# Enhanced Geothermal System Potential for Sites on the Eastern Snake River Plain, Idaho

**Robert Podgorney[1], Mike McCurry[2], Tom Wood[1], Travis McLing[1],
Ahmad Ghassemi[3], John Welhan[4], Greg Mines[1], Mitch Plummer[1],
Joe Moore[5], Jerry Fairley[6], and Rachel Wood[7]**

**[1]Idaho National Laboratory**
**[2]Idaho State University**
**[3]Oklahoma University**
**[4]Idaho Geological Survey**
**[5]Energy and Geoscience Institute, University of Utah**
**[6]University of Idaho**
**[7]Washington State University**

***Keywords***

*Enhanced Geothermal System, Snake River Plain, groundwater, modeling, heat flow*

## Introduction

The Snake River volcanic province overlies a thermal anomaly that extends deep into the mantle and represents one of the highest heat flow provinces in North America (Blackwell and Richards, 2004). This makes the Snake River Plain (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 SRP 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 the mid-crustal sill complex (e.g., Blackwell, 1989).

## Geologic Setting

Geology of the Eastern Snake River Plain (ESRP) is dominated by the Yellowstone-Snake River Plain hot spot track (Figure 1). The ESRP is a northeast trending shallow physiographic depression (~0.5 km) and deep structural sag (~5 km) that cuts across the north to northwest trending Basin and Range Province (e.g., Pierce and Morgan, 1992; Rodgers et al., 2002; Smith et al., 2009). It is bounded on northern and southern margins by inward dipping early Miocene volcanic and sedimentary deposits and Mesozoic to Paleozoic sedimentary deposits of the Cordilleran miogeocline.

The plain is underlain by up to 2 km of Holocene to early Pliocene basalt lavas (Kuntz et al. 1992; Whitehead, 1992). The basalts were erupted from numerous widely scattered shield volcanoes and from NW trending volcanic rifts. The volcanic rifts root into systems of dikes that appear to have also acted to accommodate regional crustal extension of the plain (Kuntz et al., 2002; Rodgers et al., 1990). Detailed studies of basalt core at INL indicate that basalt lavas have accumulated at nearly constant rates in that area for the last 4 m.y. (Champion et al., 2002).

Coalesced shield and rift-related basalt lavas periodically dammed stream drainages, in particular from the northern margin of ESRP. As a result fluvial, lacustrine and eolian sedimentary deposits are intercalated with the basalts in many areas, particularly close to the margins of the plain (e.g., Geslin et al., 2002; Bestland et al., 2002; Houser, 1992).

Geologic controls to the thermal state of the crust are mainly related to magma transfer and storage processes. With some notable exceptions (e.g. Craters of the Moon, and Cedar Butte) ESRP basalts are nearly primitive in composition indicating that they had little residence time in the crust prior to their eruption (Leeman et al., 2009; Kuntz et al., 1992). However 1-3% of the lavas, such as Craters of the Moon and Cedar Butte, are highly chemically evolved (McCurry et al., 2008). Petrological, geochemical and experimental work indicates that these basalts evolved while residing in the crust and experienced extreme polybaric fractional crystallization of primitive basalt magma, some which occurred at shallow crustal levels (Putirka et al., 2009; McCurry et al., 2008). They may constitute thermal anomalies within a larger, already hot region of crust (McCurry and Welhan, 2012).

**Figure 1.** Location map of the Snake River Plain showing the proposed volcanic centers and their relative ages.

Basalts overlie voluminous rhyolitic ignimbrites and lava flows. The latter erupted from a series of diachronous, time-transgressive volcanic fields in genetic association with the Yellowstone mantle plume (Figure 1). Although rhyolites are largely obscured by burial by younger basalts except along the margins of the ESRP, their extents and magnitudes are inferred from a combination of deep borehole data, regional geophysics and exposures of deposits along the margins of the ESRP.

Individual fields were active for 2-4 m.y., producing rhyolite accumulations of 1-5 km thick, mostly within nested caldera systems (e.g., Morgan and McIntosh, 2005; Bonnichsen et al., 2008). Limited borehole data at INL (INEL-1 and WO2; Doherty et al., 1979; McCurry and Rodgers, 2008) and Kimberley (Project Hotspot, Shervais et al., 2013; 2011) indicate that the rhyolite is relatively dense, and weakly to strongly hydrothermally altered. Additionally, recent petrologic and geochemical work suggests that greater intensity of hydrothermal of rhyolite occurred within many nested caldera systems, further reducing porosity and permeability (Bindeman et al., 2007; Watts et al., 2011).

Rhyolites have been used as probes of crustal energy and mass balances for the central and ESRP (Nash et al., 2006; McCurry and Rodgers, 2009; Leeman et al., 2008; Christiansen and McCurry, 2008). Based mainly upon isotopic arguments McCurry and Rodgers argue that an amount of basalt magma was added to the middle crust that was equivalent to a layer of gabbro 14 km thick. Leeman et al. arrived at a similar conclusion on the basis of independent petrologic, geochemical and energy balance arguments.

Deeper crustal structures and lithologies are likely dominated by shingled thrust faults of the Cordilleran fold and thrust belt, granitic plutons subjacent to buried calderas, and at lower levels by products of basalt-crust interaction and large-scale lower crustal flow (Rodgers and McCurry, 2009; Christiansen and McCurry, 2008; Yuan et al., 2010).

