).* These ring fractures are our proposed target for fluid up flow.

This sequence is overlain by 100-300 m of basalt, commonly with a thin horizon of fine- to medium grained fluvial sediments separating the rhyolite from the basalt. Where the Twin Falls rhyolite lava flow is not present, lake sediments continue upwards to the base of the basalt. This succession is well-documented in water wells and geothermal wells through the region, with the contact of "rhyolite" underlying sediment (all that can be discerned from most drillers records) varying in elevation from as low as 2300 feet above sea level (650 m asl) to a high of 3400 feet asl (1100 m asl) (see appendix).

We have compiled and mapped surface structural elements in a region surrounding Twin Falls between about longitudes 114ºW and 115.6ºW and latitudes 42º-43ºN (Figure 5). Lineaments were identified from existing geologic maps, from lineations in the shaded relief map, or from offsets in contours that define lineaments (Figure 5). Using the live GeoMapApp projection, sun illumination angles were altered to enhance the visibility of lineaments with different orientations.

The lineaments form three groups, based on orientation and location (Figure 5). West of Buhl and north of the Bruneau-Jarbidge eruptive center, the lineaments trend approximately 275º-285º, or roughly parallel to range front faults in the western SRP *(e.g., Shervais et al 2002; Wood and Clemens, 2002)*. Lineaments with these trends also form the northern border of the Bruneau-Jarbidge eruptive center *(Bonnichsen et al 2008).* South and west of this region, the lineaments trend more northerly (~325º), including those within the Bruneau-Jarbidge eruptive center (Figure 5). This includes the Buhl-Berger lineament identified by *Street and DeTar (1987),* which cuts Berger Butte and may control its elongate shape. Finally, lineaments in the Cassia Mountains and in the Rogerson graben trend ~NS to 005º, more or less parallel to regional basin and range trends. There are some exceptions to these groups: Hansen Butte near Kimberly appears to be cut by an EW-trending fault, and there are many small cross-faults within the Cassia Mountains.

Overall, the pattern suggests a transition from western SRP orientations in the NW to Basin-and-Range orientations in the south. For the most part these lineaments represent normal faults that offset topography, and many form small graben that can be in both the topographic map and in the shaded relief map. The lineaments are more common where the underlying basement rock is older (rhyolite, lake sediments, or Paleozoic sediments), less common where underlain by Tertiary basalt, and essentially absent in areas covered by Quaternary basalts. This relationship implies that the faulting itself is older than Quaternary, and most likely formed coevally with the western SRP graben and Basin-and-Range extension. We note, however, that the absence of surface manifestations of these faults in the Quaternary basalts does not mean that they are absent in the subsurface. Indeed, it seems likely that since some faults are present in the late Pliocene age basalts, faulting continued up to the Pliocene-Pleistocene boundary, and that faults with these same orientations are likely to underlie the younger Quaternary basalts. The orientation of Rock Creek Canyon south of Twin Falls is subparallel to the Berger Butte trend, suggesting that the course of this creek is itself control by pre-existing fractures.

Also shown on the 10 m DEM topographic map are measured flow directions for ash-flow tuffs in the Cassia Mountains, as mapped by *McCurry et al (1996),* along with the southern extent of these ash-flow sheets (Figure 5). These flow directions are based on hundreds of field measurements and document clearly a source vent located north of the central Cassia Mountains, in the vicinity of Kimberly, Idaho. As we noted earlier, post-caldera rhyolite flows are exposed in the Snake River Canyon NW of Kimberly, suggesting that the now buried southern margin of the caldera vent which erupted these ash flows is somewhere near Kimberly, and that the central vent lay somewhere north of Kimberly. The inferred boundary of the Twin Falls caldera complex is shown on Figure 5 as a dashed white line.

