PROCEEDINGS, 45th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2020
SGP-TR-216

Play Fairway Analysis in Geothermal Exploration: The Snake River Plain Volcanic Province

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Keywords: Play fairway analysis, Snake River Plain, exploration

ABSTRACT

The Snake River Plain (SRP) volcanic province has long been considered a target for geothermal development. It overlies a thermal anomaly that extends deep into the mantle and represents one of the highest heat flow provinces in North America. Nonetheless, systematic exploration has been hindered by lack of a conceptual model, and regional characterization of geothermal resource potential has not been performed previously. Play Fairway Analysis (PFA) is a methodology adapted from the petroleum industry that integrates data at the regional or basin scale to define favorable plays for exploration in a systematic fashion. The success of play fairway analysis in geothermal exploration depends critically on defining a systematic methodology that is grounded in theory and adapted to the geologic and hydrologic framework of real geothermal systems.

This study focused on identifying three critical resource parameters for exploitable hydrothermal systems in the Snake River Plain: heat source, reservoir and recharge permeability, and cap or seal. Data included in the compilation for *heat* were heat flow, the distribution and ages of volcanic vents, groundwater temperatures, thermal springs and wells, helium isotope anomalies, and reservoir temperatures estimated using geothermometry. *Permeability* was derived from stress orientations and magnitudes, post-Miocene faults, and subsurface structural lineaments based on magnetic and gravity data. Data for *seal* included the distribution of impermeable lake sediments and clay-seal associated with hydrothermal alteration below the regional aquifer. These data were used to compile *Common Risk Segment* (CRS) maps for *heat, permeability* and *seal*, which were combined to create a *Composite Common Risk Segment* (CCRS) map for all of southern Idaho that reflects the risk associated with geothermal resource exploration and helps to identify favorable resource areas.

Our evaluation suggests that important undiscovered geothermal resources may be located in several areas of the SRP, including the WSRP (associated with buried lineaments capped by lacustrine sediment), at lineament intersections in the CSRP, and along the margins of the eastern SRP. These blind resources are associated with temperatures sufficient to support electricity production and may be exploitable with existing deep drilling technology. We are testing our methodology by drilling a geothermal test well in Camas Prairie, Idaho.

1. INTRODUCTION

The Snake River volcanic province (SRP) has long been considered a target for geothermal development. It overlies a thermal anomaly that extends deep into the mantle and represents one of the highest heat flow provinces in North America. Nonetheless, systematic exploration has been hindered by lack of a conceptual model, and a regional characterization of geothermal resource potential has not been performed previously. Play Fairway Analysis is an approach to exploration that integrates data at the regional scale in order to define exploration targets (plays) in a methodical fashion. These data are evaluated systematically in order to define areas that have a high likelihood of success. The success of play fairway analysis in geothermal exploration depends critically on defining a systematic methodology that is grounded in theory and adapted to the geologic and hydrologic framework of real geothermal systems.

Play Fairway Analysis represents a new approach to the discovery of buried or blind geothermal systems. *Nielson et al., 2015*, proposed an approach that uses direct and indirect indicators of geothermal potential in order to identify the three critical geothermal resource parameters: *heat source, reservoir,* and *seal.* In our previous papers, we developed this approach more fully, using Arc

GIS as the most effective tool to compile and process large volumes of geospatial data (*e.g., DeAngelo et al, 2016; Shervais et al., 2015, 2016, 2017, 2018; Garg et al., 2016; Glen et al., 2017, 2018; Nielson et al., 2015, 2017*). Below, we summarize our methods and results, and present a brief evaluation of Play Fairway Analysis as applied to the Snake River Plain.

2. CONCEPTUAL MODEL

The Play Fairway paradigm for geothermal energy defines three critical parameters: *heat source* (HEAT), *reservoir* (PERM), and *seal* (SEAL). HEAT represents the temperature of the crust, either from volcanism or deep-seated heat flow. The reservoir (PERM) is represented by permeable zones in the crust that may contain hydrothermal water. These are typically fault zones that create open fracture space by either slip or dilation. Finally, some sort of SEAL must be present to thermally insulate the system. This may be an external seal such as lake sediments, or an internal self-seal from hydrothermal alteration *(Nielson and Shervais 2014; Nielson et al., 2015)*.

We originally defined four play-types in southern Idaho: (a) basaltic sill-complexes, with fault-controlled permeability and a volcanic heat source; (b) shallow silicic intrusions and domes, which may create their own permeability during intrusion; (c) Basin-and-Range systems, with fault-controlled permeability and a deep heat source; and (d) granite-based systems, such as those in the Idaho Batholith. Our focus in this project has been on the first play type: thermal anomalies associated with basalt sill complexes in the middle crust, and their shallow cupolas in the upper crust (*Nielson and Shervais, 2014; Nielson et al., 2017*).

Our conceptual model for the SRP play-type derives its heat from a layered basaltic sill complex in the middle to upper crust. This basaltic sill complex is long-lived because individual sills are ~100-200 m thick, and because the intrusion of multiple sills pre-heats the crust, minimizing heat loss. Basaltic sills tend to pond at levels of neutral buoyancy, so subsequent intrusions will cluster near this level, at or just above previously intruded sills (*e.g., Shervais et al., 2006*).

Heated fluids are focused along conduits created by fault zones that have been imaged by regional geophysical studies (*Glen et al., 2017*). The location and orientation of these faults is thought to be controlled by the distribution of a sill complex within the crust. Crust modified by sill complex intrusion will tend to act as a rigid block in response to strain, localizing strain along its margins. As a result, the faults trend essentially parallel to the long axis of the WSRP gravity high (*Glen et al., 2017*). Fine-grained sediments in Miocene-Pliocene Lake Idaho deposits provide a seal for the geothermal system.