## Data Review

The ESRP has been studied extensively for more than 6 decades, largely from a perspective of water resource management, environmental remediation, and seismic activity associated with regional agriculture and historical missions at the INL. More recently, the ESRP has been the focus of interest for geothermal resources, being specifically identified as one of the most promising locations for EGS development (MIT, 2006). This section provides a discussion of some of the data that could be best to evaluate the feasibility and potential for EGS on the ESRP.

## Water Resources

Precipitation on the ESRP ranges from about 20 centimeters/year in the lower elevations in the west to about 35.5 centimeters/year in the higher elevations in the northeast. The majority of the water supply originates in mountains on the north and east sides of the basin, including the southern portion of the Yellowstone Plateau. Within the boundaries of the ESRP, rainfall is insufficient to support commercial levels of agriculture without irrigation that requires substantial diversions from surface and groundwater systems. The Snake River flows along the southern margin of the plain, fed by tributaries flowing out of the mountains on the south and east side of the plain. A few tributaries from the northern valleys flow into the Snake River, but many disappear through seepage into the permeable Snake River Plain basalts.

Beneath the ESRP lies the prolific Eastern Snake River Plain Aquifer (SRPA), which covers approximately 28,000 square kilometers of eastern Idaho. It has been declared a sole source aquifer by the U.S. Environmental Protection Agency, due to the nearly complete reliance on the aquifer for drinking water supplies in the area. The aquifer is considered to be unconfined but may locally respond as a confined aquifer during short duration pumping. This is presumably due to vertical stratification and the presence of lower permeability sediments interbedded among the basalt layers.

Groundwater recharge occurs mainly in the north and east portions of the plain, resulting in generally southwest trending flow lines. Natural discharge from the aquifer occurs primarily along two reaches of the Snake River where the collective discharge is about 150 cubic meters per second. The SRPA is hosted in layered basalts with sediment occasionally deposited between layers. Highly fractured rubble zones at the contacts between layers provide the primary conduit for ground-water flow. The aquifer has a very high transmissivity, and routinely delivers yields exceeded several thousand gallons per minute to individual production wells, often with little measured drawdown, which has very positive implications for working fluid and cooling water options. The thickness of the SRPA is shown on Figure 2 (Whitehead, 1992).

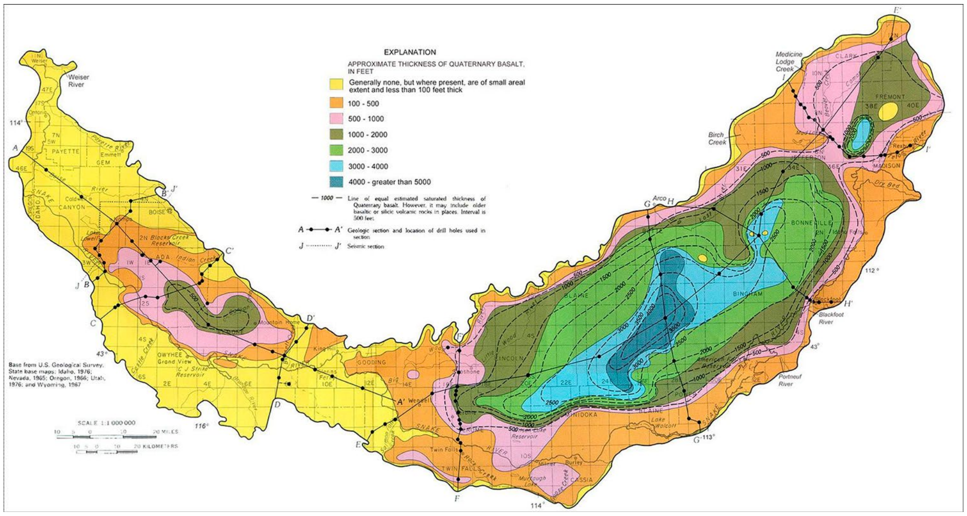

**Figure 2.** Thickness of the SRPA from Whitehead, 1992.

## Subsurface Temperatures and Heat Flow

Only a few deep exploration wells extend to depths sufficient to completely penetrate the base of the ESRP aquifer, and it is only these holes that provide information on aquifer thickness. For those drill holes that penetrate the entire thickness of the aquifer (Figure 3) the inflection point in the temperature gradient beneath the relatively isothermal section can be used to identify the effective base of the aquifer, the depth at which the regional