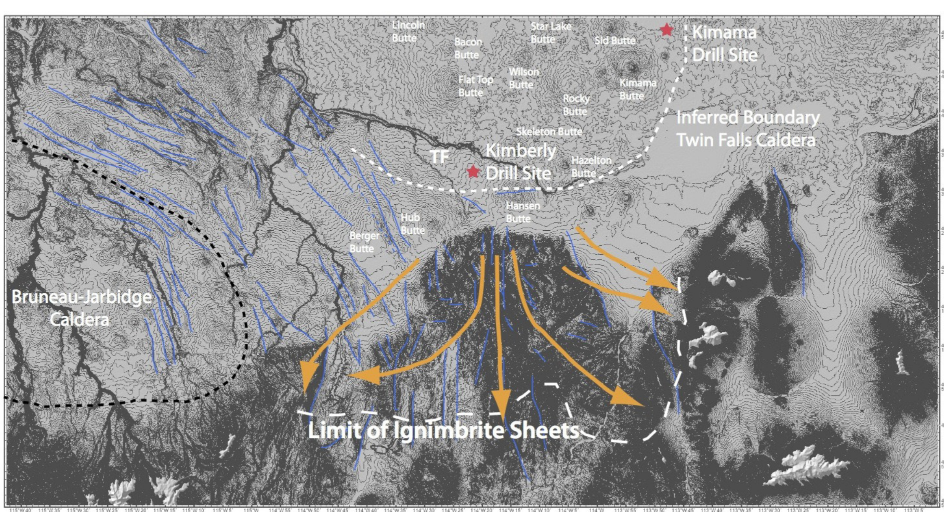

Figure 5. Shaded relief-topographic map with 10m contour interval from NASA 10m DEM. Blue lines show mapped faults from published data or lineaments mapped from DEM data. Yellow lines show flow directions in ash flow sheets, short dashed line shows inferred margin of Twin Falls eruptive complex. TF= Twin Falls.

In order to clarify the possible location of the source vent for the Cassia Mountains ash-flow tuffs, we produced a Bouguer gravity map of the central SRP covering an area slightly larger than the 10 m DEM topographic map. The Bouguer gravity map is characterized by low gravity along the margins corresponding to sediment-filled basins, rhyolite ash flows, or Paleozoic carbonate basement (Figure 3B). The pronounced gravity high to the west continues beneath the western SRP, and may represent a buried horst block within the WSRP graben (see section on Mountain Home drill site for detailed discussion of the western SRP gravity structure). North of Twin Falls is a prominent gravity low surrounded by a rim of slightly higher gravity material (dashed white line). We interpret this structure to represent a buried caldera complex associated with eruption of the ash flow tuffs. The Kimberly drill site lies along the southern margin of this structure, which lies more-or-less where we predicted it based on geologic mapping. We also note that the Kimama drill site lies along the NE margin of this same structure, and we may find analogous fracture porosity at that site (Figure 3B).

The area underlain by the ring-like structure is covered with a more-or-less uniform carapace of Quaternary basalts, so it cannot be interpreted to result from the distribution of surface basalt flows. The relative density contrast, the shape, and the size of this structure are all consistent with its interpretation as a buried eruptive complex *(e.g. Morgan et al 1984)*. It also lies in the appropriate location for the source vent of the Cassia Mountain ash-flows. Richard Smith of INL developed the concept of using gravity to locate buried caldera complexes in the mid-1990's, which he applied to the eastern SRP with some success *(Smith et al 1994)*. We believe that his approach will also work in the central SRP and provides an innovative way to see below the thick carapace of basalt, and to test the geothermal potential of these ring fracture systems.

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: Figure 18) have documented elevated temperatures at depth that are close to those needed to sustain geothermal development, and elevated groundwater temperatures are found in some areas *(Lewis and Stone 1988; Arney 1982; Arney et al 1982, 1984)*. A prominent gravity anomaly in the regional Bouguer gravity map has been shown near Boise to represent an uplifted horst block in the subsurface *(Wood, 1994)*. This same gravity high extends to the east beneath Mountain Home.

The primary science goal of the Mountain Home drill core is to assess the geothermal potential under Mountain Home AFB, building on results from a geothermal test well drilled in 1985-86 *(Lewis and Stone, 1988)*. The previous geothermal test well had a BHT of 93ºC, but it was not possible to perform a pump test due to the hole size. Our goals for this hole are to first sample basalts and lacustrine sediments in the upper 300 m of the section, which were not sampled by the existing Mountain Home Air Force Base (MH-AFB) MH-1 test hole, and second to deepen this hole with sufficient bore to carry out a robust flow test of the hydrothermal waters.

