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Geothermal Play Fairway Analysis of the Snake River Plain: Phase 2

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ABSTRACT

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. Phase 2 of our Play Fairway Analysis of the Western Snake River Plain (WSRP) province in southern Idaho had three primary goals: first, to fill data gaps in critical areas in order to better define potential prospects, second, to integrate these data into new thermal and structural models, and finally, to infer the location of potential resources and drilling targets that could be validated during Phase 3. Prospects in the WSRP identified as potential target resources for Phase 3 validation include the Mountain Home region close to the Air Force

Base, and the Camas Prairie. The Mountain Home region represents a blind geothermal resource in an area of high heat flow and young volcanism. The Camas Prairie is a, structurally controlled resource in an area with indicators of magmatic heat. New geophysical data acquired at these sites includes reflection seismic, gravity and magnetic surveys, and a magnetotelluric field survey. New geochemical data collection focused on the Camas Prairie, and included the aqueous and isotope geochemistry of hot springs, cold springs, and wells (geothermal, groundwater, and irrigation). New field mapping, sampling, and basalt flow chronology was also conducted at Camas Prairie. Integrated results from Phase 1 and 2 studies suggest that the system near the Mountain Home Air Force Base is located at ~1.5–2.3 km depth, and the structurally-controlled system at Camas Prairie is shallower, with upper reservoir depths perhaps only ~0.5–0.7 km.

1. Introduction

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 based upon identifying the presence and magnitude of required components of geothermal systems (Nielson *et al.,* 2015). It then interrogates these data to highlight which plays have the highest likelihood of success (*prospects*). *Play Fairway Analysis* may provide greater technical rigor than traditional geothermal exploration approaches, and facilitates quantitative risk-based decisions even when data are sparse or incomplete. Our DOE-funded PFA project in the Snake River Plain *(SRP)* of southern Idaho was designed to assess the potential for geothermal energy associated with high heat flow in a volcanic province associated with passage of the Yellowstone hotspot (Shervais *et al.,* 2016). This project has completed two phases at this point: Phase 1 (Dangelo et al., 2016; Garg et al., 2016; Shervais *et al.,* 2016) focused on collation of existing data and creation of a methodology to assess that data within the framework of the PFA paradigm, resulting in the identification of a number of prospects within our study area. Phase 2 (Glen et al., 2017; Neupane et al., 2017; Nielson et al., 2017) focused on the collection of new data to fill data gaps for two of the prospects that were identified in our Phase 1 analysis, and which offer the potential to verify our analysis of exploration risk and validate the PFA method in Phase 3.

We analyzed direct and indirect indicators of geothermal potential in order to characterize the three critical geothermal resource parameters: *heat source, permeable reservoir,* and *seal* (Nielson *et al.,* 2015; Shervais *et al.,* 2016*)*. Raw data were compiled into an ArcGIS database with multiple *data layers* for each parameter. These *data layers* were processed using either density functions or interpolations to produce *evidence layers*. *Risk maps* represent the product of *evidence* and *confidence layers*, and are the basic building blocks used to construct *Common Risk Segment (CRS)* maps for *Heat, Permeability*, and *Seal*. In a final step, these three maps were combined into a *Composite Common Risk Segment (CCRS)* map for identification of undiscovered geothermal resources (DeAngelo *et al., 2016)*.

Our Phase 1 assessment indicated several areas with significant undiscovered geothermal resource potential within the Snake River Plain *(SRP)*. Our results identify *eight areas with multiple prospects*, each of which may contain resources that are equal to or exceed the system

associated with the 10 MWe Raft River geothermal field. Four of these areas are in the Western Snake River Plain (WSRP) and include blind systems, two are in the Central Snake River Plain (CSRP), and two are Basin-and-Range play types in eastern and southeastern Idaho (Figure 1).

Phase 2 goals were: (1) to select focus sites from the areas deemed highly prospective in Phase 1 for more detailed study, (2) to obtain new field data for our selected focus sites, including new structural, gravity, magnetic, seismic, magnetotelluric, radiometric age dating, and geochemical data, in order to fill data gaps and better characterize these sites prior to selection of a Phase 3 verification site, (3) to carry out advanced thermal reservoir modeling, including fully coupled thermal-hydrologic-geochemical modeling and stress-strain analysis, and to refine our conceptual model for SRP geothermal systems, and (4) to integrate the new and existing data into our Arc GIS models, and to update our *Common Risk Segment* and *Composite Common Risk Segment* maps.

2. New Data Acquisition

Based on our assessment of Phase 1 data, two representative regions were chosen for further study, to fill data gaps and refine our assessment tools. The Mountain Home region of the WSRP was chosen to represent blind systems in an area of relatively high heat flow and young volcanism. This area includes the town of Mountain Home, Mountain Home Air Force Base, and the Bostic 1A wildcat petroleum well, which helped identify the Hot Dry Rock potential for this area (Arney et al., 1982) (Figure 1). The Camas Prairie region was chosen to represent a central SRP system with strong structural controls and indicators of magmatic heat input, including high helium isotope ratios and moderate fluid reservoir temperatures (Figure 1).

2.1 Field Mapping and Sampling

Field studies focused on structural mapping of faults and fault intersections along The Pothole fault system in Camas Prairie. Data collected include strike and dip directions of measured polished surfaces, striated surfaces that document slip directions, or topographically apparent faults. In addition, young volcanic vents in the region that had not yet been dated, and several older vents, were visited to collect samples for $^{40}Ar/^{39}Ar$ age dating and for whole rock geochemistry. Twelve of these samples were sent to the Geochronology Laboratory at Oregon State University for $^{40}Ar/^{39}Ar$ dating, and all were analyzed for major and trace elements by XRF spectrometry.