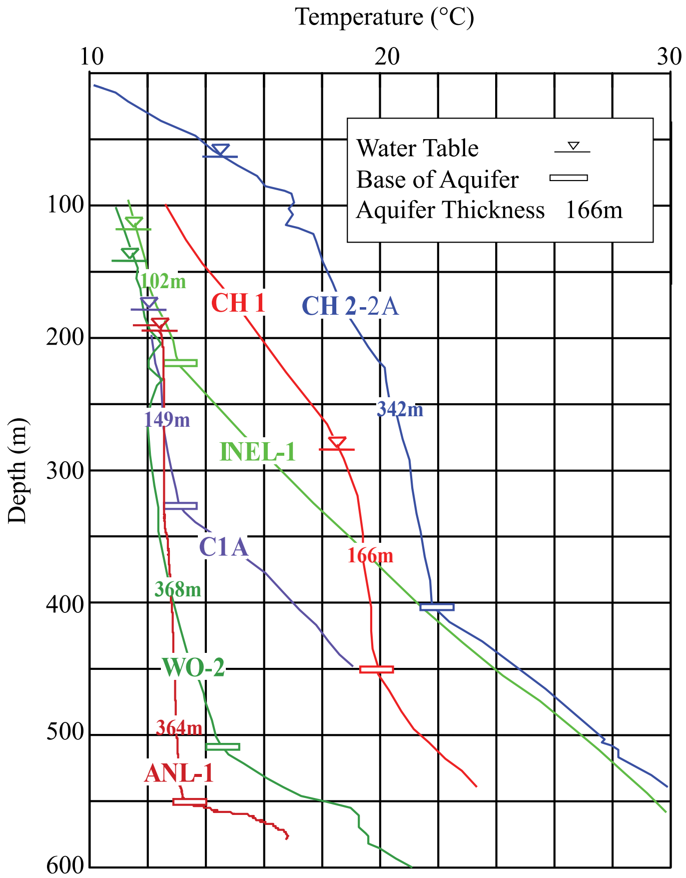

**Figure 3.** Temperature logs from selected deep wells on the ESRP.

conductive geothermal gradient is unaffected by movement of cool aquifer waters.

The lack of vertical variation in temperature is interpreted to be the result of a fast-moving flow of water in the highly transmissive upper aquifer. As illustrated in Figure 3, the bottom of the isothermal section is usually abrupt, and below that depth the gradient increases to reflect the conductive transfer of heat from the deep crust and upper mantle. Below the aquifer, measured heat fluxes are approximately 110 milliwatts/m2 (Blackwell et al. 1992). The nearly constant measured heat flow over large areas of the ESRP (on a kilometric scale) supports the idea of conductive heat flow from great depth (Blackwell and Steele 1992). The abrupt transition from "isothermal" to conductive gradient (temperature inflection point) corresponds to the upper limit of alteration and mineralization of basalts, as evidenced in drill cores for several wells (Morse and McCurry 2002). The abrupt transition is coincident with the change in water chemistry described by McLing et al (2002).

The temperatures at depth below the active ground water system are some of the highest estimated for the United States. As shown on Figure 4, temperatures in excess of 200 degrees C are expected for large portions of the ESRP at a depth of 3 km, which corresponds to geothermal gradients on the order of 45 to 60 degrees C/km. In addition, recent magnetotelluric (MT) data (Kelbert et al., 2012) suggest partial melt conditions may occur at depths as shallow as 15km, with an MT signature that resembles Yellowstone National Park in areas near the Great Rift of Idaho.

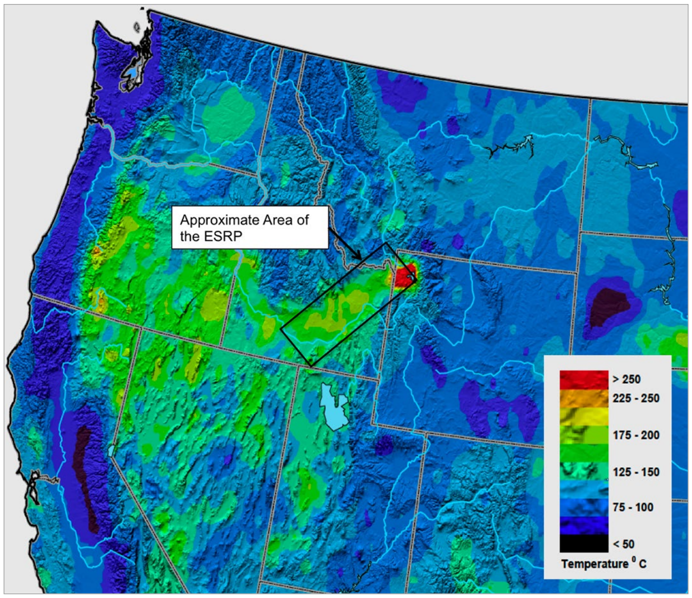

**Figure 4.** Estimated subsurface temperatures of a portion of the western United States at a depth of 3 km (from SMU temperature data, 2005).

The aquifer temperature distribution at the water table (Figure 5) can be mapped by using temperature-logging data from numerous groundwater wells in the ESRP. There is a concentration of wells in and near the INL Site, but many additional wells are distributed across the entire ESRP (Brott et al. 1978; Ziagos and Blackwell 1986). Figure 4 shows that the much of the central part of the aquifer, the background temperature is about 11 to 13ºC, punctuated by several anomalously warm and cool areas. The cool areas, with temperatures as low as 6ºC, occur near the Yellowstone Plateau and Island Park caldera recharge areas and in recharge areas originating in major drainages along the northern margin of the plain. Warm areas, in which temperatures reach about 18ºC or