3. METHODS

The initial phase of this project relied in large part on the compilation of existing data from geologic maps and databases. Sources include geologic maps published by the U.S. Geological Survey (USGS) and Idaho Geological Survey, digital compilations of post-Miocene faults, state-wide gravity and airborne magnetic surveys, water and well log data from the USGS and Idaho Department of Water Resources, and published reports from the geologic literature. New data collection during Phase 2 included geologic mapping, chemical and age analysis of young volcanic rocks, geophysical surveys of gravity, magnetics, and magnetotellurics, seismic transects, water chemistry and multicomponent estimates of reservoir temperatures, stable isotope composition of water, and He isotope compositions (*Glen et al., 2017; Shervais et al., 2017; Neupane et al., 2016*).

Our workflow uses ArcGIS as our primary software tool because it is universally available, and because it is capable of integrating and analyzing a wide range of spatial data types. Data were assembled from a range of sources and imported into ArcGIS to create a series of evidence layers for later analysis. Evidence layers are defined as primary data layers in which the data may be pre-processed, e.g., fault segments weighted by their slip or dilation tendency, or volcanic vents weighted by size and age (*DeAngelo et al., 2016*). Our three critical geothermal resource parameters of *heat source*, *reservoir*, and *seal* were each compiled from a range of data. Details on our field, geochemical, and geophysical methods are summarized elsewhere (*Shervais et al., 2016, 2017, 2018; Glen et al., 2017; Nielson et al., 2015; Neupane et al., 2016).*

Data layers typically consist of either continuous functions that are sampled episodically, or discontinuously distributed attributes that must be converted into continuous functions. For example, heat flow is a continuous function, but it can only be measured in a few locations where deep wells penetrate conductive horizons. We use the ArcGIS function *Bayesian Empirical Kriging* to interpolate between these measurements and produce an estimate for the distribution of heat flow as a continuous function. The same approach is used with groundwater temperatures. In contrast, discontinuous data such as volcanic vents and fault segments are evaluated using a *kernel density function* that calculates the density of points (vents) or line segments (faults) within a given radius (*DeAngelo et al., 2016).*

Data uncertainties (confidence levels) were compiled from an evaluation of map scale, standard error of kriging interpolations, and station spacing for geophysical measurements. *Common risk segment* (CRS) maps were created for each geothermal parameter (HEAT, PERM, SEAL) using a weighted compilation of evidence layers multiplied by their respective confidence levels (*e.g., Shervais et al., 2015; DeAngelo et al., 2016*). Finally, all three parameters were combined into a single *composite common risk segment* (CCRS) map for all of southern Idaho. The CCRS map was used to identify potential geothermal plays, after which specific areas of interest were re-evaluated using higher resolution data processing *(e.g.,* smaller density function radius, smaller pixel size in compilations). Data processing was facilitated by the construction and use of Python scripts that perform geoprocessing and calculations, and return results.

Prior to the selection of sites for test drilling, prospective areas were subject to intensive collection of new data, including detailed geologic mapping and field studies, radiometric dating of basaltic vents, seismic reflection surveys, high-resolution gravity and magnetic surveys, magnetotelluric surveys, geochemical sampling and analysis campaigns of thermal wells and hot springs (water chemistry, stable isotope chemistry, and multicomponent geothermometry) (*DeAngelo et al., 2016; Shervais et al., 2015, 2016, 2017, 2018; Glen et al., 2017; Neupane et al., 2016; Nielson et al., 2017; Garg et al., 2016, 2017*). These data were collected in two focus areas: the WSRP near Mountain Home, Idaho, and Camas Prairie, Idaho. In addition, detailed geologic, geophysical, and thermal modeling was carried out. The new data were used to fill data gaps in the original data compilation, and to build new *CRS* maps at higher resolution in ArcGIS. The new high-resolution *CRS* and *CCRS* maps were then used for test well site selection.

3.1 SOURCE (HEAT)

There are multiple metrics from which to infer heat sources in the crust. These include: (1) heat flow, (2) groundwater temperature data (which are more abundant and widely distributed than heat flow data), (3) the distribution of volcanic vents, (4) hot spring and well water multicomponent equilibrium reservoir temperatures, and (5) He isotope compositions in hot spring and well water. Heat flow is uniformly high across the SRP (~110 mW/m^2), except where shallow thermal flux is masked by advective transport of heat through shallow aquifers. The effect of shallow aquifers is to suppress conductive gradients above and within the aquifer. This affects most of the ESRP (e.g., McLing et al., 2016) and areas around Boise, Idaho, where coarse alluvial deposits mask underlying heat flow. In other areas, heat flow is abnormally elevated by convective upflow of deep thermal water, creating high apparent heat flow in the near surface that overlies normal heat flow at depth. These affects can be mitigated by screening of data, but it is difficult to remove their impact entirely. One approach to mitigate this problem is to use groundwater temperatures, which vary systematically across the SRP, and represent a much larger database since nearly all water wells have temperatures recorded.

An alternate measure of potential heat is the distribution of young volcanic vents. Young basalt vents are more common in the ESRP; however, clusters of young basalt vents also occur in the WSRP (*Shervais and Vetter, 2009*). We compiled data on the distribution and location of vents from publications, unpublished reports, and geologic maps. These data were weighted by vent size and age, since large young vents represent larger enthalpy source in the crust than smaller and/or older vents. Weighting by size also mitigates (but does not eliminate) the bias created by the weathering and disappearance of small satellite vents in older terranes.

