PROCEEDINGS, Thirty-Ninth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 24-26, 2014
SGP-TR-202

Conceptual Model for Snake River Plain Geothermal Systems

Dennis L. NIELSON and John W. SHERVAIS

Geoscience Technology & Engineering, LLC, 2075 S. Pioneer Rd, Salt Lake City, UT 84104

dnielson@dosecc-ex.com

Department of Geology, Utah State University, Logan UT

john.shervais@usu.edu

Keywords: basalts, layered mafic intrusions, buried geothermal system, core drilling, temperature while drilling

ABSTRACT

The Snake River Plain (SRP) is part of the largest heat flow anomaly in the US. It is characterized by thick sequences of young flood basalts that have erupted following the passage of the Yellowstone plume. However, apart from the obvious hydrothermal systems in the Yellowstone caldera, only a few small high-temperature hydrothermal systems are known, and these are located on the margins of the province. This observation is consistent with conventional wisdom that suggests basaltic provinces are poor targets for geothermal exploration because the low viscosity of basalt results in rapid flow to the surface along narrow conduits rather than forming shallow magma chambers that are large enough to support high-temperature fluid convection. Slim-hole exploration drilling (MH-2) at Mountain Home Air Force Base has intersected fluids with temperature of about 150^{O} C at a depth of 1745 m. The fluids flowed to the surface through 60 mm pipe at a rate of 42 liters/minute. Comparison with results of a 1986 exploration well (MH-1) in the same area suggests that the system has a lateral extent of at least 5 km. No dikes or sills are present in the core from MH-2; however, a prominent gravity high that trends obliquely across SRP may represent either a basement horst block, basalt sill complex or both. Water chemistry and fluid inclusions also document high temperatures (140-195°C) and chemical equilibrium with basalt or andesite. We propose that heat is provided by a sill complex of *Layered Mafic Intrusions* (LMI) that underlie the axial portion of the SRP, roughly delineated by the gravity high. While individual intrusions have limited heat capacity, the intrusion of multiple LMI sills into the same crustal levels will heat the surrounding country rock and prepare the ground for future intrusions.

INTRODUCTION

The Snake River Plain (SRP) volcanic province (Fig. 1) is part of the largest heat flow anomaly in the US (Blackwell and Richards, 2004). The SRP lies north of the Basin and Range province, which hosts active geothermal systems in northern Nevada and central Utah. It is subdivided into eastern (ESRP) and western (WSRP) segments that have different structural orientations and geologic histories. The ESRP represents the track of the Yellowstone hotspot – a deep-seated mantle plume that has remained relatively fixed in space as the North American plate moved to the southwest (Smith et al., 2009). As the plate moved over the plume, a number of large silicic caldera complexes formed through melting of continental crust. As the magma chambers beneath these calderas solidified and were able to sustain brittle fracturing, basalts were able to reach the surface and form the extensive lava flows that are seen today. In the ESRP relatively young felsic volcanics occur east of the Great Rift (e.g., Big Southern Butte), but none are found west of the rift (~W113.5º).