2.2 Geophysical Studies

Geophysical field studies included active source reflection seismic, gravity and magnetic surveys, and a magnetotelluric (MT) field campaign (Glen et al., 2017). Boise State University acquired ~56 km of active source seismic data along five north-south and two east-west county roads in Camas Prairie,using an accelerated weight drop source and land streamer seismic system to image stratigraphy and faults, and to identify depth to bedrock beneath Camas Prairie (Glen et al., 2017). The USGS collected data at 1659 gravity stations and over 725 line-km of ground magnetic data for this project. They also collected hundreds of rock-property measurements on outcrops and samples (including magnetic susceptibility, density, and magnetic remanence) to constrain potential field modeling and integrated ground water well logs into our analyses. These

data have been used, along with previously acquired data from Project Hotspot (e.g., Shervais et *al.*, 2013; Shervais, 2014; Liberty *et al.*, 2015; Kessler *et al.*, 2017) to define basement structures (faults and lineaments) and to create detailed crustal density models.
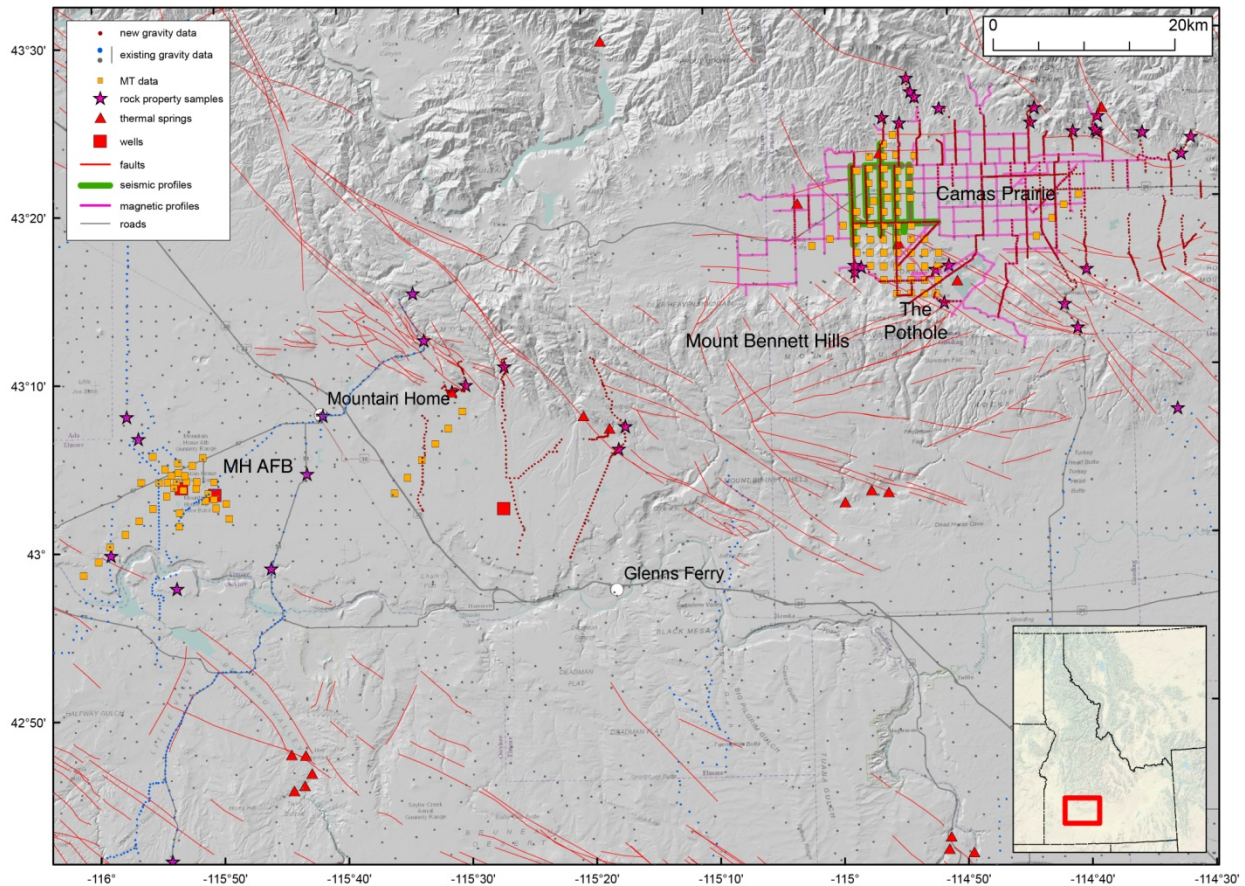

Figure 1. Location map for Snake River Plain PFA, showing data locations, faults, and main features. MH AFB = Mountain Home Air Force Base.

The MT survey was carried out in three study areas: 33 stations were acquired around the two deep drill holes (MH-1 and MH-2) on Mountain Home Air Force Base (Figure 2). The station array was designed to tie into the deep drill hole stratigraphy, and to capture structures identified in previous high-resolution gravity surveys. Another 63 stations were acquired in Camas Prairie, covering the same area surveyed by our new seismic, gravity and magnetic campaigns. Six more stations were acquired along a profile crossing a previously identified gravity anomaly near the Bostic 1A deep drill hole.In all three locations, MT was used to identify the presence and extent of a thick conductive layer corresponding to the known distribution of lacustrine sediments and possible alteration zones that are interpreted to represent a seal above any potential geothermal resource (Glen *et al.*, 2017).