Hot springs and thermal wells are most commonly located on the margins of the SRP, or in the adjacent hills, and are often associated with mapped faults (or occur in linear arrays that suggest underlying fault control). Reservoir temperatures calculated using multicomponent geothermometers (*Neupane et al., 2014*) and $^3He/^4He$ ratios (*Dobson et al., 2015*) both indicate areas with high crustal temperatures and permeability. In particular, high $^3He/^4He$ isotope ratios imply recent mantle-derived magmatic input and the presence of deep faults that allow migration to the surface with little mixing of crustal fluids.

3.2 Reservoir Permeability (PERM)

Permeability in geothermal systems results largely from faulting. Permeability is assessed using both mapped surface faults and subsurface faults inferred from potential field data (gravity, magnetics). Our measures of permeability include: (1) mapped post-Miocene faults, (2) lineaments defined by upper crustal gravity gradients, (3) lineaments defined by mid-crustal gravity gradients, and (4) lineaments defined by magnetic gradients. Each of these data layers was evaluated twice, weighted for dilation tendency and slip tendency, to create eight separate evidence layers. In addition, seismic reflection profiles collected across critical structures more precisely define the location and dip of these fault zones (*Glen et al., 2017, 2018)*.

The most productive hydrothermal resources in the Great Basin occur in complex fault interaction zones that have a dilational component that results in open fractures along some part of the fault, i.e., fault intersections, step-overs, and accommodation zones (*Faulds et al., 2013*). The scale of mapping in southern Idaho is generally not sufficient to document these structures, or these structures have been obscured on the surface by young volcanism and cannot be mapped in geophysically defined lineaments. A proxy for fault intersections is fault density, because high fault densities favor multiple intersections. We weight faults by dilation tendency and slip tendency, as described in Methods, and processed using a kernel density function. A similar exercise was carried out for buried structures using maximum horizontal gradients in the gravity and magnetic anomalies to define buried lineaments. These lineaments suggest significant permeability along the northern and southern margins of a major, basin-wide gravity anomaly in the western SRP. This hidden permeability was confirmed by the exploration well MH-2 drilled by Project Hotspot (Shervais et al., 2012; *Nielson and Shervais, 2014; Kessler et al., 2017*), which encountered an artesian hydrothermal system at 1745 m depth, characterized by <50% core recovery, suggesting high permeability and large fracture apertures.

3.3 Seal (SEAL)

The SRP geothermal system has two potential seals (*Nielson and Shervais, 2014*): (a) fine-grained lacustrine sediments, which are largely impermeable and (b) self-seal of volcanic rocks by hydrothermal alteration. Lake sediments deposited by paleo- Lake Idaho are widespread in the WSRP (*e.g.,* Bruneau, Glens Ferry, and Chalk Hills Formations), forming an impermeable seal 0.5-1.6 km thick (Wood and Clemens, 2002). Lake sediments are more restricted in the CSRP and ESRP and are typically found along the margins of the plain, north or south of the axial volcanic high. Self-seal by alteration is also common in geothermal systems. In the

SRP, the base of the Snake River Aquifer is controlled by the onset of clay alteration, so we are able to use the geophysically defined aquifer thickness as a proxy for self-seal (*Lindholm, 1995*).

Magnetotelluric arrays deployed in the WSRP and Camas Prairie were used to confirm the location and thickness of clay-rich zones. We deployed 140 sites with three component antennae, divided between the two sites, and supplemented with additional two component antennae arrays (Glen et al., 2017, 2018).

4. RESULTS

4.1 Heat

Heat flow data are heterogeneously distributed, with the highest density of measurements found in the WSRP and across the border in eastern-most Oregon. Gradient wells in the ESRP are clustered at the Idaho National Lab (INL) site and along the eastern edge of the plain near Island Park caldera, with scattered coverage elsewhere (*e.g., Williams and DeAngelo, 2008; 2011; Blackwell et al., 1989; Blackwell and Richards, 2004*). The data show relatively high heat flow throughout the SRP (90-110 mW/m^2), but it is poorly constrained in the eastern plain due to the cooling effect of the SRP aquifer and features hot spots proximal to known geothermal areas due to convective upflow.

Groundwater temperature reflects thermal flux from below. Groundwater and surface flow from the mountains of eastern Idaho and Wyoming is characterized by temperatures ~8ºC, which represents the baseline temperature of the Snake River Aquifer in the eastern and central SRP. Groundwater temperatures increase gradually from NE to SW in this region in response to thermal flux from below the aquifer (*e.g., McLing et al., 2002, 2016; Blackwell et al., 1992; Smith, 2004*), with local variability depending on flow channelization (*McLing et al., 2016*). Further, ground water temperatures are uniformly high in the WSRP due to the thick insulating layer of lacustrine sediments.

Vent maps show that young basaltic vents are densest in the eastern SRP, with clusters at Craters of the Moon and the Spencer-Highpoint volcanic rift zone. Clusters of anomalously young vents are also found in the western SRP, comprising high-K lavas less than 700 ka that represent rejuvenated magmatic actively long after passage of the Yellowstone plume (*Shervais and Vetter, 2009*).

Hot spring and well data are scattered largely along the margins of the plain and in the adjacent hills. Springs are commonly aligned along fault zones, especially in the Mount Bennett Hills and the adjacent Camas Prairie. Multicomponent geothermometers indicate high reservoir temperatures for Banbury Hot Springs, and for hot springs along the margins of the Mount Bennett Hills and ESRP, as well as for artesian hydrothermal water from the deep well MH-2 (WSRP). Helium isotope data present a similar picture, with high $^3He/^4He$ ratios found in thermal waters from Camas Prairie, Banbury, Arco, and the Blackfoot areas (*Dobson et al., 2015; Neupane et al., 2014*).