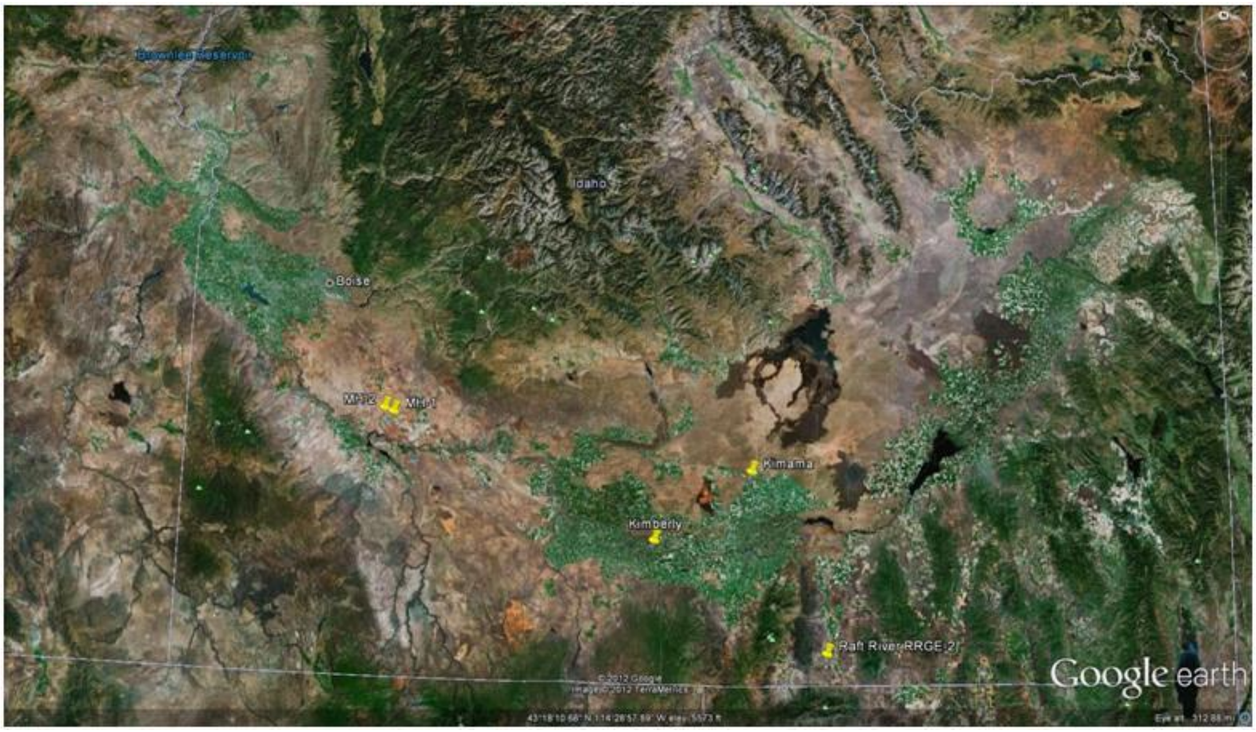

Figure 1. Image of the Snake River Plan showing holes drilled by the Hotspot project. Raft River is also shown for reference.

The WSRP lies to the north of the presumed plume track and is controlled by northwest-trending structures that are distinct from the Basin and Range faulting and probably related to reactivation of Cordilleran structures. No rhyolite volcanism younger than 9 Ma is present. Resurgent basalt volcanism (900-200 ka or less) formed long after the plume passed, driven by back-flow of plume material to the West. This resurgent basalt volcanism is plume-derived and postulated to be associated with delamination of subcontinental lithospheric mantle (Shervais and Vetter, 2009).

Although the SRP demonstrates young volcanic activity that is both widespread and voluminous, there has been relatively little geothermal exploration. We believe that this is the consequence of the lack of hot spring activity (except on the margins of the province) and the largely basaltic nature of the volcanism. Basaltic terrains are not generally considered to be viable exploration targets for high-temperature geothermal systems. Smith and Shaw (1975) pointed out that basalt is channeled rapidly from depth to the surface through fractures forming dikes that cool rapidly. In contrast, rhyolitic magmas commonly form chambers in the shallow crust and are therefore more capable of providing a larger and longer-lived heat source for hydrothermal circulation.

However, there are well documented hydrothermal geothermal systems in areas of basaltic volcanism without associated rhyolites. The south eastern rift of Kilauea Volcano on the island of Hawaii hosts the Puna geothermal system. Active extension and dike intrusion provides a continuous source of basaltic magma. Teplow et al. (1994) document a dacite melt intersected by injection well KS-13 at depth of 2480 to 2488 m in the Puna field. Although there are no exposed flows of dacitic composition, the authors speculate that this dacite has differentiated from basalt. They have calculated that the magma intersected by drilling had a temperature of about 1050o C, and on the basis of thermal arguments, they suggest a body with a minimum circular dimension of 1 km and a thickness of at least 100 m.

Another well documented geothermal system specifically related to basaltic volcanism is located on the Reykjanes peninsula in Iceland (Fridleifsson et al., 2014). The character of the heat source has yet to be determined, but it is hypothesized to be either a sheeted dike complex or a major gabbroic intrusive body. Drilling in the Krafla field, where there is young rhyolite volcanism, intersected magma of rhyolite composition. Petrologic studies have shown that the magma was formed through the partial melting of altered basalt (Elders et al., 2011; Zierenberg et al., 2013).