Mountain Home AFB sits on the southern edge of this prominent gravity anomaly, as can be seen in the more detailed Bouguer gravity map in Figure 6. This gravity high that has been interpreted by *Shervais et al (2002)* to represent a buried horst block with the larger western SRP graben. This interpretation is consistent with reflection seismic data from Boise-Caldwell area that documents a buried horst block below the Glenns Ferry formation *(Wood 1994)*. Confirming this interpretation requires that we run new seismic reflection surveys in the area adjacent to MH-AFB; these surveys are planned for September 2010. Figure 6 shows the positive gravity anomaly that lies just north of the base, along with planned seismic reflection profiles. These reflection profiles should delineate basement structure in some detail and lead to a clearer understanding of the nature of the prominent positive gravity anomaly.

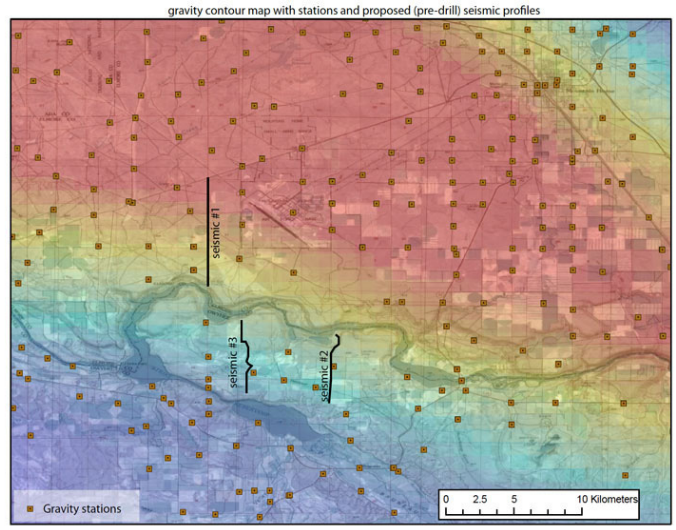

Figure 6. Gravity contour map of Mountain Home, Idaho, region (western SRP), with gravity stations shown, along with seismic traverse lines. Proposed drill site sits on southern edge of inferred horst block in subsurface.

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 volcanic active regions with high heat flow offer significant geothermal energy potential, and many of these areas have not been explored for economic resources. However, the application of traditional geophysical methods can be problematic -- especially in bi-modal volcanic terranes where young basalts impede seismic wave transmission and present challenges to detailed interpretations.

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 to [1] identify new geothermal resources in the undeveloped Snake River Plain region, or failing that, to [2] characterize the thermal regime at depth in such a way as to further exploration goals in more focussed 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 2011)*, high resolution seismic surveys *(e.g., Liberty 1998; Liberty et al 1999; Janik and Liberty 2004; Bradford et al 2006)*, vertical seismic profiles of the wells *(Schmitt xxxx)*, and high-resolution gravity and magnetic surveys *(Glen and Ponce, 2002; Glen et al, 2006)*.

We are using a combination of traditional geologic tools (geologic mapping, petrologic studies, and geochemical investigations of rocks and suppress 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 are currently underway and will be reported at a later date, when they are complete. At this time, the Kimama well has been competed at 1912 meters (6275 feet) and Kimberly completed to 1958 m (6423 feet). The aquifer was found to be three times thicker than elsewhere (1000 meters; 3300 feet), suppressing the thermal gradient. Nonetheless, temperatures of 70-80ºC were noted after drilling and are expected to rise as equilibrium is approached. Further preliminary results are report in this volume *(Kessler and Evans, 2011; Potter et al 2011; Sant et al 2011)*.

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References

Arney, B.H., 1982, Evidence of former higher temperatures from alteration minerals, Bostic 1-A well, Mountain Home, Idaho, *Geothermal Resources Council Trans*., 6, 3-6.

Arney, B.H., F. Goff, and Harding Lawson Ass., 1982, Evaluation of the hot dry rock geothermal potential of an area near Mountain Home, Idaho, Los Alamos Nat. Lab Report LA-9365-HDR, 65 pp.

Arney, BH, Gardner JN, Belluomini, SG, 1984, Petrographic Analysis and Correlation of Volcanic Rocks in Bostic 1-A Well near Mountain Home, Idaho, Los Alamos Nat. Lab Report LA-9966-HDR, 37 pp.

Baker, SJ, and Castelin, PM, 1990, Geothermal resource analysis in Twin Falls County, Idaho, Part II; in *Geothermal Investigations in Idaho,* Idaho Dept. Water Resources, Water Information Bulletin No. 30, Part 16, 36 pages.

Blackwell, DD and M. Richards. 2004. Geothermal Map of North America. Amer. Assoc. Petroleum Geologists, Tulsa, Oklahoma, 1 sheet, scale 1:6,500,000.