The *CRS* map for *heat source* highlights several areas with high thermal potential: (a) large portions of the WSRP, including the Boise thermal district, areas south and west of Boise (Marsing-Kuna area), the Mountain Home area (both the town and AFB), the Castle Creek-Bruneau known geothermal resource area, and part of Bruneau-Jarbidge eruptive center; (b) the CSRP, including the Camas Prairie-Mount Bennett Hills region, Magic Hot Springs, and the Banbury-Miracle Hot Springs area; and (c) the ESRP, including Craters of the Moon and Great Rift, the Arco area, and the Spencer-High Point rift, which trends EW and intersects the margin of Island Park caldera.

4.2 Permeability

Aside from Basin-and-Range system faults, mapped faults are largely restricted to the margins of the SRP with high densities in the Mount Bennett Hills and parts of the Owyhee Plateau. Buried structures and lineaments, defined by gravity and magnetic gradients, suggest significant permeability along the northern and southern margins of a major gravity anomaly in the WSRP, as well as structures aligned with Basin-and-Range systems in the ESRP. Our *CRS* map for *permeability* highlights several highly favorable areas for the basaltic sill play-type: (a) the WSRP, where high permeability is found in linear trends sub-parallel to the WNW-trend of the western plain range front faults or to the oblique trend of the central gravity high; (b) the CSRP, where high permeability is found in the Camas Prairie-Mount Bennett Hills area, near Fairfield, Idaho; (c) the ESRP, focused largely on the Arco rift zone that extends northward up the Big Lost River valley and southward past Big Southern Butte; and (d) the Blackfoot-Gem Valley region of SE Idaho. More detailed mapping of structural features in Camas Prairie resulted in the identification of two prominent faults: a basin-bounding fault along the southern margin of the Camas Prairie and the Pothole fault zone (*Glen et al., 2018*). There is an apparent right-stepover in the Pothole fault zone that results in interpreted extension across the area where the two fault systems intersect – this location, near Barron's Hot Spring, is where the USU-Camas-1 well was targeted.

4.3 Seal

Lacustrine sediments indicate seals associated with paleo-Lake Idaho in the western SRP, paleo-Lake Burley in the central SRP, paleo-Lake Tarleton in the eastern SRP, and Camas Prairie. The *CRS* map for *seal* shows that the distribution of seal is extensive, with most areas having either significant thicknesses of lacustrine sediments or a basal aquifer seal (ESRP). Hot springs located along the margins of the SRP show where the seal does not exist or has been breached by faulting. Detailed magnetotelluric results from the WSRP and Camas Prairie document low-resistivity clay caps above both target areas. The cap around Mountain Home in the WSRP thins towards the range front, and is interpreted as lacustrine sediments, based on data from drill core. The Camas Prairie cap is localized around hot springs along The Pothole fault system and is interpreted as a clay self-seal related to hydrothermal alteration.

4.3 Composite Common Risk Segment (CCRS) Map

The *Composite Common Risk Segment* (CCRS) map for southern Idaho is shown in Figure 1. The *CCRS* map represents a product of the three *CRS* maps discussed above (HEAT, PERM, SEAL), each of which is a weighted average of its individual evidence layers. Given the fairly widespread distribution of seal rocks, and high regional heat flow, much of the potential is controlled by permeability.