Worldwide, the most extensive hydrothermal activity related to basaltic volcanism is the venting (Black Smokers) associated with submarine spreading centers. The hydrothermal activity occurs in narrow zones above axial magma chambers (Alt, 1995).

A common feature of the above examples of active hydrothermal systems related to basaltic heat sources is the presence of a high-level magma chambers that have sufficient volume and longevity that they can sustain convective circulation. As the above examples also show, felsic melts may be formed through partial melting or differentiation, and these rocks may not be exposed at the surface.

THE SNAKE RIVER VOLCANIC PROVINCE

Within the SRP, a number of studies have presented evidence for high-level basaltic magma chambers (sill complexes). Young basaltic volcanism is present throughout the region, with vents as young as 200 ka or less in the western SRP (Shervais et al., 2002; White et al., 2002; Shervais and Vetter, 2009), and ≤2,000 years old in the eastern SRP (Kunz et al, 1982; Shervais et al, 2005). Additional observations include:

Documentation of a mafic sill or sill complex in the mid-crustal region beneath both the eastern and western SRP by seismic methods (e.g., Pakiser and Hill, 1967; Peng and Humphries, 1997).

Geochemical evidence for a layered mafic sill complex beneath both the eastern and western SRP, based on fractionation-recharge cycles in basalt flows sampled as drill core (Shervais et al., 2006).

The Graveyard Point Sill, exposed near the southern margin of the western SRP, documents a single layered basaltic sill up to 160 m thick (White, 2009) confirming the existence of sills inferred from seismic data and lava chemistry.

High-resolution gravity mapping by the USGS defines an ~EW trending gravity high that lies at an oblique angle to the axis of the WSRP; this gravity high has been interpreted as a horst block, and may be cored by a mafic sill complex (Shervais et al., 2002; 2013). The alignment of this gravity high is approximately parallel to a fault system mapped north of Mountain Home, which lies at an oblique angle to the range front fault system (Shervais et al., 2002).

Further support for the presence of a sill complex comes from olivine gabbro xenoliths in basalt from Sid Butte, which lies just a few km west of the Kimama drill site (Matthews, 2000). These xenoliths have modes and compositions appropriate for basalt fractionation at mid-crustal levels and suggest that basalts found on the surface were processed through this sill complex.

HOTSPOT PROJECT

The Hotspot project was designed to investigate the geothermal potential of the SRP through slim-hole coring and scientific evaluation at three sites (Figure 1; Shervais et al., 2012). These are located at Kimama in the center of the ESRP; at Kimberly near the southern margin of the ESRP; and at Mountain Home Air Force base in the central part of the WSRP. Both the Kimberly and Mountain Home sites are located in areas that have warm wells and hot springs; whereas, the Kimama site has neither surface nor subsurface thermal manifestations. The coring operations and temperature measurements have been discussed in detail (Delahunty et al. 2012; Nielson et al., 2012). The Kimberly hole demonstrated that low-temperature resources along the southern flank of the SRP can have considerable depth extent and are higher volume than previously anticipated. The overall architecture of this large low-temperature system deserves further investigation; however, for this presentation, we wish to focus on the results of the holes at Kimama and Mountain Home.

The temperature profile of the Kimama hole is shown in Figure 2. Based on regional relationships, this hole was expected to encounter older volcanic rocks of rhyolite composition at a depth of approximately 1200 m. However, the hole was drill to a total depth of 1913 m and completed through a stacked sequence of horizontal basalt flows with only thin sedimentary layers present. The Kimama hole doubled the known thickness of the fresh water Snake River aquifer that has a measured temperature of 13^o to 17^o C. Beneath the thermal masking effect of the aquifer, a conductive temperature gradient of ~75^o C/Km was measured.