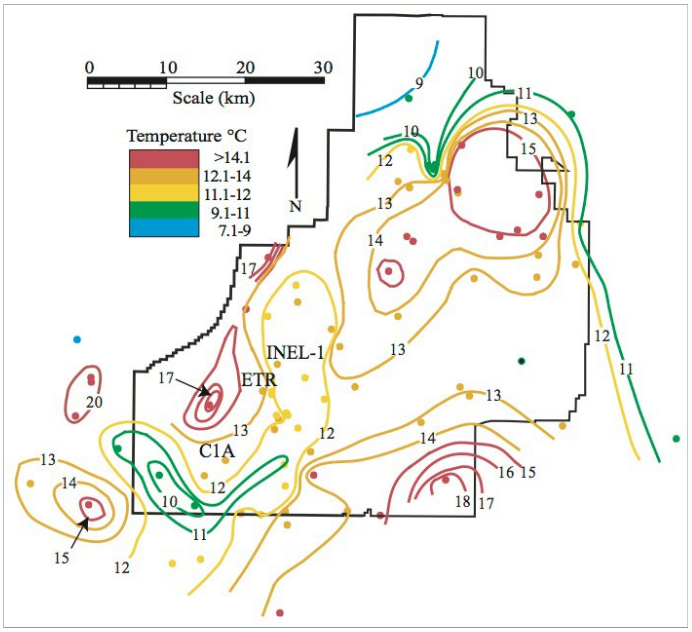

**Figure 5.** Locations at the INL of high geothermal activity as manifest by thermal anomalies in the aquifer (from McLing et al.).

greater at the water table, occur all along the margins of the ESRP, except in places where recharge from major drainages enter the system. The warm zone at the southeast corner of the INL Site (Figure 5) occurs along the axis of the ESRP, where interbeds are few, but where volcanic source areas with porous near-vent facies are abundant (Hackett and Smith 1992). In this instance, the aquifer temperatures may be affected by a strong geothermal circulation system below the cold portion of the aquifer. The interpretation that this thermal anomaly is caused by the presence of a strong geothermal circulation may imply that this area is a good target for geothermal exploration.

### *Tectonic Setting/Seismicity*

The INL operatives a seismic monitoring program that utilizes 27 permanent seismic stations for the purpose of determining the time, location, and size of earthquakes occurring in the vicinity of the INL. The seismic data are compiled to develop an historical database that defines the zones and frequency of earthquake activity. Seismic stations are located within and around the INL near potential earthquake sources that include major range-bounding normal faults and volcanic rift zones. Additionally, GPS receivers are co-located at 16 seismic stations for the purpose of determining rates of crustal deformation. GPS velocities are used to identify regions of higher crustal deformation rates (such as Yellowstone, Wyoming) relative to regions of lower deformation rates (e.g. Snake River Plain, Idaho). Interestingly, while some of the deepest open rifts in the world can be found on the Snake River Plain, more recent data from the GPS velocities suggest that large portions of the plain are isostatic to only minorly extensional. This also corresponds to observations in deep open coreholes that do not exhibit breakouts for as long as 20 years at depths of nearly 3 km.

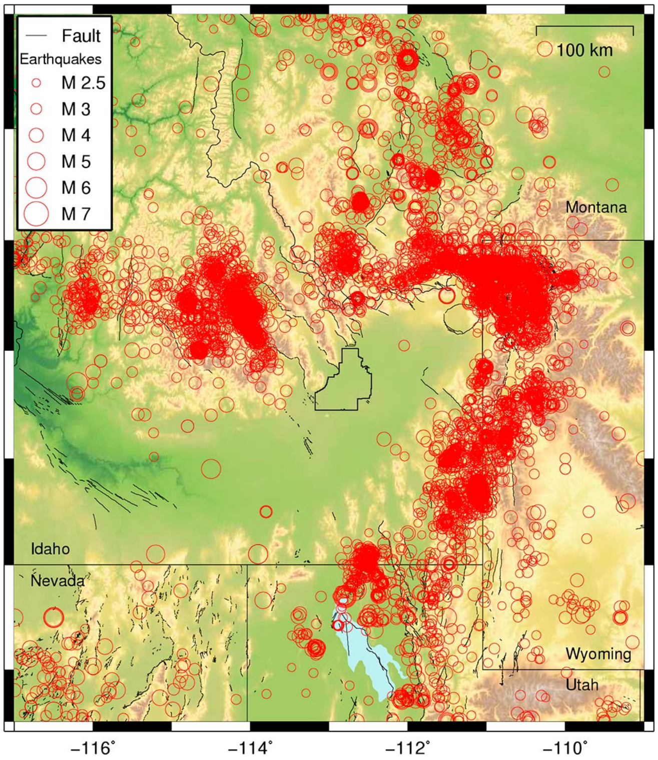

**Figure 6.** Map of earthquake epicenters from 1972 to 2010 in the vicinity of the ESRP (Carpenter et al., 2010)

In general, local earthquake activity is primarily restricted to the Basin and Range mountains surrounding the ESRP, with few earthquakes occurring within the ESRP (Figure 6). Even though micro-earthquakes ($M < 2.0$) occur within the ESRP, earthquake monitoring by the INL seismic network for the last 38 years indicates that the ESRP has been seismically inactive relative to the surrounding Basin and Range Province (Jackson et al., 1993b). Interestingly, the epicenter of the 1983 (magnitude 7.3) Borah earthquake was located about 100km from INL's nuclear facilities, but no significant damage occurred. This is attributed to the alternating layers of hard basalt and soft sediment that lie beneath the Snake River Plain. This attenuation reduces the seismic risk from natural and induced seismic occurrences.