2.3 Water Chemistry

Natural springs and wells were sampled in the Camas Prairie, Mount Bennett Hills, and western SRP regions, and several previously sampled locations were resampled to assess seasonal variations. These samples were analyzed for major and trace elements, and stable isotopes of oxygen, hydrogen, and helium. The chemical data were used to compute equilibrium reservoir temperatures using cation, silica, and multi-component geothermometry, O and H stable isotopes were used to identify the source of geothermal fluids and potential water–rock interaction, and helium isotope ratios were used to track mantle volatile inputs.
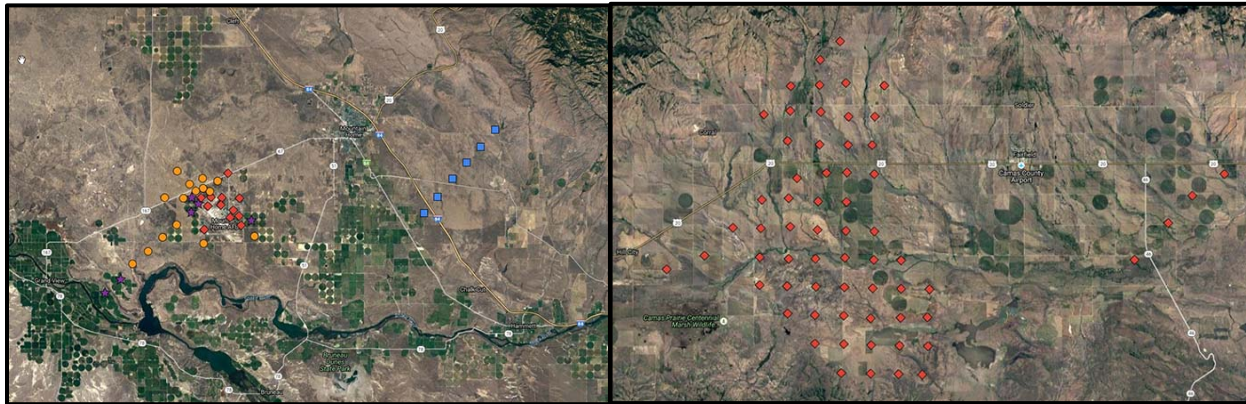

Figure 2. Locations of magnetotelluric stations: (a: left) MT station locations in Mountain Home AFB region. Red: MH-AFB sites, orange: BLM sites by AFB, purple: private land sites, blue: Bostic traverse sites (BLM); (b: right) MT station locations in Camas Prairie. The array is designed to capture structures associated with the Pothole Fault system.

3. Results

3.1 Field Mapping and Sampling

3.1.1 Western SRP

Volcanic vents in the Mountain Home region include older tholeiitic basalts (700 ka to 1.2 Ma surface flows), and younger high-K transitional alkali basalts (700-355 ka; Shervais and Vetter, 2009). These younger high-K basalts are ubiquitous in the WSRP and along the South Fork Boise River to the north, where they range in age from 100 ka to 2.1 ka in age.

The Mountain Home region is characterized by two fault systems: a range-front fault system that trends about N60W and an oblique fault system that trends about N85W (Shervais *et al.*, 2002). Surface faults are only exposed north of Mountain Home, close to the range front, but subsurface systems with similar orientations may be inferred from lineations defined by steep gravity and magnetic gradients.

3.1.2 Camas Prairie-Mount Bennett Hills

The Camas Prairie-Mount Bennett Hills region contains two dominant fault sets that strike WNW and ENE (Figure 3). In general, the WNW-trending faults are found in the eastern Mount Bennett Hills, east of the Pothole Fault, whereas the ENE-trending faults are found in the western Mount Bennett Hills, west of the Pothole fault (Figure 3). Young volcanic rocks in Camas Prairie are tholeiitic basalts erupted around 700 ka.
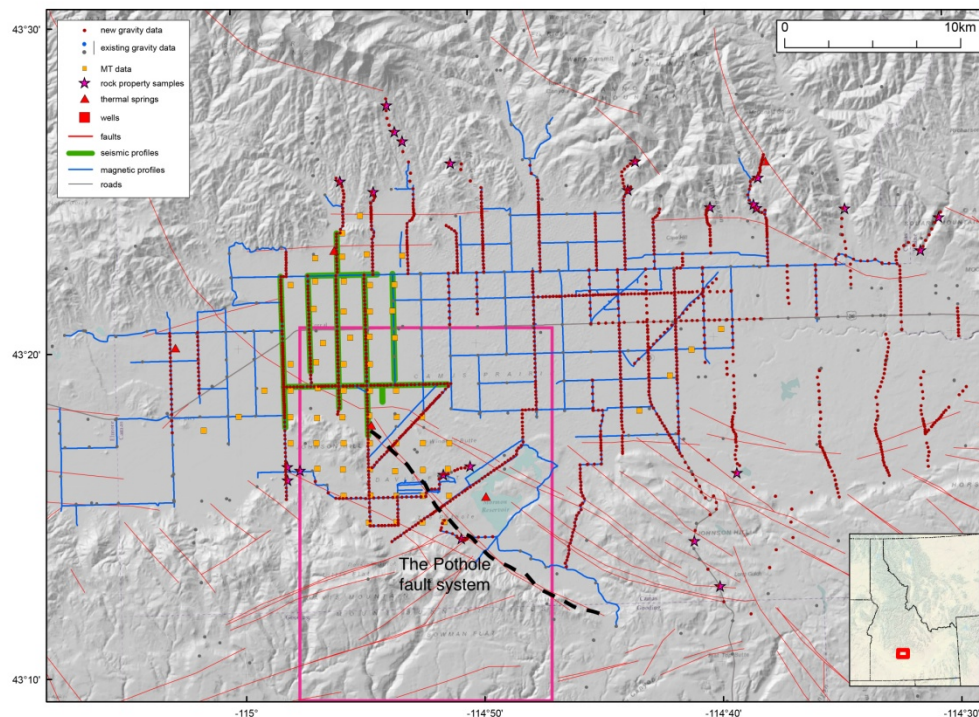

Figure 3. The Camas Prairie-Mount Bennett Hills region contains two dominant fault sets that strike WNW and ENE. In general, the WNW-trending faults are found in the eastern Mount Bennett Hills, east of the Pothole Fault, whereas the ENE-trending faults are found in the western Mount Bennett Hills, west of the Pothole fault. WNW-trending faults are also found along the range front near Mountain Home, where they interact with faults that trend almost EW.