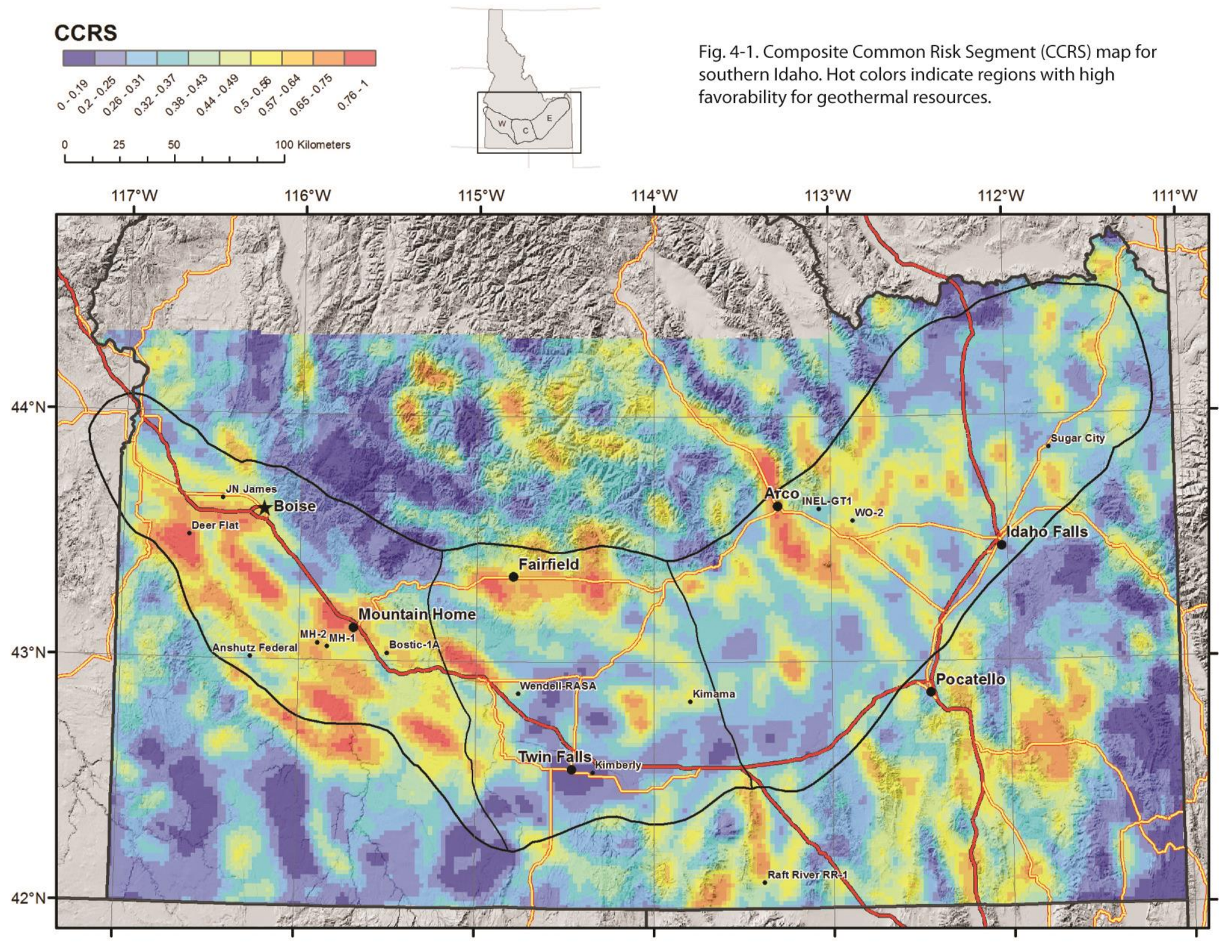

Figure 1. Composite Common Risk Segment (CCRS) map for southern Idaho. Hot colors indicate high geothermal potential, cool colors indicate low geothermal potential.

4.4 Drilling

In order to confirm predictions based on our evaluation of *heat*, *permeability*, and *seal*, two sites were initially considered to drill test wells: the area around Mountain Home Air Force Base (AFB) and Camas Prairie. The Mountain Home site is underlain by high geothermal gradients (72 ºC/km; *Lachmar et al, 2012, 2019; Nielson et al, 2018*), sits over a well-defined subsurface lineament (*Glen et al, 2017*), and is overlain by a thick lacustrine seal (*Shervais et al, 2012*). This site was not chosen for drilling because the target depth could not be reached within the budget available, and a deep well that was previously drilled at this site as part of Project Hotspot (MH-2) already confirmed the presence of a hydrothermal system at depth (e.g., Shervais et al., 2012; Kessler et al., 2017). The second site, at Camas Prairie, sits above the intersection of several well-defined lineaments (both buried and surface mapped), is associated with thermal waters with reservoir temperatures estimated at 110-120ºC and high $^3He/^4He$ values, and has a target depth that was within budget.

Drilling of the USU Camas-1 well began in September 2018. Approximately 1045' of basin-fill sediments were penetrated before encountering bedrock, and casing was set at 1138' to isolate deeper hydrothermal systems from the basin fill. Rotary drilling continued to 1608' through granitoids, assumed to correlate with the Idaho Batholith, cut by dikes of rhyolite and andesite (inferred from well logs and cuttings). A reservoir test was completed in late October 2018. Sampling of the well in July 2018 showed that it had pressurized and flowed without pumping, releasing a gas phase assumed to be CO_2. A maximum temperature of ~82ºC was recorded in the flowing well at ~340 m (1115 ft); the bottom hole temperature was slightly lower. Core drilling in October 2019 deepened the well to 2028 feet, with 100% core recovery. The primary lithology is porphyritic granite cut by dikes of pink to grey andesite/rhyolite. Veins of calcite and quartz are common, often with chlorite and sulfide mineralization. Slicks are common on fracture surfaces (Figure 2). The downhole temperature is consistently high at 82ºC, but multicomponent geothermometry indicates mixing with a reservoir at ~120ºC. A full suite of geophysical logs was obtained – these are depicted in Figure 3.

5. DISCUSSION AND CONCLUSIONS

5.1 Plays in the Snake River Plain

A preliminary assessment of potential new geothermal prospects based on our regional scale Play Fairway Analysis indicates several areas where undiscovered blind geothermal resources may be found (Figure 1). The highest potential is found in the WSRP, where steep horizontal gradients in gravity along the margins of the WNW-trending gravity high imply permeability at depth. The WSRP also features high heat flow, high geothermal gradients, high groundwater temperatures, and clusters of anomalously young volcanic vents document high heat flux in the crust, and widespread lake sediments over one km thick provide a robust seal. Prior deep drilling in this area has intersected high permeability zones with an artesian hydrothermal system, high-temperature mineralization, and hydrothermal breccias (*Shervais et al., 2012; Kessler et al., 2017; Lachmar et al., 2012, 2019*). Another fairway is the Banbury-Miracle hot springs area, which lies within a major zone of regional fault intersections, with high fault density and relatively young volcanic activity (late Pleistocene); surface manifestations include hot springs with high calculated reservoir temperatures and elevated $^3He/^4He$ ratios. The Camas Prairie area is underlain by relatively young volcanic rocks and characterized by complex fault intersections along The Pothole fault system. The Pothole fault system is marked by numerous springs, including hot springs with high calculated reservoir temperatures and high $^3He/^4He$ ratios (Neupane et al., 2017; *Dobson et al., 2015*). The margins of the ESRP are characterized by high heat flow and young volcanism but lack significant indicators of subsurface permeability; these areas are not good prospects for hydrothermal systems but may be viable enhanced geothermal system sites.

Figure 2. Slickenlines on fracture surface in drill core, USU Camas-1 test well.

5.2 Validation of the Model by Test Drilling

Initial Play Fairway Analysis of the Camas Prairie region predicted a hydrothermal resource with a temperature ~110ºC at around 2000' to 2500' depth. This depth was based on geophysical assessment of multiple fault intersections between the Pothole fault system and a buried range-front fault system, as well as smaller faults associated with a step-over in the Pothole fault system (Glen et al., 2018). Magnetotelluric surveys indicated a clay seal above this at ~1000' depth (*Glen et al., 2017*). Our test well encountered an inflow zone at ~1145' depth; geochemical and isotopic analysis indicate a mixed hydrothermal/meteoric provenance for this water, with a resulting downhole temperature (82ºC) lower than the predicted reservoir temperature.