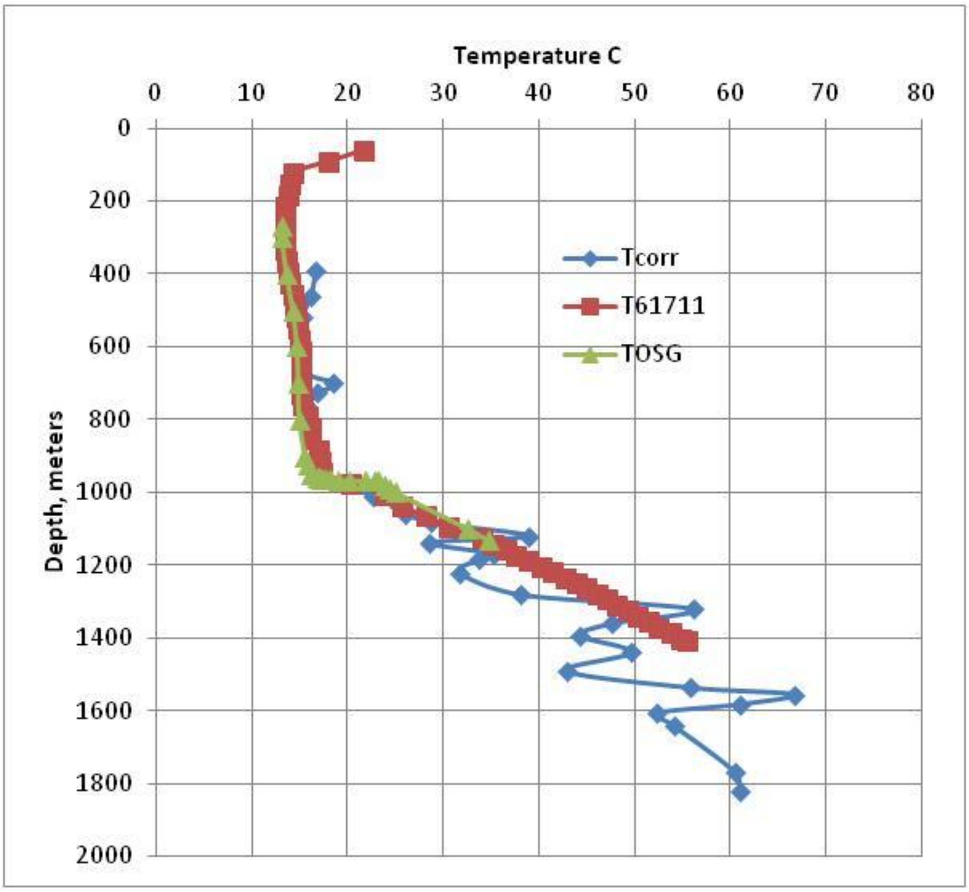

Figure 2. Temperature with depth for the Kimama corehole. Tcorr are data collected during drilling, T61711 is data collected 6 months after drilling and Tosg is data collected by the Operational Support Group of ICDP. See Nielson et al., 2012 for further discussion.

In 1986 a geothermal test well (MH-1) was drilled at Mountain Home AFB to a depth of 1342 m (Lewis and Stone, 1988; Armstrong et al., 2012). MH-1 had a maximum measured temperature of 93^{o} C at 1219 m. The Hotspot hole (MH-2) was located 4.7 km to the northwest of MH-1. The temperature depth measurements from MH-1 are shown in Figure 3 and closely follow those from MH-2.