Geologic reconnaissance mapping of the Pothole Fault system for this project documents more complex structures. The Pothole fault system is characterized by two dominant fault sets, which strike WNW and NNW. Both are predominantly east/northeast dipping. Fault striations were most commonly dextral-normal and secondarily normal. These orientations are more or less consistent with the attitudes of the major features at depth in the Camas basin, as interpreted from the geophysical studies described above. Relative ages of these fault sets could not be determined by cross-cutting relationships, however, the NNW striking faults cut Cretaceous basement, the Oligocene Challis Volcanic Group, and the Pothole volcanic crater (*circa* 700 ka), so these fault systems remained active into the late Pleistocene. We expect that right-stepping geometries between the two WNW- and NNW-striking, right-oblique fault systems (releasing steps) are more conducive to permeability development and geothermal circulation than left-stepping (restraining steps) geometries (Figure 4).

3.2 Geophysical Studies

3.2.1 Western SRP

A regional potential field model was developed for the western SRP based on high-resolution gravity data collected across the plain. In addition, seismic reflection results associated with the MH-2 borehole (Liberty *et al*., 2015) and new MT data (below) were used to refine this model. The dominant feature is a prominent gravity high that extends nearly the full length of the western SRP. This high is primarily modeled as a dense mafic root and sill complex intruded into the lower and middle crust (Figure 5). The featureis accentuated by a horst block in the upper crust consisting largely of dense mafic lavas (Glen *et al*., 2017).
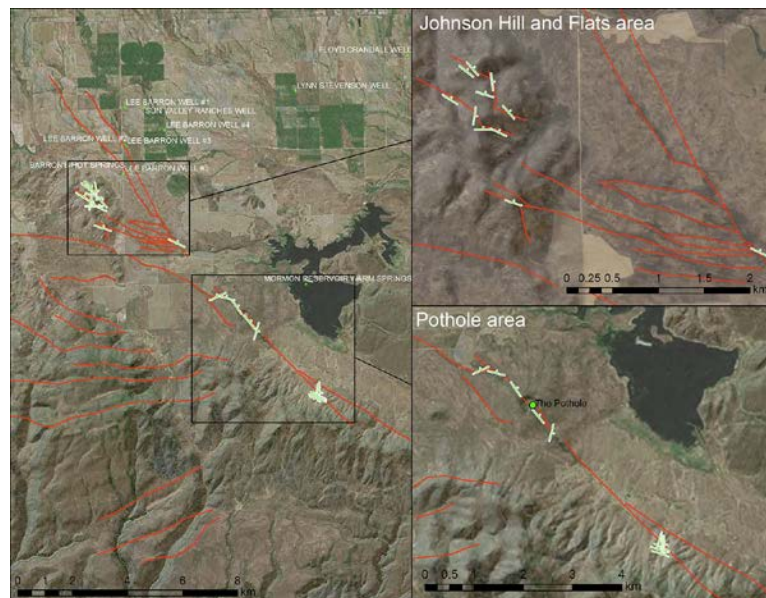

Figure 4. Detailed fault map of the Pothole area with fault attitude measurements and some hot springs and thermal wells shown

A 3D MT inversion was made with the Mountain Home data. The resistivity structure recovered by this inversion is shown in Figure 6. Low resistivity (1-10 Ohm-m) distribution in the 3D resistivity cube outlines the lateral and depth extent of what would be considered a seal for a potential geothermal reservoir. This includes both sedimentary layers and possible alteration zones. The uppermost resistive layer (200-500 Ohm-m) is representative of near surface unaltered porous basalts, whereas increased resistivity (50-70 Ohm-m) underneath the low resistivity structure is representative of volcanic formations (basalt, rhyolite) that could be associated with the presence of geothermal fluids. Similar structures were deduced on the eastern side of the basin, close to Bostic 1A, using MT data collected in 1980 by Unocal.

3.2.2 Camas Prairie-Mount Bennett Hills

Seismic results suggest bedrock (volcanic rocks or granite) depths of less than 1.0 km beneath the southern margin of Camas Prairie, and define a complex network of active faults that correspond to locations of elevated groundwater temperatures (Figure 7). These faults offset basement (inferred to be older volcanic and granitic rocks), and overlying strata, and show that the depocenter of the basin is located towards its southern margin. Multiple, basin-wide unconformities are identified with late Quaternary sediment fill of less than 0.2 km thick along the basin margins. This interpretation is consistent with those defined by gravity and magnetic surveys: residual isostatic gravity and magnetic grids in Camas Prairie delineate a number of intra-basin structures that reflect two dominant sets of trends, west- to west-northwest-trending structures that reflect the major structural grain, and a NW-trending set that appears to control the sub-basin geometry. These structures have little or no surface expression. 2D inversions of MT data along several N-S profiles in Camas Prairie deduced resistivity structures that support gravity and magnetic data interpretation. The outline of the basin east of stations CP15-17 (Figure 8) is clearly seen by a change in resistivity from low to high to the SW.
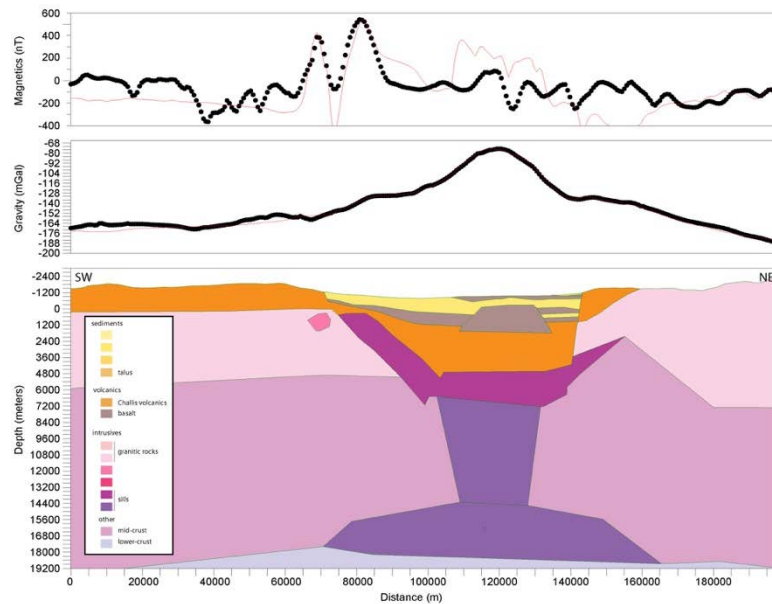