Blackwell, DD, 1978, Heat flow and energy loss in the western United States, in *Cenozoic Tectonics and Regional Geophysics of the Western Cordillera,* Memoir 152, eds. R. B. Smith, and G. P. Eaton, Geol. Soc. Am., Boulder, CO.

Blackwell, DD, 1980, Geothermal-gradient and heat-flow data, pp. 23-29, in Preliminary geology and geothermal resource potential of the Western Snake River Plain, Oregon, eds. D. E. Brown, G. D. McLean, G. L. Black, and J. F. Riccio, Ore. DOGAMI Open File Rep. 0-80-5, Portland.

Blackwell, DD, 1989, Regional implications of heat flow of the Snake River Plain, northwestern United States: *Tectonophysics*, v. 164, p. 323-343.

Blackwell, DD, Steele, J.L., and Carter, L.C., 1989, Heat flow data base for the United States, in Hittleman, A.M., Kinsfather, J.O., and Meyers, H., eds., Geophysics of North America CD-ROM, Boulder, Colo, Natl. Oceanographic and Atmospheric Adm., Natl. Geophys. Data Center.

Blackwell, DD, JL Steele and LS Carter, 1991, Heat flow patterns of the North American continent: A discussion of the DNAG geothermal map of North America, in D.B. Slemmons, E.R. Engdahl, and D.D. Blackwell eds., Neotectonics of North America, Geol. Soc. Amer. DNAG Decade Map Volume 1, 423-437.

Blackwell, DD, SA Kelley, and JL Steele, 1992, Heat flow modeling of the Snake River Plain, Idaho, Dept. of Geological Sciences, Southern Methodist Univ, US Dept of Energy Contract DE-AC07-761DO1570, 109 pp.

Bonnichsen, B., Leeman, W., Honjo, N., McIntosh, W., and Godchaux, M., 2008, Miocene silicic volcanism in southwestern Idaho: geochronology, geochemistry, and evolution of the central Snake River Plain: *Bulletin of Volcanology*, v. 70, no. 3, p. 315-342.

Bradford, J., Liberty, L.M., Lyle, M.W., Clement, W.P., and Hess, S.S., 2006, Imaging complex structure in shallow seismic-reflection data using prestack depth migration, *Geophysics*, v. 71, p. B175-B181.

Brott, CA, DD Blackwell, and JC Mitchell, 1976, Heat flow study of the Snake River Plain region, Idaho, p. 195 pp., in *Geothermal Investigations in Idaho*, Idaho Dept. Water Resour., Water Info. Bull., 30 (8).

Brott, CA, DD Blackwell, and JC Mitchell, 1978, Tectonic implications of the heat flow of the western Snake River Plain, Idaho, *Geol. Soc. Am. Bull*., 89, 1697-1707, 1978.

Brott, CA, DD Blackwell, and JP Ziagos, 1981, Thermal and tectonic implications of heat flow in the eastern Snake River plain, Idaho, *J. Geophys. Res.*, 86, 11709-11734, 1981.

Brown, DE, GD McLean, and GL Black, 1980, Preliminary geology and geothermal resource potential of the western Snake River plain, Oregon, Oregon Dept. Geol. Min. Indus, Open-File Rep O-80-5, 114p.

Brown, DW, 2000, A Hot Dry Rock Geothermal Energy Concept Utilizing Supercritical CO2 Instead of Water, Proceedings of the TwentyFifth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, Jan. 24–26, 2000, Paper SGPTR165.

Christiansen, RL, 2001, The Quaternary and Pliocene Yellowstone Plateau Volcanic Field of Wyoming, Idaho, & Montana, Geology of Yellowstone National Park, U.S. Geological Survey Professional Paper 729, 1-156.

Cooke, MF, Shervais, JW, Kauffman, JD and Othberg, KL, 2006a, Geologic Map of the Dietrich Butte Quadrangle, Lincoln County, Idaho: Idaho Geological Survey, Moscow Idaho, DWM-63 scale 1:24,000.

Cooke, MF, Shervais, JW, Kauffman, JD and Othberg, KL, 2006b, Geologic Map of the Dietrich Quadrangle, Lincoln County, Idaho: Idaho Geological Survey, Moscow Idaho, DWM-66 scale 1:24,000.