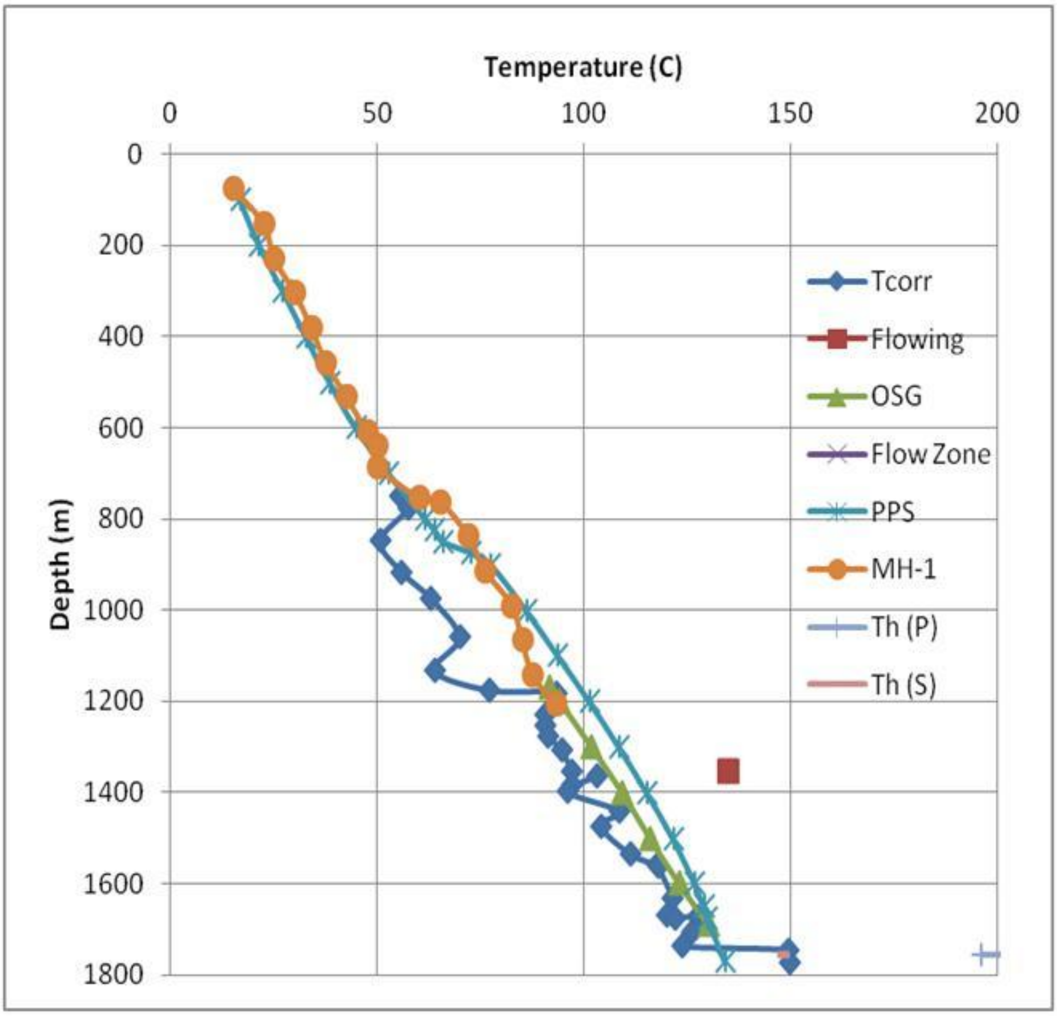

Figure 3. Temperature with depth for MH-2 at Mountain Home Air Force Base. Tcorr was measured during drilling. OSG was measured by the Operational Support Group of ICDP. PPS was measured by Pacific Process Systems. Flowing temperature was measured while the well was flowing to the surface. Th (P) and Th (S) are primary and secondary fluid inclusion measured by J. Moore. The temperature profile for well MH-1 is also shown.

MH-2 reached total depth of 1821.4 m. During the coring, mud returns were lost at 1745 m where artesian flow to the surface was also encountered. Our bottom hole temperature probe shows a corrected temperature of 149.4^{o} C at 1745 m and 1772 m. However, this temperature exceeds the limit of our probe, and the data was extrapolated from the buildup curve. In order to continue coring, the hole was treated with mud and lost circulation material that effectively stopped the artesian flow.

The core from MH-2 is presently being logged in detail; however, a brief inspection shows some interesting features. We wanted to determine the character of the flow zone encountered at 1745 m, but core recovery through this interval was poor and there were no clear indication of the character of the faults that cut the zone. In the course of this inspection, we identified hydrothermal breccias (Nielson et al. 2012) that are typical jigsaw puzzle breccias whose voids have been partially filled by quartz + calcite (bladed) and include pyrite and chalcopyrite. A late filling of crystalline laumontite forms a coating but does not completely fill the voids. Hydrothermal brecciation indicates that P-T conditions were along the boiling point curve suggesting temperatures of formation of about 340^{o} C with cooling to the present observed 134^{o} to 150^{o} C.

While the well was flowing, a temperature probe was suspended in the hole at 1355.1 m and measured 134.6^{o} C. The flow at the surface through NQ pipe (60.3 mm inner diameter) was estimated at 42 liters/minute. Samples of the fluid were analyzed (Lachmar et al., 2012) and geothermometers indicate temperatures of 140-195°C and water that is in equilibrium with basalt or andesite. In order to continue coring, the hole was treated with mud and lost circulation material that effectively stopped the artesian flow.