Figure 5. Two-dimensional geophysical model along across the western SPR. The top and middle panels show observed (black circles) and model (black line) anomalies for magnetics and gravity, respectively. The bottom panel shows the potential field model with individual model bodies colored by rock units. Profile through Mountain Home. From Glen et al., 2017.
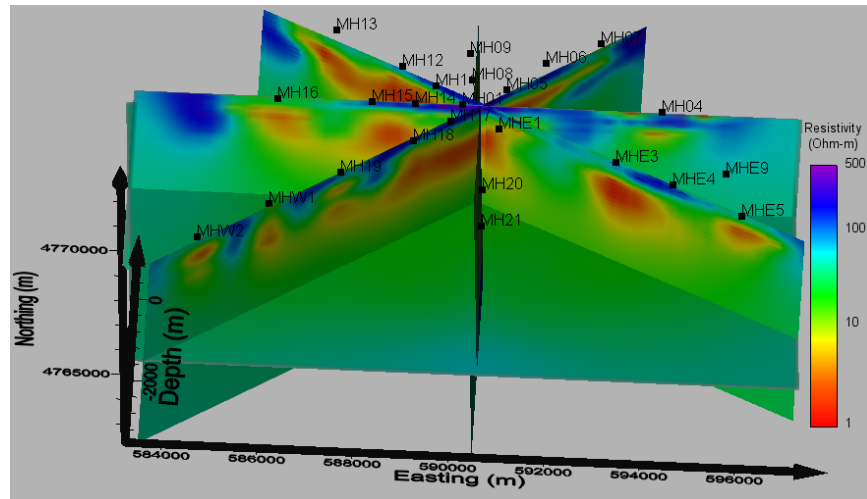
Figure 6. Fence diagram of final resistivity structure deduced by 3D MT inversion for the Mountain Home region. Low resistivity zones represent potential clay seals from lake sediments or alteration, or both. Crossing point on the fence panels is the MH-2 deep well. The deduced resistivity model shows clear change in the resistivity response from high to low when crossing the highest gravity-gradient that identifies a regional fault at the SW valley boundary. Within the basin, a thick sedimentary layer, at some places up to 1,500 m, has a low resistivity and overlies higher resistivity volcanic formations.
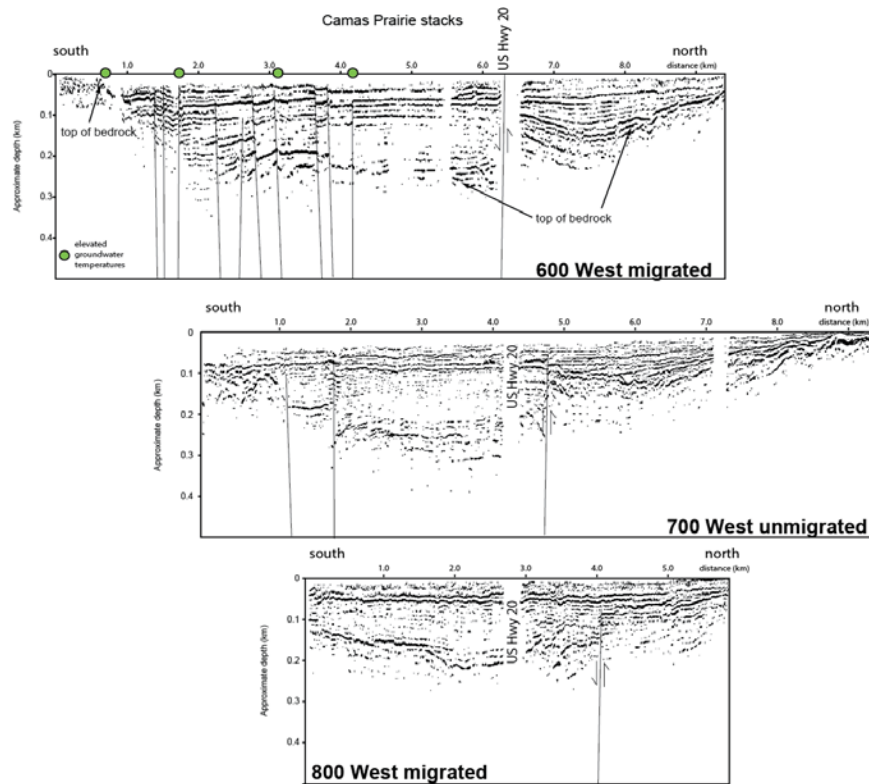

Figure 7. Seismic reflection profiles across Camas Prairie; locations shown in Figure 2 (600W to 900W profiles). All profiles run NS. Numerous faults in basement are evident as offsets in highly reflective markers. A major buried EW-trending fault lies under US HW20. The 600W profile shows location of thermal springs (green dots) relative to seismically identified faults. These faults correlate with offsets in gravity and magnetic potential fields, and are being integrated into the overall structural models.
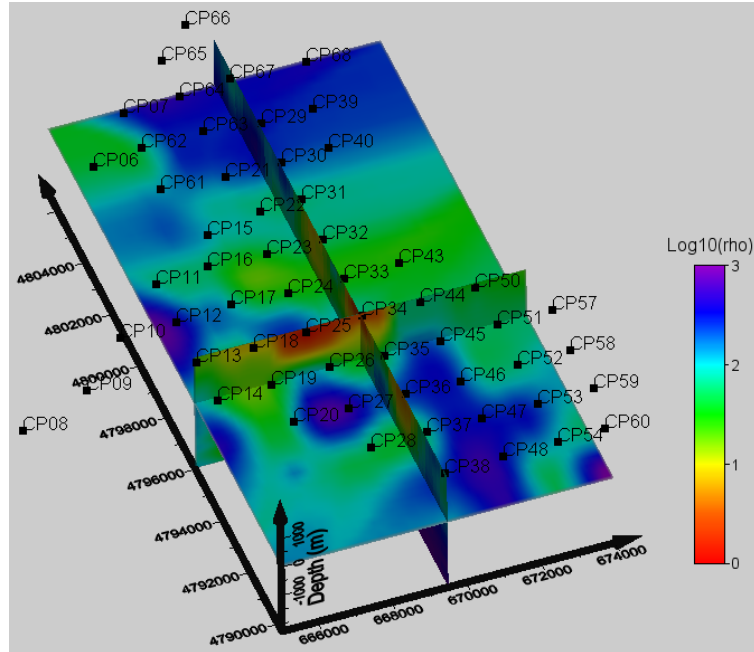
Figure 8. Fence diagram from 3D composite resistivity cube and depth slice of final resistivity structure deduced by MT inversion at Camas Prairie. The outline of the basin east of stations CP15-17 is clearly seen by change in resistivity from low (green) to high (blue) to the SW. Axes are Northing (to upper left) and Easting (to lower right).