### *Data Assimilation and Integration*

The data described above, along with other types and sources of information (gravity, magnetics, resistivity, MT, etc.) are being combined in what has been titled the "Virtual Snake River Plain" (Figure 7), a three-dimensional immersive environment where subsurface data can be viewed and analyzed in unique ways. The data are spatially integrated and projected on 4 sides of a 3 dimensional "Cube". The full usefulness is still being explored, but the immersive data environment allows for new and exciting avenues to explore the existing exploration data and to also help direct and plan for future data collection efforts.

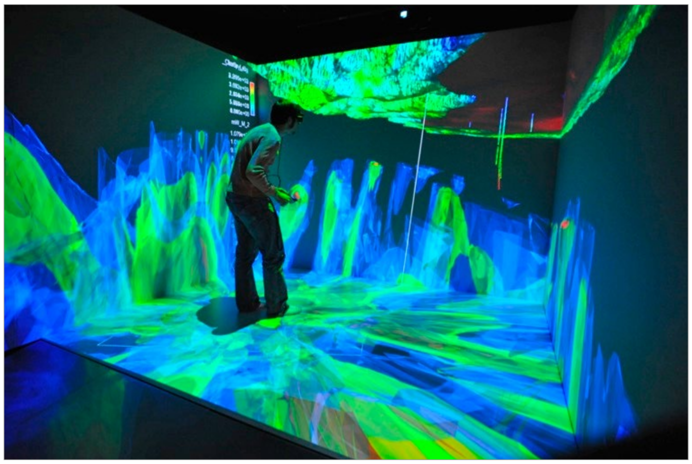

**Figure 7.** Researchers from INL and the Center for Advanced Energy Studies (CAES) are creating a "Virtual Snake River Plain" — a three-dimensional immersive environment where subsurface data from the Snake River Plain can be viewed and analyzed in unique ways.

## Preliminary EGS Evaluation

### *Well Drilling*

Exploration, production, and injection well drilling are major cost components of any geothermal project. Even for high-grade resources, they can account for 30% of the total capital investment; and with low-grade resources, the percentage increases to 60% or more of the total. The current state of the art in geothermal drilling is essentially that of oil and gas drilling, incorporating engineering solutions to problems that are associated with geothermal environments, i.e., temperature effects on instrumentation, thermal expansion of casing strings, drilling hardness, and lost circulation.

The steps in EGS reservoir development involve identifying a suitable site, creating the reservoir, and operating and maintaining the reservoir. Each step requires implementation of technologies specialized for the uniquely challenging geothermal environment (DOE, 2008).

The development of an EGS in Southeast Idaho will follow a stepwise process with the purpose of collecting sufficient information at each step to proceed in a cost effective manner to the next step. The process goal is to create an EGS reservoir that can operate economically. The logical steps that must be taken to complete an EGS economic reservoir project are: (1) finding a site; (2) creating the reservoir; and (3) operating the reservoir.

As a first order estimate of cost for EGS drilling at an ESRP site, the historical drilling and lithological data from INEL-1 (Mann, 1986) will be updated with modern drilling and simulation methods. This will form the basis for design and contracting of for EGS well drilling. Steps or decision points will be incorporated into the project-drilling plan to track and guide well drilling.

## *Geomechanical Modeling*

The proposed EGS provides a unique setting for investigation of geomechanical issues and coupled processes related to reservoir creation, stimulation, and sustainability. The development plan considers drilling and completion of a well through interlayered basalt and sediments (1500 feet) and altered basalt and rhyolite and/or welded ash flows in deeper zones Although, the rhyolite appears to be fairly competent as suggested by the lack of breakouts in the deep borehole was (drilled some 30 years ago), wellbore stability issues related to shear and dilation of natural fractures could be encountered. Therefore, drilling trajectory would need be optimized from both wellbore stability and future stimulation needs.

Geomechanical analysis and modeling will focus on site characterization and building an earth model for the proposed site to guide drilling and stimulation and MEQ interpretations. This is accomplished by integrating various data such as regional stress data, natural fracture data, and analysis of wellbore breakouts, etc. Regional geology is largely extensional, there are rift zones on the plane that run mostly east-west, and go as deep as 1000 feet or so. Drilling-induced crack and any new breakouts would be analyzed to ascertain the in-situ stress directions and to establish bounds on the stress magnitudes. The stress regime is likely to be heterogeneous in view of rock heterogeneity and structural variation within the systems. Therefore, large-scale geomechanical studies combined with well logs would be called upon to assess stress heterogeneity.

The earth model will be used as a basis to establish probable conceptual models for reservoir development strategy (wellbore trajectory, etc.) and the stimulation using coupled geomechanics/flow simulations. Different options such as a long vertical section and a lateral or a deviated borehole from a shallower depth to the target zone at 12000-15000 feet would be considered. A complete wellbore stability for fractured rock would be carried out taking into account thermal and poromechanical effects on intact rock and fractured that would be encountered while drilling.

Current plans call for a multistage fracture stimulation plan with a flow rate goal of 1000 gpm. Wellbore trajectory and the resulting zone of the stimulated volume will need to be fully assessed. The stimulation modeling will rely on field and lab rock mechanical data to analyze permeability enhancements and its evolution. Core samples from some of the deepest wells on the Plain are currently being studied.