Beneath 213 m of basalt, the hole encountered a sequence of fine-grained sedimentary rocks of laccustrine origin to a depth of 847 m. Below this, the lithology to the bottom of the hole is dominated by basalt and basaltic sediment; no dikes or sills were encountered (Shervais et al., 2012) We wanted to determine the character of the flow zone encountered at 1745 m, but core recovery through this interval was poor and there were no clear indication of the character of the faults that cut the zone. In order to resolve this issue, a televiewer log was run in the hole; however the temperature exceeded the tool's limit, so it was only possible to log above the flow zone. The primary fracture orientation is N80W, approximately parallel the gravity high (Kessler and Evans, 2011).

The temperatures measured in MH-2, the presence of hydrothermal brecciation and the apparent size (4.7 Km strike length) implies that the system has a magmatic association (Nielson, 1993). It is also important to state that the coring has just intersected the top of the geothermal zone, so the lateral extent, thickness and temperature of the reservoir has not been fully determined.

Geologic mapping in MH area document two fault systems that offset Pliestocene-age and older lavas: (a) faults sub-parallel and related to the N55-60W trending range front fault system, and (b) coeval and younger faults that trend ~N80W; these faults are subparallel to trend of the gravity high. These faults commonly intersect, with offsets that suggest both systems active simultaneously.

CONCEPTUAL MODEL OF MOUNTAIN HOME GEOTHERMAL SYSTEM

We propose that the Mountain Home Geothermal System derives its enthalpy from a layered basaltic sill complex in the middle to upper crust. The SRP basaltic sill complex is long-lived because (a) each individual sill is ~100-200 m thick, and (b) the intrusion of multiple sills into the same level of crust pre-heats this crust, minimizing heat loss from subsequent intrusions. Basaltic sills tend to pond at levels of neutral buoyancy (Ryan, 1987), and subsequent intrusions will also cluster near this level, at or just above previously intruded sills.

Conduits for heated fluids are provided by N80W faults that have been mapped at the surface and measured by borehole imaging in MH-2. These faults trend essentially parallel to the long axis of the gravity high, which is interpreted to represent an uplifted horst block. The location and orientation of these faults are thought to be controlled by the distribution of sill complexes within the crust: crust modified by sill intrusion will tend to act as a rigid block, localizing strain along its margins. Because the horst block lies near the axis of the western SRP, these conduits conduct fluid upwards far from the range front system.

The thick section of fine-grained sediment in the upper part of the Mountain Home section is thought to provide a cap on the geothermal system. This cap both prevents the system from discharging at the surface and serves to seal the system against the ingress of cold water as was observed at the Kimama site.

CONCLUSIONS

If this conceptual model is valid, we may expect to find similar temperature resources and fracture systems in the western SRP associated with both the northern and southern flanks of the gravity high, and possibly over the central part of the high where cross-faults are indicated. This model may also apply to the eastern SRP, which has a well-imaged crustal sill complex, gabbro xenoliths in basalt that show processing of magma through crustal magma chambers, and very young basaltic volcanism (≤2 ka) documenting an active magmatic system. The eastern SRP also features thick sections of fluvial and lacustrine sediments adjacent to the axial volcanic high which could serve as a seal for the geothermal system, and prevent the influx of cold groundwater over the system. These geothermal plays should be assessed quantitatively in light of this model, and may constitute a significant recoverable geothermal resource.

Acknowledgements: Drilling funding was provided by the U. S. Department of Energy (DE-EE0002848), the International Continental Scientific Drilling Program; additional support for drilling at Mountain Home AFB was provided by the U. S. Air Force Air Combat Command.

REFERENCES

Alt, J. C.: Subseafloor processes in mid-ocean ridge hydrothermal systems, in AGU Geophysical Monograph **91**, (1995), 85-114.

Blackwell, D. D. and Richards, M.: Geothermal map of North America: American Association of Petroleum Geologists. (2004)

Delahunty, C., Nielson, D. L. and Shervais, J. W.: Deep core drilling of three slim geothermal holes, Snake River Plain, Idaho: Geothermal Resources Council Transactions, **36**, (2012), 641-648.

Elders, A., Friðleifsson, G. Ó., Zierenberg, R.A., Pope, E. C., Mortensen, A. K., Guðmundsson, Á., Lowenstern, J.B., Marks, N.E., Owens, L, Bird, D. K., Reed M., Olsen N.J., and Schiffman, P.: Origin of a rhyolite that intruded a geothermal well while drilling at the Krafla volcano, Iceland,. *Geology*, **39**, (2011), 231-234.