Cooke, M., 1999, Petrology, Geochemistry, and Hydrology of basaltic volcanism, Central Snake River Plain, Idaho, M.Sc. Thesis, University of South Carolina, 1999.

DeRaps, M., 2009, Basaltic volcanism: surface flows and core, Western Snake River Plain, Idaho, M.Sc. Report, Utah State University, 2009.

Embree, GF, Lovell, MD, and Doherty, DJ, 1978, Drilling data from Sugar City Exploration Well, Madison County, Idaho, USGS Open File Report 79-1095, columnar section, scale ca. 1:120, one sheet.

Fleischmann, DJ, 2006, Geothermal development needs in Idaho, Geothermal Energy Association publication for the Department of Energy, 51 pp.

Ge, S., 1998, Estimation of groundwater velocity in localized fracture zones from well temperature profiles, *Journal of Volcanology and Geothermal Research,* v. 84, , p. 93-101.

Geist, D, Teasdale, R, Sims, E, and Hughes, S, 2002, Subsurface volcanology at TAN and controls on groundwater flow, *GSA Special Paper 353*, 45-59.

Genter, A., Traineau, H., 1996, Analysis of macroscopic fractures in granite in the HDR geothermal well EPS-1, Soultz-sous-Forêts, France, *Journal of volcanology and geothermal research*, vol. 72, no1-2, pp. 121-141.

Glen JMG and Ponce DA, 2002, Large-scale fractures related to inception of the Yellowstone hotspot: *Geology*, v. 30, p. 647–650.

Glen JMG, Payette S, Bouligand M, Helm-Clark C, Champion D, 2006, Regional geophysical setting of the Yellowstone Hotspot track along the Snake River Plain, Idaho, USA. EOS Trans. AGU, 87(52), V54-1698.

Goodwillie A. and Ryan B., 2009, User Guide for GeoMapApp version 2, Lamont-Doherty Earth Observatory, Columbia University, http://www.geomapapp.org

Hackett, W.R., R.P. Smith, and Soli Khericha, 2002, Volcanic hazards of the Idaho National Engineering and Environmental Laboratory, southeast Idaho, in Bill Bonnichsen, C.M. White, and Michael McCurry, eds., *Tectonic and Magmatic Evolution of the Snake River Plain Volcanic Province:* Idaho Geological Survey Bulletin 30, p. 461-482.

Hobson, V.R., 2009, Remote sensing of basaltic volcanics, Central Snake River Plain, Idaho, M.Sc. Report, Utah State University, 2009.

James, D, Roth, J, Fouch, M, and Carlson, R, 2009, Upper mantle velocity structure of the Pacific Northwest: Implications for geodynamical processes during the late Cenozoic, Abstract, Earthscope National Meeting, Boise Idaho, 12-15 May 2009; http://www.iris.edu/hq/esreg/page/abstracts.

Janik, A., Lyle, M., and Liberty, L.M., 2004, Seismic expression of Pleistocene paleoceanographic changes in the California Borderland from digitally acquired 3.5 kHz subbottom profiles and Ocean Drilling Program Leg 167 drilling: Journal of Geophysical Research, v. 109.

Johnson, TM, RC Roback, TL McLing, TD Bullen, DJ DePaolo, C. Doughty, RJ Hunt, RW Smith, L. DeWayne Cecil, and MT Murrell. 2000. Groundwater 'fast paths' in the Snake River Plain aquifer: Radiogenic isotope ratios as natural groundwater tracers. *Geology* 28, (10) (Oct): 871-874.

Kauffman, JD, Othberg, KL, Gillerman, VS, Garwood, DL, 2005a, Geologic Map of the Twin Falls 30x60 minute Quadrangle, Idaho: Idaho Geological Survey, Moscow Idaho; DWM-43, Scale: 1:100,000.

Kauffman, JD, Othberg, KL, Shervais, JW, Cooke, MF, 2005b, Geologic Map of the Shoshone Quadrangle, Lincoln County, Idaho: Idaho Geological Survey, Moscow Idaho; DWM-44, Scale: 1:24000.

Kessler, James A.; Evans, James P., 2011, Fracture Distribution in Slimholes Drilled for Project Hotspot: The Snake River Geothermal Drilling Project and the Implications for Fluid Flow. Geothermal Resources Council Transactions, vol. 35, in press.