## *Heat Flow/Resource Recovery Modeling*

A preliminary model for evaluating the energy recovery and long-term performance of the created geothermal reservoir will be constructed based upon the geomechanical modeled described above. The model will include an evaluation of pressure and temperature evolution in the created reservoir, and provide insight for the required number of simulation legs. This modeling is currently being developed and will be described in detail as part of the oral presentation.

## *Economic Evaluation*

With the projected 1,000 gpm of geothermal fluid flow and a resource temperature range of 175°C to 225°C, it is estimated that a binary plant designed for the application could produce 3 to 5 MW of power (with the higher output associated with the higher temperature resource). The installed cost for the binary plant is expected to be ~$3,250 for the 175°C resource and ~$2,750 for the higher temperature (225ºC) resource. The abundance of ground water on the Snake River Plain offers options for heat rejection that could allow more power to be produced and/or lower power plant capital costs. These options would explored as specific locations are evaluated for their resource potential.

The costs for drilling will significantly impact the project costs. This is especially true if extensive drilling is required to locate (exploration) and confirm the adequacy of a resource. Time also becomes an important factor due to its impact on costs to finance these activities. If it is assumed that existing wells on the Snake River Plain can be utilized to provide the information necessary to locate an EGS project, then these costs can be minimized, but not eliminated. Assuming costs of $2M for these non-drilling evaluation activities and all permitting activities, the remaining costs would be to provide a doublet (production and injection well and stimulated reservoir). Drilling costs are highly variable, especially in a location where there is little prior experience to build upon. Geothermal wells drilled to 4 km are estimated to cost ~$10M, while a well drilled to 5 km could cost ~$16M. This drilling cost would provide the incentive to use an existing well for either production or injection. Assuming that a well exists that could be re-worked at a cost equivalent to the difference between a 4 and 5 km well, it is estimated that the drilling costs associated with a doublet would be $16 – $22 M. Stimulation costs are estimated to be $2 -$3 M for the doublet. In total the costs to develop the doublet, with site evaluation, permitting surface piping and management/engineering, would be $20 - $30M. Though these costs would provide an impetus to use more efficient plants that would have a higher cost, it is not likely that the performance would be increased by much more than 10 to 20% of the output indicated using current conversion technologies.

Assigning the lower range of field costs to the 175ºC resource, the overnight capital costs for the project are expected to ~$10,000 per kW. Assigning the higher field costs to the 225ºC resource, the capital costs are expected to be ~$8,500 per kW. This lower cost directly a consequence of being able to produce more power from the higher temperature fluid.

## Summary and Conclusions

The geologic characteristics and evolution of the Eastern Snake River Plain are consistent with transfer of large amounts of magma advected heat at mid- to upper-crustal levels. We speculate that some of this heat is stored below surficial basalt lavas, within underlying dense, hydrothermally altered rhyolites that infill large nested calderas. Cryptic hydrothermal systems may occur within caldera-related fracture systems, or megabreccias near caldera collapse scarps. Blind hot zones are also possible below young chemically evolved volcanoes on the ESRP.

Other factors in addition to high temperatures and high heat flow that support EGS development are also prevalent on the ESRP. A number of deep exploration wells exist, and hundreds groundwater wells provide additional information on the character and makeup of the subsurface. The abundant cold groundwater resource can provide a significant heat sink for power generation, and also provide working fluid and makeup water as necessary. Regional stress and earthquake data suggest that the Plain is extensional to isotropic and "quiet".

The seismic risks of the eastern Snake River Plain have been extensively investigated because of the nuclear facilities at Idaho National Laboratory. The epicenter of the 1983 (magnitude 7.3) Borah earthquake was located about 100km (70 miles) from INL's nuclear facilities, but no significant damage occurred. This is attributed to the alternating layers of hard basalt and soft sediment that lie beneath the Snake River Plain. This attenuation reduces the seismic risk from natural and induced seismic occurrences.

Additional studies are currently underway to better understand the EGS potential for the eastern SRP. These include GIS and VSRP analysis of existing data, new geotechnical and geomechanical analysis of core samples, geochemical studies of water-rock interaction, and numerical modeling studies of fracturing, fluid flow, and heat recovery.

## References

Bestland, E. A., Link, P. K., Lanphere, M. A., & Champion, D. E. (2002). Paleoenvironments of sedimentary interbeds in the Pliocene and Quaternary Big Lost Trough (eastern Snake River Plain, Idaho). *Geological Society of America Special Paper*, *353*, 27–44.

Bindeman, I. N., Watts, K. E., Schmitt, A. K., Morgan, L. A., & Shanks, P. W. C. (2007). Voluminous low δ18O magmas in the late Miocene Heise volcanic field, Idaho: Implications for the fate of Yellowstone hotspot calderas. *Geology*, *35*(11), 1019. doi:10.1130/G24141A.1

Blackwell, DD. (1989). Regional implications of heat flow on the Snake River Plain, Northwestern United States. *Tectonphysics*, 164(2-4). pp. 323-343

Blackwell D.D. and M. Richards. (2004). Geothermal map of North America. AAPG, Tulsa OK, 1 sheet, Scale 1:6,500,000