3.2 Water Chemistry

Our new water chemistry results for the Camas Prairie and Mount Bennett Hills (Neupane *et al.,* 2017) show that, in general, cooler groundwater and spring samples are Ca-HCO$_3$-type waters, whereas hot spring and thermal well samples are Na-HCO$_3$-type waters (Figure 9). A mixing trend is observed between Ca-HCO$_3$ and Na-HCO$_3$ water types. Oxygen and hydrogen stable isotopic results show that most of the samples show a small degree of shift to the right, whereas a few water samples show significant shift to the right of the meteoric water lines, which is indicative of oxygen isotope exchange during high-temperature water-rock interaction in hydrothermal systems, or could indicate a water component derived from degassing magmas (Giggenbach*,* 1992). In general, water chemistry and isotopic compositions indicate that the hydrothermal system waters in Camas Prairie area are dominantly meteoric in origin with some modification from water-rock interaction, possibly, at high temperature.

We used multicomponent and conventional (quartz, Na-K, Na-K-Ca) geothermometry to estimate reservoir temperatures in Camas Prairie (Neupane *et al.,* 2017*).* The geochemical and geothermometry analysis indicates two interesting areas, one on the southern side and the other on the northern side of the Prairie, with estimated reservoir temperatures as high as 200ºC in the north and 110ºC in the south. Water chemistry and isotopic results suggest that the highest temperature resource is a mixture between deeply circulated fluids with a magmatic affinity and local meteoric recharge. The water geochemistry suggests that there are two potential geothermal resource types: one associated with the Idaho Batholith to the north, and a second related to

elevated heat flow associated with Quaternary volcanism and intrusions within the Snake River Plain province.
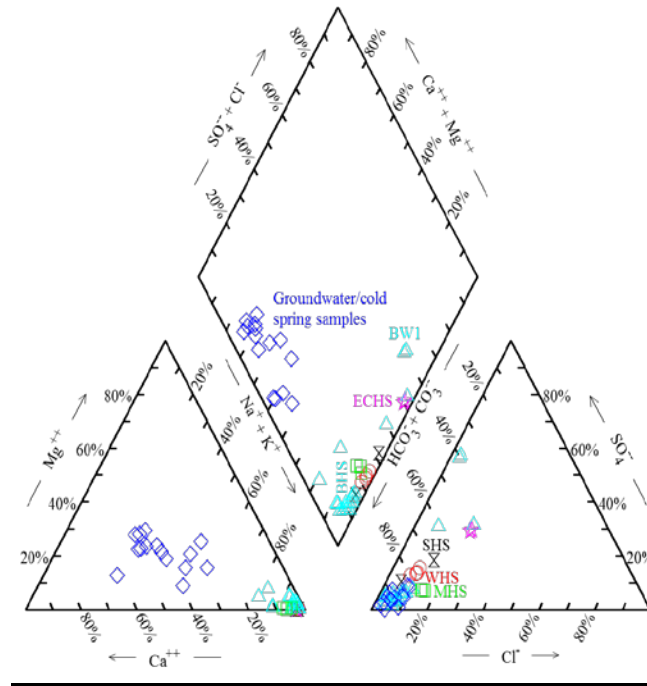

Figure 9. Piper diagram representing chemistry of water samples from Camas Prairie area. Samples are grouped as groundwater/cold springs (blue diamonds), Barron Hot Springs area (BHS, cyan triangles; BW1 indicates recent (2014 and 2016) water chemistry data of high sulfate water samples of the Barron Well 1), Sheep/Wolf Hot Springs (SHS, black hourglasses), Wardrop Hot Springs area (WHS, red circles), Elk Creek Hot Springs (ECHS, magenta stars), and Magic Hot Springs area (MHS, green squares). From Neupane et al., 2017.

4. Model Refinement

Advanced thermal modeling based on new and existing data include updated and refined ArcGIS models used to compare different data sets quantitatively, detailed stress and strain analysis, thermal reservoir and hydrologic modeling, and refined conceptual models.

4.1 Thermal Reservoir and THC Models

Preliminary thermal reservoir models were refined using new geological, geophysical, heat flow, and well data, as well as 3-D lithological and permeability models developed under other project tasks. In addition, a thermal-hydrologic-chemical (THC) model was developed that integrates magmatic cooling with THC evolution, looking at fluid flow along faults and alteration history as a function of the longevity of the heat source (Nielson *et al.,* 2017). This model combines aspects of the Mountain Home geothermal system with an exposed Pliocene sill (White, 2007) as our analogue for a shallow crustal intrusion as a heat source (Nielson and Shervais, 2014).

4.2 Detailed Stress-Strain Analysis

The orientation of stress fields is a critical part of defining reservoir characteristics. Our detailed structural mapping of fault systems in Camas Prairie allowed us to evaluate local stress regimes and the strain response to that stress, yielding refined estimates of the local stress fields and their orientation. The stress data are used to weight fault and lineament slip and dilation tendencies, both of which are proxies for permeability on these structures. These data can be compared with regional stress and strain estimates from previous studies (e.g., Payne *et al.*, 2012; Kessler *et al.*, 2017).