5.3 Assessment of Play Fairway Analysis in Geothermal Exploration

The Play Fairway approach to geothermal exploration appears to offer a robust methodology for integrating large volumes of geologic, geophysical, and geochemical data systematically, in a way that can be evaluated at a range of scales and resolutions. The final products can be used to infer potential resources more effectively than traditional approaches, with less reliance on expert opinions. It can be adapted easily to a range of play types in different geothermal settings, and when implemented properly, facilitates decision making in regions where data coverage is sparse, or uneven in distribution and quality. Evaluation of data uncertainty is built into the system, allowing users to set their level of comfort. In southern Idaho, it has allowed us to identify several potential geothermal resources in the Snake River Plain region that had only received minor attention previously.

We present an approach to Play Fairway Analysis, based on previously discussed conceptual models (*e.g., Nielson and Shervais, 2014; Nielson et al., 2015*), that is adapted for use in geothermal exploration. We use a systematic workflow of custom Python scripts with ArcGIS functions to automate data analysis and compile results. We find that Play Fairway Analysis is a robust approach to geothermal exploration that eliminates much of the subjective analysis and replaces it with an objective methodology that is adaptable to different geotectonic settings and scalable from regional scales (100s of km) to local scales (100s of meters). The adaptive nature of our ArcGIS approach is that different evidence layers may be toggled off by weighting to zero, or on by other, non-zero weights. The nature and weight of individual evidence layers used in each *CRS* map can be customized for different geotectonic settings based on different conceptual models and the types of data available. Scale can be customized by using different areas for pixel elements in the data array (1-2 km for large areas, 100 m or less for small areas) and by adjusting the search radius in kernel density functions.

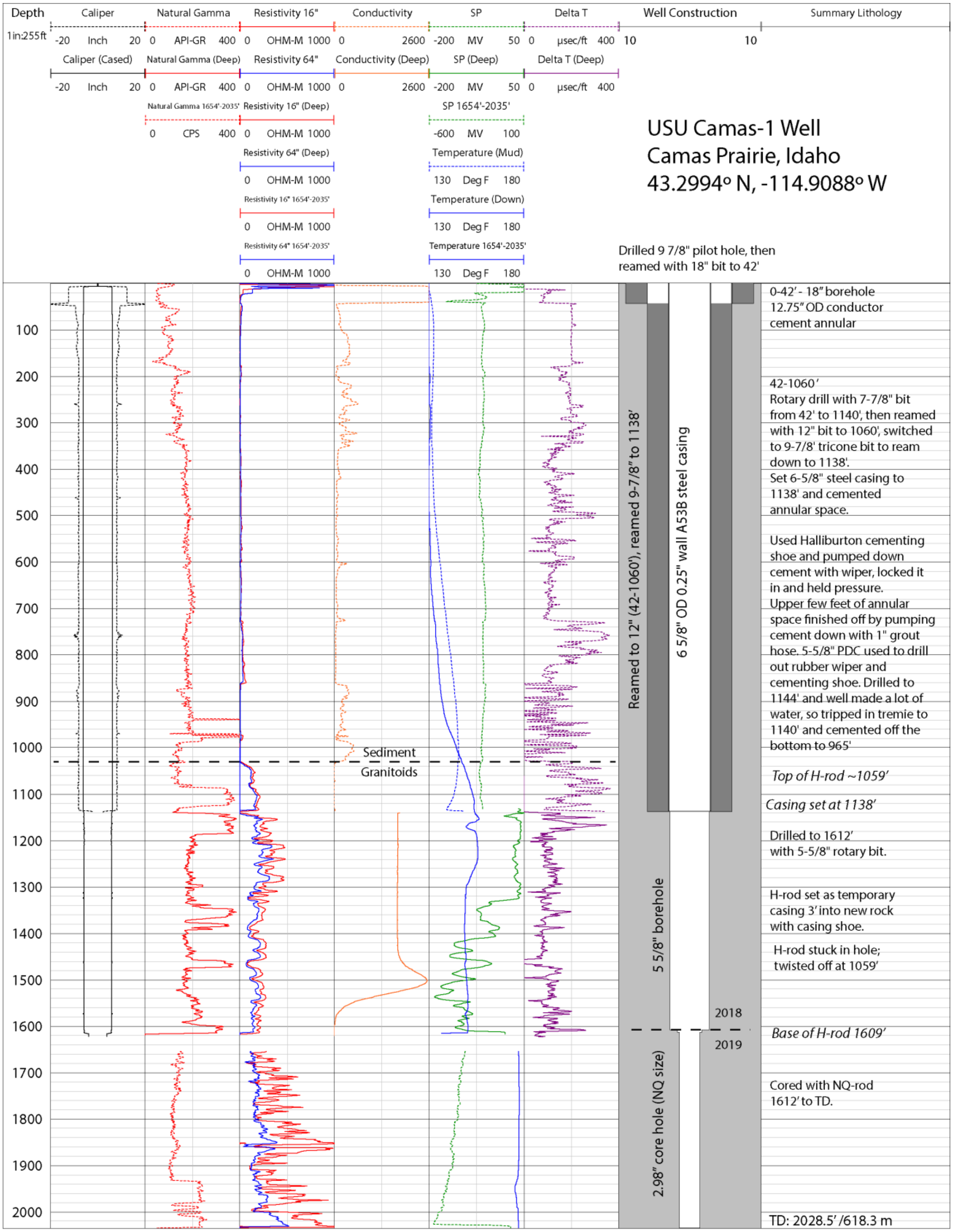

Figure 3. Wireline geophysical logs and "as built" well diagram for USU Camas-1. Rotary drilled from surface to 1612'; core drilled from 1612' to TD at 2028.5'. Dashed line indicates contact of basin fill sediment with bedrock.