Bonnichsen, B., Leeman, W. P., Honjo, N., McIntosh, W. C., & Godchaux, M. M. (2007). Miocene silicic volcanism in southwestern Idaho: geochronology, geochemistry, and evolution of the central Snake River Plain. *Bulletin of Volcanology*, *70*(3), 315–342. doi:10.1007/s00445-007-0141-6

Carpenter, S., S. Payne, J. Hodges, and R. Berg. (2010) INL seismic monitoring report annual report: January 1, 2010-December 31, 2010. INL/EXT-11-23143

Champion, D. E., Lanphere, M. A., & Kuntz, M. A. (2002). Accumulation and subsidence of late Pleistocene basaltic lava flows of the eastern Snake River Plain, Idaho. In P. K. Link & L. L. Mink (Eds.), *Geological Society of America Special Paper* (Vol. 353, pp. 175–192). Geological Society of America. Retrieved from http://books.google.com/books?hl=en&lr=&id=hQct9VqBmWQC&pgis=1

Christiansen, E. H., & McCurry, M. (2007). Contrasting origins of Cenozoic silicic volcanic rocks from the western Cordillera of the United States. *Bulletin of Volcanology*, *70*(3), 251–267. doi:10.1007/s00445-007-0138-1

Doherty, D. J., McBroome, L. A., & Kuntz, M. A. (1979) Preliminary geological interpretation and lithologic log of the exploratory geothermal test well (INEL-1), Idaho National Engineering Laboratory, eastern Snake River Plain, Idaho. U. S. Geological Survey Open-File Report 79-1248.

DOE (2008). Evaluation of Enhanced Geothermal Systems Technology, Geothermal Technologies Program, EERE.

Geslin, J. K., Link, P. K., Riesterer, J. W., Kuntz, M. A., & Fanning, C. M. (2002). Pliocene and Quaternary stratigraphic architecture and drainage systems of the Big Lost Trough, northeastern Snake River Plain, Idaho. *Geological Society of America Special Paper*, *353*, 11–26.

Houser, B.B. (2002). Quaternary stratigraphy of an area northeast of American Falls Reservoir, eastern Snake River Plain, Idaho. *Geological Society of America Memoir*, *179*, 269-288.

Jackson, S. M., I. G. Wong, G. S. Carpenter, D. M. Anderson, and S. M. Martin (1993b). Contemporary Seismicity in the eastern Snake River Plain, Idaho based on Microearthquake Monitoring, Bulletin of the Seismological Society of America, v. 83, no. 3, June, p. 680-695.

Kelbert, a., Egbert, G. D., & deGroot-Hedlin, C. (2012). Crust and upper mantle electrical conductivity beneath the Yellowstone Hotspot Track. *Geology*, *40*(5), 447–450. doi:10.1130/G32655.1

Kuntz, M. A., Anderson, S. R., Champion, D. E., Lanphere, M. A., & Grunwald, D. J. (2002). Tension cracks, eruptive fissures, dikes, and faults related to late Pleistocene-Holocene basaltic volcanism and implications for the distribution of hydraulic conductivity in the eastern Snake River Plain, Idaho. *Geological Society of America Special Paper*, *353*, 111–133.

Kuntz, M.A., Covington, H.R., & Schorr, L.J. (1992). An overview of basaltic volcanism of the eastern Snake River Plain, Idaho. *Geological Society of America Memoir*, *179*, 227-267.

Leeman, W. P., Annen, C., & Dufek, J. (2008). Snake River Plain - Yellowstone silicic volcanism: implications for magma genesis and magma fluxes. *Geological Society, London, Special Publications*, *304*(1), 235–259. doi:10.1144/SP304.12

Leeman, W. P., Schutt, D. L., & Hughes, S. S. (2009). Thermal structure beneath the Snake River Plain: Implications for the Yellowstone hotspot. *Journal of Volcanology and Geothermal Research*, *188*(1-3), 57–67. doi:10.1016/j.jvolgeores.2009.01.034

Mann, L. J. (1986) Hydraulic properties of rock units and chemical quality of water for INEL—a 10,365-foot deep test hole drilled at the Idaho National Engineering Laboratory, Idaho. U. S. Geological Survey Water-Resources Investigations Report 86-4020.

McCurry, M., & Welhan, J. (2012). Do Magmatic-related geothermal energy resources exist in southeast Idaho? *GRC Transactions*, *36*, 699–707.

McCurry, M., & Rodgers, D. W. (2009). Mass transfer along the Yellowstone hotspot track I: Petrologic constraints on the volume of mantle-derived magma. *Journal of Volcanology and Geothermal Research*, *188*(1-3), 86–98. doi:10.1016/j.jvolgeores.2009.04.001

McCurry, M., Hayden, K. P., Morse, L. H., & Mertzman, S. (2008). Genesis of post-hotspot, A-type rhyolite of the Eastern Snake River Plain volcanic field by extreme fractional crystallization of olivine tholeiite. *Bulletin of Volcanology*, *70*(3), 361–383. doi:10.1007/s00445-007-0143-4

McLing, T. L., Smith, R. W., and Johnson, T.M., (2002) Chemical Characteristics of Thermal Water Beneath the Eastern Snake River Plain Aquifer, GSA Special Paper 353-13.

MIT, (2006). The future of geothermal energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st century. Idaho Nationl Laboratory report INL/EXT-06-11746.