4.3 Basaltic Sill Conceptual Model

One of the axes on our *Play Risk Matrix* is confidence in the *conceptual model*. Although much of our effort has been focused on data and its statistical treatment, the *conceptual model* remains an important issue. We have refined our preliminary conceptual model (Nielson and Shervais, 2014), integrating new data and the results of the thermal reservoir and THC modeling. This model is based on the intrusion of a mid- to upper-crustal basaltic sill complex (Figure 10), where the magma supply rate exceeds the extension rate of crustal deformation, leading to a build-up of heat that drives geothermal circulation (Nielson et al., 2017).
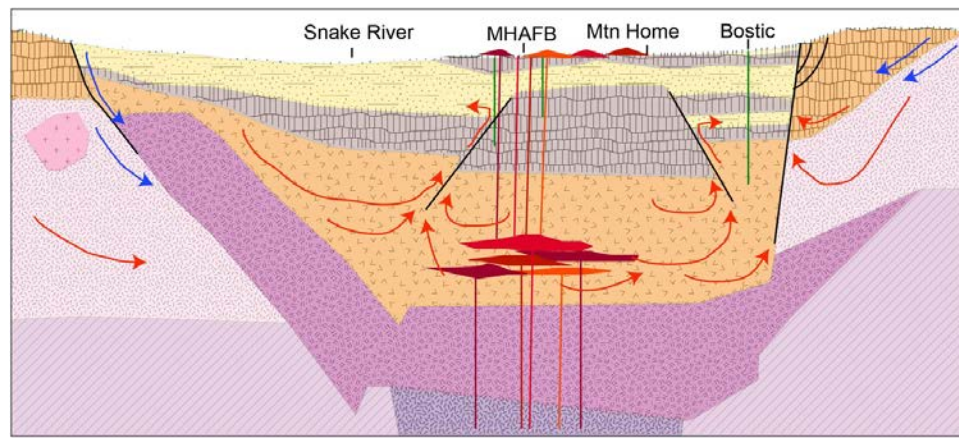

Figure 10. Cartoon illustrating our conceptual model of the structure and geothermal system of the western SRP relevant to the Mountain Home and Bostic study areas. Older volcanic rocks (dark pink) form a basin-wide sag structure, with young sills intruded around 2 km below present surface. This young sill complex (≤355 ka) drives hydrothermal circulation of deep convecting fluids. These fluids are in equilibrium with mafic volcanic rocks, shifting its oxygen isotope concentration to lighter values. High extension with respect to magma supply results in feeder dikes and rapid ascent to the surface whereas high magma supply with respect to extension produces sills or plutons. We have proposed that the Graveyard Point Sill, located in eastern Oregon, is an analog for the buried mafic heat source of the Mountain Home geothermal system. On the basis of field mapping (e.g., White, 2006), we estimate that the Graveyard Point sill had an average thickness of 100 m, a total volume of about 3 km^3, and was emplaced at a temperature of ~1200ºC.

4.4 GIS Methodology

We recast our initial GIS methodology (DeAngelo *et al*., 2016) into a format that will read data weights, including intra- and inter- CRS weight factors and confidence weights, from a look-up table that can be easily reprogrammed to evaluate new combinations of data and weights. We also prepared high resolution (500 m and 100 m) CRS and CCRS maps to aid in prospect evaluation, carried out a sensitivity analysis on our CRS maps to reveal which data types they are most sensitive to, and prepared new CRS maps with different combinations of weight factors to evaluate how different expert opinions affect the final products. We also validated our GIS methodology by utilizing the input data set developed by the Modoc Plateau play fairway project (Siler *et al.,* 2017) and compared their output maps with those generated using our methodology – good agreement between the two methods was observed.

5. Data Integration and Analysis

5.1 Data Integration

New data and model results from Phase 2 were collated with existing data to update our CRS and CCRS maps for the Snake River Plain, and for our primary focus areas: (1) the western SRP blind systems near Mountain Home, Idaho, and the Bostic 1A deep well, and (2) the central Camas Prairie region near Fairfield, Idaho. As in Phase 1, the distribution of heat was assessed using measured thermal gradients, interpolated heat flow values, the distribution of volcanic vents (weighted by age, size, and composition), groundwater temperatures in non-thermal wells, measured temperatures of thermal waters from springs and wells, calculated cation, silica, and multicomponent geothermometry of thermal waters from thermal springs and wells, and the distribution of ^{3}He/^{4}He in thermal waters (DeAngelo *et al.,* 2016; Shervais *et al.,* 2016; Neupane *et al.,* 2014, 2017; Dobson *et al.,* 2015).

Permeability was assessed using the weighted sum of mapped faults, magnetic lineaments, and gravity lineaments (DeAngelo *et al.,* 2016; Shervais *et al.,* 2016). Fault and lineament segments were weighted using slip and dilation tendencies, based on new data for regional stress orientation (Glen *et al.,* 2017; Kessler *et al.,* 2017). As in Phase 1, structural intersections were assessed using density functions as a proxy for fault/lineament density, where high fault (or lineament) densities tend to favor multiple intersections (Shervais *et al., 2016*). Detailed mapping of the Pothole Fault system in the Camas Prairie-Mount Bennett Hills allowed us to further identify specific configurations of fault intersections (e.g., Faulds et al., 2013) that are more favorable to permeability.

On a regional scale there are two potential seal types: (a) fine-grained lacustrine sediments, which are largely impermeable, and (b) self-seal of volcanic rocks by hydrothermal alteration (Nielson and Shervais, 2014). Locally, we were able to use 2D and 3D arrays of MT stations to document the occurrence of low resistivity seals in both of our focus areas.