Acknowledgments

This work was supported by U.S. Department of Energy Award EE-0006733. Further support was provided by Utah State University and the U.S. Geological Survey. This work was also supported with funding by the Assistant Secretary for Energy Efficiency and Renewable Energy, Geothermal Technologies Office, of the U.S. Department under the U.S. Department of Energy Contract No. DE-AC02-05CH11231 with Lawrence Berkeley National Laboratory. We wish to thank Travis McLing (Idaho National Laboratory) and Tom Wood and Cody Cannon (University of Idaho) for generously sharing unpublished geothermometry results, and our colleagues for stimulating discussions. We wish to thank Roy Mink of Mink GeoHydro Inc., for assistance in the field, Camas Creek Ranch and Ranch Manager Rod Gonsales for use of the drill site, and the USGS Research Drilling Unit for drilling services. We also like to thank all of the land owners around Mountain Home and Camas Prairie who generously allowed us access for geophysical surveys, and BLM Boise office for access to BLM land. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

REFERENCES CITED

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

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

Blackwell, D.D., S.A. Kelley and J.L. 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.

DeAngelo, J, Shervais, JW, Glen, JM, Nielson, DL, Garg, S, Dobson, P, Gasperikova, E, Sonnenthal, E, Visser, C, Liberty, LM, Siler, D, Evans, JP, and Santellanes, S., 2016, GIS Methodology for Geothermal Play Fairway Analysis: Example from the Snake River Plain Volcanic Province. *Proceedings Forty-First Workshop on Geothermal Reservoir Engineering, Stanford University*, Stanford, California, February 22-24, 2016 SGP-TR-209.

Dobson, P.F., B.M. Kennedy, M.E. Conrad, T. McLing, E. Mattson, T. Wood, C. Cannon, R. Spackman, M. van Soest, and M. Robertson, 2015, He Isotopic Evidence for Undiscovered Geothermal Systems in the Snake River Plain. Proceedings, Fortieth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 26-28, 2015 SGP-TR-204.

Faulds, J.E., N.H. Hinz, G.M. Dering and D.L. Siler, 2013, The Hybrid Model-The Most Accommodating Structural Setting for Geothermal Power Generation in the Great Basin, Western USA. *Geothermal Resources Council Transactions* 37, 3–10.

Garg, S, Nielson, DL, Shervais, JW, Sonnenthal, E, 2016, Thermal modeling of the Mountain Home Geothermal Area. *Proceedings Forty-First Workshop on Geothermal Reservoir Engineering, Stanford University*, Stanford, California, February 22-24, 2016 SGP-TR-209.

Garg, S. Gasperikova, E, Nielson, DL, Shervais, JW, 2017, Mountain Home Geothermal Area: Natural State Model. *Geothermal Resources Council Transactions*, v41, 2731-2742.

Glen, JMG, Liberty, L, Gasperikova, E, Siler, D, Shervais, JW, Ritzinger, B, Athens, N, Earney, T, 2017, Geophysical Investigations and Structural Framework of Geothermal Systems in west and southcentral Idaho; Camas Prairie to Mountain Home. *Proceedings, 42nd Workshop on Geothermal Reservoir Engineering, Stanford University*, Stanford, California, February 13-15, 2017, SGP-TR-212.

Glen, J.M.G., Liberty, L., Peacock, J., Gasperikova, E., Earney, T., Schermerhorn, W., Siler, D., Shervais, J., and Dobson, P., 2018, A geophysical characterization of the structural framework of the Camas Prairie geothermal system, southcentral Idaho. *Geothermal Resources Council Transactions* 42, 466–481.

Kessler, JA, Bradbury, KK, Schmitt, DR, Shervais, JW, Pulsipher, MA, Rowe, FE, Varriale, J, Evans, JP, 2017, Geology and *in situ* stress of the MH-2 borehole, Idaho, USA: Insights into Western Snake River Plain structure from geothermal exploration drilling, *Lithosphere*, doi:10.1130/L609.1.

Lachmar, T.E., Freeman, T.G., Kessler, J.A., Batir, J.F., Evans, J.P., Nielson, D.L., Shervais, J.W., Chen, X., Schmitt, D.R., and Blackwell, D.D., 2019, Evaluation of the geothermal potential of the western Snake River Plain based on a deep corehole on the Mountain Home AFB near Mountain Home, Idaho. Geothermal Energy 7, 26. doi:10.1186/s40517-019-0142-7.

Lachmar, TE, Freeman, TG, Sant, CJ, Walker, JR, Batir, JF, Shervais, JW, Evans, JP, Nielson, DL, Blackwell, DD, 2017, Effect of an 860-m thick, cold, freshwater aquifer on geothermal potential along the axis of the eastern Snake River Plain, Idaho. *Geothermal Energy*, 5:28, doi:10.1186/s40517-017-0086-8.

Lachmar, TL, Freeman, T., Shervais, JW, Nielson, DE, 2012, Preliminary Results: Chemistry and Thermometry of Geothermal Water from MH-2B Test Well. *Geothermal Resources Council Transactions*, vol. 36, 689-692.

Liberty, LM, Schmitt, DR, and Shervais, JW, 2015, Seismic imaging through the volcanic rocks of the Snake River Plain: Insights from Project Hotspot. *Geophysical Prospecting*, doi:10.1111/1365-2478.12277.

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.

McLing, T.L., R.W. Smith and T.M. Johnson, 2002, Chemical characteristics of thermal water beneath the eastern Snake River Plain, in Link, P.K., and Mink, L.L., (eds.), Geology, Hydrogeology, and Environmental Remediation: Idaho National Engineering and Environmental Laboratory, Eastern Snake River Plain, Idaho: Geological Society of America Special Paper 353, 2002), 205–211.