Kucks, R.P., 1999, Bouguer gravity anomaly data grid for the conterminous US: in, U.S. Geological Survey, National geophysical data grids; gamma-ray, gravity, magnetic and topographic data for the conterminous United States: U.S. Geological Survey Digital Data Series DDS-9.

Kuntz, M. A., 1992, A model-based perspective of basaltic volcanism, eastern Snake River plain, Idaho, in Link, Kuntz, and Platt, eds., *Regional geology of eastern Idaho and western Wyoming*, Memoir 179: Boulder, Co, Geological Society of America, p. 289-304.

Kuntz, MA, Champion, DE, Spiker, EC, Lefebvre, RH, and McBroome, LA, 1982, The great rift and the evolution of the Craters of the Moon lava field, Idaho: Idaho Bureau of Mines and Geology, Bulletin v. 26, p. 423-437.

Kuntz, M.A., Skipp, Betty, Champion, D.E., Gans, P.B., Van Sistine, D.P., and Snyders, S.R., 2007, Geologic map of the Craters of the Moon 30' x 60' quadrangle, Idaho: U.S. Geological Survey Scientific Investigations Map 2969, 64-p. pamphlet, 1 plate, scale 1:100,000.

Lewis RE, and HW Young, 1989, The Hydrothermal System in Central Twin Falls County, Idaho, USGS Water-Resources Investigations Report 88-4152, 44 pages.

Lewis, RE, and Stone, MAJ, 1988, Geohydrologic data from a 4,403-foot geothermal test hole, Mountain Home Air Force Base, Elmore County, Idaho: U.S. Geological Survey Open-File Report 88-166, 30 p.

Liberty, L.M., 1998, Seismic reflection imaging of geothermal aquifer in urban setting, Geophysics, 1285-1294.

Liberty, L.M., W.P. Clement, and M.D. Knoll, 1999, Surface and borehole seismic characterization of the Boise Hydrogeophysical Research Site, Proc. Environmental and Engineering Geophysical Society, 723-732.

Lindholm, G.F., 1996, Summary of the Snake River regional aquifer-system analysis in Idaho and eastern Oregon: U.S. Geological Survey Professional Paper 1408-A, 59 p.

Matthews, S., 2000, Geology of the Owinza Butte, Shoshone SE, and Star Lake Quadrangles: Snake River Plain, Southern Idaho, M.Sc. Thesis, University of South Carolina, 2000.

Matthews, SH, Shervais, JW, Kauffman, JD, & Othberg, KL, 2006a, Geologic Map of the Star Lake Quadrangle, Jerome and Lincoln Counties, Idaho: Idaho Geological Survey, Moscow Idaho, DWM-67 scale 1:24,000.

Matthews, SH, Shervais, JW, Kauffman, JD, & Othberg, KL, 2006b, Geologic Map of the Shoshone SE Quadrangle, Jerome and Lincoln Counties, Idaho: Idaho Geological Survey, Moscow Idaho, DWM-62 scale 1:24,000.

McCurry, M., Watkins, AM, Parker, JL, Wright, K, and Hughes, SS, 1996, Preliminary volcanological constraints for sources of high-grade rheomorphic ignimbrites of the Cassia Mountains, Idaho: Implications for the Evolution of the Twins Falls Volcanic Center. *Northwest Geology*, vol. 26, 81-91.

McLing, Travis L., Robert W. Smith, and Thomas M. Johnson. 2002. Chemical characteristics of thermal water beneath the eastern Snake River Plain; Geology, Hydrogeology, and Environmental Remediation; Idaho National Engineering And Environmental Laboratory, Eastern Snake River Plain, Idaho. Geological Society of America SP353: 205-211.

Morgan LA, 1990, Lithologic description of the "Site E Corehole" Idaho National Engineering Laboratory, Butte County, Idaho; US Geological Survey Open File Report OF-90-487, 7 pp.

Morgan LA, Doherty DJ and Leeman WP, 1984, Ignimbrites of the eastern Snake River Plain: Evidence for major caldera-forming eruptions: *Journal of Geophysical Research*, v. 89, no. B10, 8665-8678.

Morse, L.H., and McCurry, M., 2002, Genesis of alteration of Quaternary basalts within a portion of the eastern Snake River Plain aquifer: *Geological Society of America Special Paper 353*, pp. 213-224.

Nathenson, M, TC Urban, WH Diment, and NL Nehring, 1980, Temperatures, heat flow, and water chemistry from drill holes in the Raft River geothermal system, Cassia County, Idaho, U.S. Geol. Surv. Open-File Report. 80-2001., 1980.