5.2 Data Analysis

Our new CRS and CCRS maps show that both focus areas have sites with high prospectivity for geothermal resources. In the Mountain Home region, potential drilling sites are constrained by

the *Morley Nelson Snake River Birds of Prey Conservation Area*, a BLM special use area that limits potential drill site locations. Prospective areas are found just west of Mountain Home and south of I-84, and in the area of Mountain Home Air Force Base (Figure 11). The resource in these areas has no surface expression and, based on the results from holes drilled at Mountain Home AFB, is likely located at depths of 1.5 to 2.3 km depth. In the Camas Prairie region, prospective areas are found along the Pothole fault system (Figure 3), where it forms oblique intersections with numerous small faults to the south and west (Figure 12). The resource here is indicated by thermal springs that cluster along the fault systems and elevated $^3He/^4He$ ratios (~2 R/Ra); target depths are expected to be as shallow as 0.5 to 0.7 km.
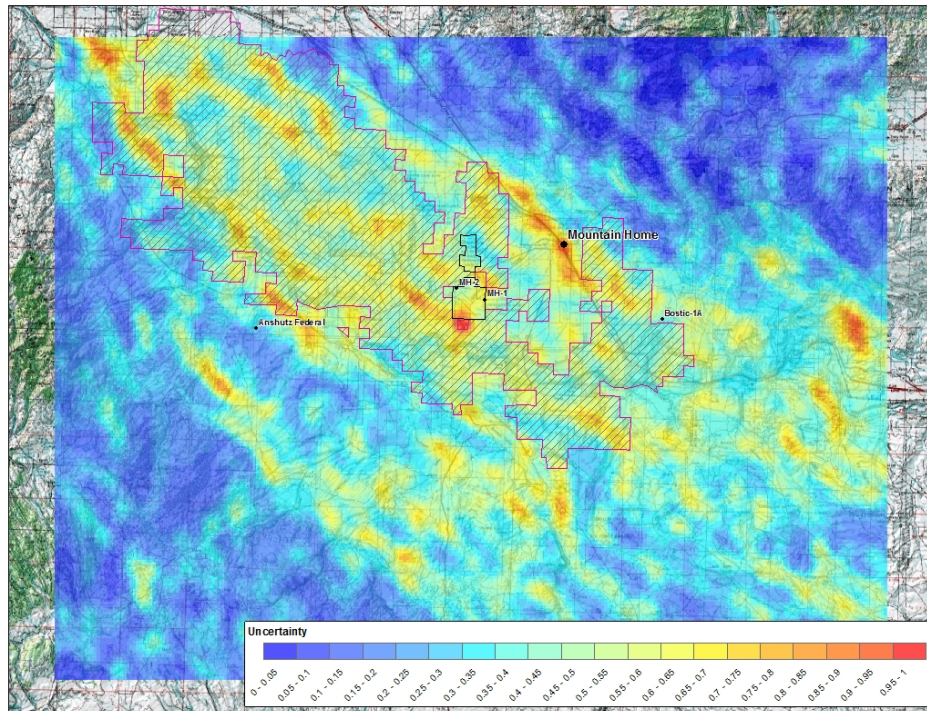

Figure 11. Composite Common Risk Segment (CCRS) map for the western SRP. Scale represents favorability scores ranging from zero (lowest, blue) to one (highest, red). Highly favorable areas are at the southern edge of Mountain Home AFB (south of MH-1 and MH-2), along the range front new the town of Mountain Home, and farther to the northwest (south of Boise, not shown). The cross-hatching indicates the Birds of Prey National Conservation area.

6. Conclusions

The Play Fairway approach to geothermal exploration appears to offer a robust methodology for integrating large amounts of diverse data into a series of products that can be used to infer potential resources more effectively than traditional approaches. It can easily be adapted to a range of playtypes in different geothermal settings, and when implemented properly, facilitates decision making in regions where data coverage is sparse, or uneven in distribution and quality.

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.
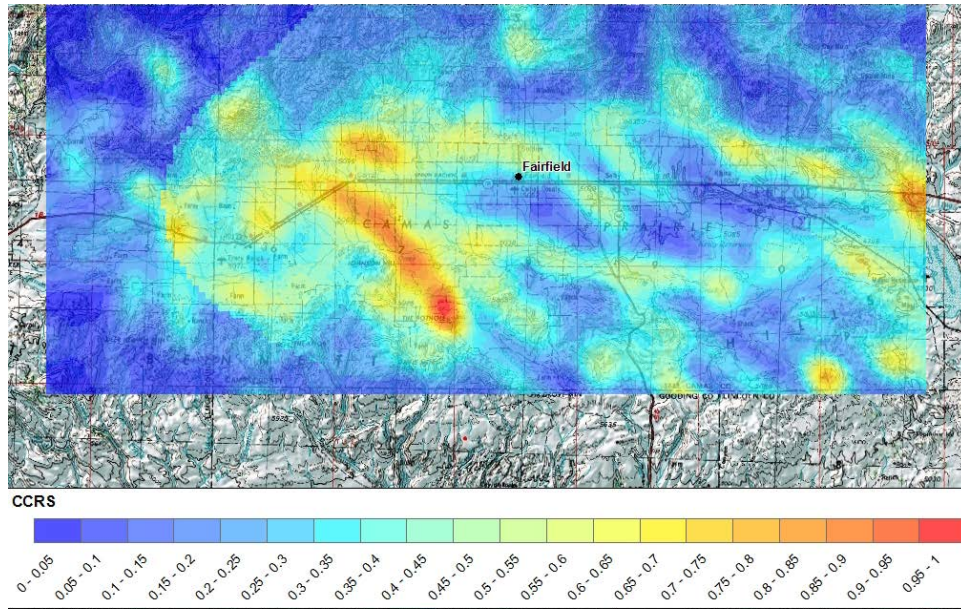

Figure 12. Composite Common Risk Segment (CCRS) map for the Camas Prairie. Scale represents favorability scores ranging from zero (lowest, blue) to one (highest, red). Highly favorable areas are along The Pothole fault system, which trends NW-SE across the map.

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