Fridleifsson, G. O. et al.: Preparation for drilling well IDDP-2 at Reykjanes: Geothermics, **49**, (2014), 119-126.

Kessler, J. A. and Evans, J. P.: Fracture distribution in slim holes drilled for Project Hotspot, *Geothermal Resources Council Transactions,* **35**, (2011), 839-842.

Kuntz, M.A., Champion, D.E., Spiker, E.C., Lefebvre, R.H., and McBroome, L.A.: The great rift and the evolution of the Craters of the Moon lava field, Idaho: Idaho Bureau of Mines and Geology, *Bulletin*, **26**, (1982), 423-437.

Lachmar, T. E., Freeman, T. G., Wood, T. R., Shervais, J. W., and Nielson, D. L.: Chemistry and thermometry of geothermal water from Mountain Home test well MH-2B: preliminary results: Geothermal Resources Council Transactions, **36**, (2012), 689-692.

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

Nielson, D.L.: The temperature-volume relationship in convective hydrothermal systems: Geothermal Resources Council Transaction, **17**, (1993), 437-442.

Nielson, D. L., Delahunty, C. and Shervais, J. W.: Geothermal systems in the Snake River Plain, Idaho, characterized by the Hotspot project: Geothermal Resources Council Transactions, **36**, (2012),727-730.

Ryan, M. P.: Elasticity and contractancy of Hawaiian olivine tholeite and its role in the stability and structural evolution of subcaldera magma reservoirs and rift systems: USGS Professional Paper 1350, (1987), 1395-1447.

Shervais, JW and Vetter, SK,: 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, (2009) 141-152.

Shervais, J.W., Shroff, G., Vetter, S. K., Matthews, S., Hanan, B.B., and McGee, J.J.: 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. M., and McCurry, M., eds., Tectonic and Magmatic Evolution of the Snake River Plain Volcanic Province: Idaho Geological Survey Bulletin **30**, (2002), 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.: Basaltic Volcanism of the Central and Western Snake River Plain: A Guide to Field Relations Between Twin Falls and Mountain Home, Idaho; in Pederson, J. and Dehler, C.M., Guide to Field trips in the western United States, Field Guide **6**, Geological Society of America, Boulder Colorado, (2005), 26 p.

Shervais, J. W., Nielson, D. L., Evans, J. P., Christensen, E. J., Morgan, L., Shanks, W. C., Delahunty, C., Schmitt, D. R., Liberty, L. M., Blackwell, D. D., Glenn, J. M., Kessler, J. E., Potter, K. E. Jean, M. M. Sant, C. J., Freeman, T. G.: Hotspot: The Snake River geothermal drilling project – initial report: Geothermal Resources Council Transactions, **36**, (2012), 767-772.

Smith, R. L. and Shaw, H. R.: Igneous-Related geothermal systems, in White, D. E. and Williams, D. L. (eds.) Assessment of geothermal resources of the United States - 1975, U. S. Geological Survey Circular 726, (1975), 58-83.

Smith, R. B. et al,: Geodynamics of the Yellowstone hotspot and mantle plume: seismic and GPS imaging, kinematics, mantle flow: J. Volc. Geothermal Research, **188**, (2009), 26-65.

Teplow, W., Marsh, B., Hulen, J., Spielman, P. Kaleikini, M., Fitch and Rickard, W.: Dacite melt at the Puna Geothermal Venture well field, Big Island of Hawaii: Geothermal Resources Council Transactions, **33**, (2009), 989-994.

White, C.M.:The Graveyard Point Intrusion: an Example of Extreme Differentiation of Snake River Plain Basalt in a Shallow Crustal Pluton. Journal of Petrology, **48**, (2007), 303-325.

Zierenberg, R.A., Schiffman, P., Barfod, G. H., Lesher, C. E., Marks, N., Lowenstein, J.B., Mortensen, A. K., Pope, E. C., Bird, D. K., Reed, M. H., Friðleifsson G.Ó. and Elders, W. A.: Composition and origin of rhyolite melt intersected by drilling in the Krafla geothermal field, Iceland, Contributions to Mineralogy and Petrology, **165**, (2013), 327-347.