Neely, KW and Galinato, G, 2007, Geothermal power generation in Idaho: an overview of current developments and future potential, Open File Report, Idaho Office of Energy Resources, 18 pp.

Neely, KW, 1996, Production history for the four geothermal district heating systems in Boise, Idaho, Geothermal Resources Council Transactions, vol. 20, pp. 137-144.

Nielson, Dennis L., Delahunty, Chris, and Shervais, John, 2011, Coring and Temperature Measurements in the Snake River Plain (Hot Spot) Project, Idaho. Geothermal Resources Council Transactions, vol. 35, in press.

Obrebski, M., R. M. Allen, M. Xue, and S.-H. Hung (2010), Slab-plume interaction beneath the Pacific Northwest, *Geophys. Res. Lett.*, 37, L14305, doi:10.1029/2010GL043489.

Paillet, F.L., 1999, Geophysical reconnaissance in bedrock boreholes--finding and characterizing the hydraulically active fractures, in Morganwalp, D.W. and Buxton, H.T., eds., U.S. Geological Survey Toxic Substances Hydrology Program--Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999: U.S. Geological Survey Water-Resources Investigations Report 99-4018C, v. 3, p. 725-733.

Paillet, F.L., 2000, Using borehole wireline methods to delineate fracture flow paths in bedrock formations (Chapter 7), in Inyang, H.I., and Bruell, C.J., eds., Remediation in rock masses: Reston Vir., American Society of Civil Engineers.

Pierce, KL, Morgan, L.A, and Saltus, RW, 2002, Yellowstone Plume Head: Postulated Tectonic Relations to the Vancouver Slab, Continental Boundaries, and Climate, in: Bonnichsen B., White C., and McCurry M., eds., *Tectonic and magmatic evolution of the Snake River Plain volcanic province*, Idaho Geological Survey Bulletin 30. Moscow, ID, United States, p. 5-33.

Peng, X and ED Humphreys, 1998, Crustal velocity structure across the eastern Snake River plain and the Yellowstone Swell. *Journal of Geophysical Research, B,* Solid Earth and Planets 103(4): 7171-7186.

Peterson, S., Widner, L. and Nelson, JR, 2004, Estimated Impacts Of Proposed Idaho Geothermal Energy Projects Department of Agricultural Economics and Rural Sociology, A.E. Extension Series No. 04-01.

Potter, Katherine E.; Shervais, John W.; Sant, Christopher J., 2011, Project Hotspot: Insight into the Subsurface Stratigraphy and Geothermal Potential of the Snake River Plain. Geothermal Resources Council Transactions, vol. 35, in press.

Sanyal, SK and SJ Butler, 2005. An Analysis of Power Generation Prospects From Enhanced Geothermal Systems. Geothermal Resources Council Transactions, 29.

Sherman, FB, 1982, Characterization of the geothermal resources of southeastern Idaho, pp. 76-87, in Geothermal Direct Heat Program Roundup Technical Conference Proceedings, ed. C. A. Ruscetta, Earth Sci. Lab., Univ. of Utah, DOE/ID/12079-71.

Shervais, J.W., and Hanan, B.B., 2008, Lithospheric topography, tilted plumes, and the track of the Snake River-Yellowstone Hotspot, Tectonics, 27, TC5004, doi:10.1029/2007TC002181.

Shervais, JW and Vetter, SK, 2009, High-K Alkali Basalts of the Western Snake River Plain: Abrupt Transition from Tholeiitic to Mildly Alkaline Plume-Derived Basalts, Western Snake River Plain, Idaho, *Journal of Volcanology and Geothermal Research*, doi:10.1016/j.jvolgeores.2009.01.023.

Shervais, J.W., Vetter, S.K., and Hackett, W.R., 1994, Chemical Stratigraphy of Basalts in Coreholes NPR-E and WO-2, Idaho National Engineering Laboratory, Idaho: Implications for Plume Dynamics in the Snake River Plain, in Proceedings of the VIIth International Symposium on the Observation of Continental Crust Through Drilling, Santa Fe, New Mexico, 1994, 93-96.