Morgan, L. a., & McIntosh, W. C. (2005). Timing and development of the Heise volcanic field, Snake River Plain, Idaho, western USA. *Geological Society of America Bulletin*, *117*(3), 288. doi:10.1130/B25519.1

Nash, B., Perkins, M., Christensen, J., Lee, D., & Halliday, a. (2006). The Yellowstone hotspot in space and time: Nd and Hf isotopes in silicic magmas. *Earth and Planetary Science Letters*, *247*(1-2), 143–156. doi:10.1016/j.epsl.2006.04.030

Payne, S. J., McCaffrey, R., & King, R. W. (2008). Strain rates and contemporary deformation in the Snake River Plain and surrounding Basin and Range from GPS and seismicity. *Geology*, *36*(8), 647. doi:10.1130/G25039A.1

Payne, S. J., McCaffrey, R., King, R. W., & Kattenhorn, S. a. (2012). A new interpretation of deformation rates in the Snake River Plain and adjacent basin and range regions based on GPS measurements. *Geophysical Journal International*, *189*(1), 101–122. doi:10.1111/j.1365-246X.2012.05370.x

Pierce, K.L. and L.A. Morgan. (1992). The track of the Yellowstone Hotspot: volcanism, faulting, and uplift. *in* Link P.K., M.A. Kuntz, and L.B. Platt eds., Regional Geology of Western Idaho and Western Wyoming, GSA Memoir 179, pp. 1-53.

Putirka, K. D., Kuntz, M. a., Unruh, D. M., & Vaid, N. (2009). Magma Evolution and Ascent at the Craters of the Moon and Neighboring Volcanic Fields, Southern Idaho, USA: Implications for the Evolution of Polygenetic and Monogenetic Volcanic Fields. *Journal of Petrology*, *50*(9), 1639–1665. doi:10.1093/petrology/egp045

Rodgers, D. W., & McCurry, M. (2009). Mass transfer along the Yellowstone hotspot track II: Kinematic constraints on the volume of mantle-derived magma. *Journal of Volcanology and Geothermal Research*, *188*(1-3), 99–107. doi:10.1016/j.jvolgeores.2009.05.014

Rodgers, D. W., Hackett, W. R., & Ore, H. T. (1990). Extension of the Yellowstone plateau, eastern Snake River Plain, and Owyhee plateau, *Geology* (18), 1138–1141.

Rodgers, D.W., H.T> Ore, R.T Bobo, N. McQuarrie, and N. Zentner. (2002). Extension and subsidence of the eastern Snake River Plain, Idaho. in C.M. White and M. McCurry eds., Tectonic and Magmatic Evolution of the Snake River Plain Province: Idaho Geologic Survey Bulletin 30, pp. 121-155.

Shervais, J. W., Evans, J. P., Christiansen, E. J., Schmitt, D. R., Liberty, L. M., Blackwell, D. D., Glen, J. M., et al. (2011). Hotspot : The Snake River Geothermal Drilling Project — An Overview. *GRC Transactions*, *35*, 995–1003.

Shervais, J. W., Schmitt, D. R., Nielson, D., Evans, J. P., Christiansen, E. H., Morgan, L., Shanks, W. C. P., et al. (2013). First results from HOTSPOT: The Snake River Plain Scientific Drilling Project, Idaho, U.S.A. *Scientific Drilling*, *15*(15, March 2013), 36–45. doi:10.2204/iodp.sd.15.06.2013

Smith, R. B., Jordan, M., Steinberger, B., Puskas, C. M., Farrell, J., Waite, G. P., Husen, S., et al. (2009). Geodynamics of the Yellowstone hotspot and mantle plume: Seismic and GPS imaging, kinematics, and mantle flow. *Journal of Volcanology and Geothermal Research*, *188*(1-3), 26–56.

Smith, R. P., T. McLing, and, M. Rohe, 2000, Implications of Water Temperature, Water Chemistry, and Regional Geophysical Setting for Flow Characteristics of the Snake River Plain Aquifer beneath the INEEL Area, INL Internal Report.

Watts, K. E., Leeman, W. P., Bindeman, I. N., & Larson, P. B. (2010). Supereruptions of the Snake River Plain: Two-stage derivation of low- 18O rhyolites from normal- 18O crust as constrained by Archean xenoliths. *Geology*, *38*(6), 503–506. doi:10.1130/G30735.1

Whitehead, R. L., & River, S. (1992). Geohydrologic Framework of the Snake River Plain Regional Aquifer System, Idaho and Eastern Oregon. *U. S. Geological Survey Professional Paper*, *1408-B*, 32.

Wood, T.R., B. Orr, C.M. Helm-Clark, M. Roddy, H. Huang, M.J. Rohe, S. Magnuson, M.A. Plummer, T. McLing, and R. Podgorney, 2005, *Operable Unit 10-08 Summary Report on the Subregional-scale Two-dimensional Aquifer Model*, Idaho Cleanup Project report ICP/EXT-05-00979, Rev. 1, 107 p.

Yuan, H., Dueker, K., & Stachnik, J. (2010). Crustal structure and thickness along the Yellowstone hot spot track: Evidence for lower crustal outflow from beneath the eastern Snake River Plain. *Geochemistry, Geophysics, Geosystems*, *11*(3), n/a–n/a. doi:10.1029/2009GC002787