McLing, T.L., Smith, R.P., Smith, R.W., Blackwell, D.D., Roback, R.C., and Sondrup, A.J., 2016, Wellbore and groundwater temperature distribution eastern Snake River Plain, Idaho: Implications for groundwater flow and geothermal potential. *Journal of Volcanology and Geothermal Research*, 320, 144-155.

Neupane, G., E.D. Mattson, T.L. McLing, C.D. Palmer, R.W. Smith, T.R. Wood, 2014, Deep Geothermal Reservoir Temperatures in the Eastern Snake River Plain, Idaho using Multicomponent Geothermometry. Proceedings, Thirty-Eighth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, Feb 24-26, 2014 SGP-TR-202.

Neupane, G., Mattson, E.D., Spycher, N., Dobson, P.F., Conrad, M.E., Newell, D.L., McLing, T.L., Wood, T.R., Cannon, C.J., Atkinson, T.A., Brazell, C.W., and Worthing, W.C., 2017, Geochemical evaluation of the geothermal resources of Camas Prairie, Idaho. *Proceedings, 42nd Workshop on Geothermal Reservoir Engineering*, Stanford University, Feb 13-15, 2017.

Nielson, DL and Shervais, JW, 2014, Conceptual Model for Snake River Plain Geothermal Systems. *Proceedings Thirty-Ninth Workshop on Geothermal Reservoir Engineering Stanford University*, Stanford, California, Feb. 24-26, 2014 SGP-TR-202.

Nielson, DL, Atkinson TA, and Shervais JW, 2018, Evaluation of the Mountain Home AFB Geothermal System for the Play Fairway Project. *Proceedings, 43rd Workshop on Geothermal Reservoir Engineering, Stanford University*, Stanford, California, February 12-14, 2018, SGP-TR-213.

Nielson, DL, Shervais, JW, Evans, JP, Liberty, L, Garg, SK, Glen, J., Visser, C., Dobson, P, Gasperikova, E. and Sonnenthal, E., 2015, Geothermal Play Fairway Analysis of The Snake River Plain, Idaho. *Proceedings Fortieth Workshop on Geothermal Reservoir Engineering, Stanford University*, Stanford, California, January 26-28, 2015 SGP-TR-204.

Nielson, DL, Sonnenthal, E., Shervais, JW and Garg, SK, 2017, Mafic Heat Sources for Snake River Plain Geothermal Systems. *Proceedings, 42nd Workshop on Geothermal Reservoir Engineering, Stanford*, California, Feb 2017, SGP-TR-212.

Nielson, DL., Delahunty, C., and Shervais, JW, 2012, Geothermal Systems in the Snake River Plain, Idaho, Characterized by the Hotspot Project. *Geothermal Resources Council Transactions*, v36, 727-730.

Shervais, J.W., S.K. Vetter, and B.B. Hanan, 2006, 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, Nielson, DL, Evans, JP, Lachmar, T, Christiansen, EH, Morgan, L., Shanks, WCP, Delahunty, C, Schmitt, DR, Liberty, LM, Blackwell, DD, Glen, JM, Kessler, JE, Potter, KE, Jean, MM, Sant, CJ, Freeman, TG. 2012, Hotspot: The Snake River Geothermal Drilling Project -- Initial Report. *Geothermal Resources Council Transactions*, v36., 767-772.

Shervais, J. W., Glen, J. M., Liberty, L. M., Dobson, P., Gasperikova, E., Sonnenthal, E., Visser, C., Nielson, D., Garg, S., Evans, J. P., Siler, D., DeAngelo, J., Athens, N., Burns, E., 2015, Snake River Plain Play Fairway Analysis - Phase 1 Report. *Geothermal Resources Council Transactions, v39, 761-769.*

Shervais, JW, Glen, JM, Nielson, DL, Garg, S, Dobson, P, Gasperikova, E, Sonnenthal, E, Visser, C, Liberty, LM, DeAngelo, J, Siler, D, Varriale, J, and Evans, JP, 2016, Geothermal Play Fairway Analysis of the Snake River Plain Volcanic Province: Phase 1. *Proceedings Forty-First Workshop on Geothermal Reservoir Engineering, Stanford University*, Stanford, California, February 22-24, 2016 SGP-TR-209.

Shervais, JW, Glen, JM, Nielson, DL, Garg, S, Liberty, LM, Siler, D, Dobson, PF, Gasperikova, E, Sonnenthal, E, Neupane, G, DeAngelo, J, Newell, DL, Evans, JP, Snyder, N. 2017, Geothermal Play Fairway Analysis of the Snake River Plain: Phase 2. *Geothermal Resources Council Transactions*, v41, 2352-2369.

Shervais, JW, Glen, JM, Siler, D, Deangelo, J, Liberty, LM, Nielson, DL, Garg, S, Neupane, G., Dobson, P, Gasperikova, E, Sonnenthal, E, Newell, DL, Evans, JP, Snyder, N, Mink, LL, 2018, Provisional Conceptual Model of the Camas Prairie (ID) Geothermal System from Play Fairway Analysis. *Proceedings, 43rd Workshop on Geothermal Reservoir Engineering, Stanford University*, Stanford, California, February 12-14, 2018, SGP-TR-213.

Smith, RP, 2004, Geologic setting of the Snake River Plain Aquifer and vadose zone. *Vadose Zone Journal* 3:47-58.

Williams, C.F. and J. DeAngelo, 2008, Mapping Geothermal Potential in the Western United States. *Geothermal Resources Council Transactions* v. 32, 181-188.

Williams, C.F., and J. DeAngelo, 2011, Evaluation of approaches and associated uncertainties in the estimation of temperatures in the upper crust of the western United States. *Geothermal Resources Council Transactions*, v. 35, 1599-1605.