Shervais, JW, Shroff G, Vetter SK, Matthews S, Hanan BB, and McGee JJ, 2002, Origin and evolution of the western Snake River Plain: Implications from stratigraphy, faulting, and the geochemistry of basalts near Mountain Home, Idaho, in: Bonnichsen B., White C., and McCurry M., eds., *Tectonic and magmatic evolution of the Snake River Plain volcanic province*, Idaho Geological Survey Bulletin 30. Moscow, ID, United States, p. 343-361.

Shervais, J.W., Kauffman, J.D., Gillerman, V.S., Othberg, K.L., Vetter, S.K., Hobson, V.R., Meghan Zarnetske, M., Cooke, M.F., Matthews, S.H., and Hanan, B.B., 2005, Basaltic Volcanism of the Central and Western Snake River Plain: A Guide to Field Relations Between Twin Falls and Mountain Home, Idaho; in J. Pederson and C.M. Dehler, Guide to Field trips in the western United States, Field Guide volume 6, Geological Society of America, Boulder Colorado, 26 pages.

Shervais, J.W., Branney, M.J., Geist, D.J., Hanan, B.B., Hughes, S.S., Prokopenko, A.A., Williams, D.F., 2006a, HOTSPOT: The Snake River Scientific Drilling Project – Tracking the Yellowstone Hotspot Through Space and Time. *Scientific Drilling*, no 3, 56-57. Doi:10.2204/iodp.sd.3.14.2006.

Shervais, J.W., Vetter, S.K. and Hanan, B.B., 2006b, A Layered Mafic Sill Complex beneath the Eastern Snake River Plain: Evidence from Cyclic Geochemical Variations in Basalt, *Geology*, v. 34, 365-368.

Shervais, JW, Cooke, MF, Kauffman, JD, and Othberg, KL, 2006c, Geologic Map of the Owinza Quadrangle, Lincoln County, Idaho, Idaho Geological Survey, Moscow Idaho: Idaho Geological Survey, Moscow Idaho, DWM-64 scale 1:24,000.

Shervais, JW, Cooke, MF, Kauffman, JD, and Othberg, KL, 2006d, Geologic Map of the Owinza Butte Quadrangle, Jerome and Lincoln Counties, Idaho: Idaho Geological Survey, Moscow Idaho, DWM-65 scale 1:24,000.

Smith, R.P., Josten, N.E., and Hackett, W.R., 1994, Upper crustal seismic and geologic structure of the eastern Snake River Plain: Evidence from drill holes and regional geophysics at the Idaho National Engineering Laboratory (INEL); EOS, v.75, no.44, p.685.

Smith, Richard P., David D. Blackwell, and Travis L. McLing. 2002. Ground water flow, aquifer geometry, and geothermal interactions inferred from temperature distribution; Snake River Plain Aquifer, South-Eastern Idaho; Geological Society Of America, 2002 annual meeting. Abstracts w Programs 34, (6).

Smith, RP, 2004, Geologic Setting of the Snake River Plain Aquifer and Vadose Zone, *Vadose Zone Journal*, Vol. 3, 47–58.

Smith, RP, DD Blackwell, TL McLing, and MJ Rohe, submitted, Temperature distribution, aquifer geometry, and groundwater flow in the Snake River Plain aquifer, Eastern Snake River Plain, Idaho.

Street, LV and RE DeTar, 1987, Geothermal Resource Analysis in Twin Falls County, Idaho, in *Geothermal Investigations in Idaho*, IDWR Water Information Bulletin No. 30, Part 15, 46 pages.

Waite GP, Smith RB and Allen RM, 2006, V_P and V_S structure of the Yellowstone hot spot from teleseismic tomography: Evidence for an upper mantle plume. *Jour Geophysical Research*, 111, B04303.

Whitehead, RL, Lindholm, GF, 1985, Results of geohydrologic test drilling in the eastern Snake River Plain, Gooding County, Idaho: *U.S. Geological Survey Water Resources Investigations Report* 84-4294, 30 p., 1 plate.

Wood, S. H., 1994, Seismic expression and geological significance of a lacustrine delta in Neogene deposits of the western Snake River plain, Idaho, *AAPG Bulletin*, 78, 1, 102-121.

Wood, SH and DM Clemens, 2002, Geologic and tectonic history of the western Snake River Plain, Idaho and Oregon, in Idaho Geological Survey Bulletin 30, p. 69-103.

Xue, M. and Allen, RM, 2010, Mantle structure beneath the western United States and its implications for convection processes, *Journal Of Geophysical Research*, Vol. 115, B07303, doi:10.1029/2008JB006079, 2010