Snake River Plain Play Fairway Analysis – Phase 1 Report

John W. Shervais[1], Jonathan M. Glen[2], Lee M. Liberty[3], Patrick Dobson[4],
Erika Gasperikova[4], Eric Sonnenthal[4], Charles Visser[5], Dennis Nielson[6], Sabodh Garg[7],
James P. Evans[1], Drew Siler[4], Jacob DeAngelo[2], Noah Athens[8], Erick Burns[8]

[1]Department of Geology, Utah State University, 4505 Old Main Hill, Logan, UT 84322-4505
[2]US Geological Survey, MS989, 345 Middlefield Road, Menlo Park, CA 94025
[3]Center for Geophysical Investigation of the Shallow Subsurface, Boise State University, Boise, ID 83725-1536
[4]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley CA 94720
[5]National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401
[6]DOSECC Exploration Services, LLC., 2075 Pioneer Rd., Suite B, Salt Lake City, UT 84104
[7]Leidos, Inc, 10260 Campus Point Drive, M/S C2E San Diego, CA 92121
[8]US Geological Survey, 2130 SW 5th Ave, Portland, OR 97201

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ABSTRACT

The Snake River volcanic province (SRP) overlies a thermal anomaly that extends deep into the mantle; it represents one of the highest heat flow provinces in North America. Our goals for this Phase 1 study are to: (1) adapt the methodology of Play Fairway Analysis for geothermal exploration to create a formal basis for its application to geothermal systems, (2) assemble relevant data for the SRP from publicly available and private sources, and (3) build a geothermal play fairway model for the SRP and identify the most promising plays, using software tools that are standard in the petroleum industry. The success of play fairway analysis in geothermal exploration depends critically on defining a systematic methodology that is grounded in theory (as developed within the petroleum industry over the last two decades) and within the geologic and hydrologic framework of real geothermal systems.

Our preliminary assessment of the data suggests that important undiscovered geothermal resources may be located in several areas of the SRP, including the western SRP (associated with buried lineaments defined by gravity or magnetic anomalies, and capped by extensive deposits of lacustrine sediment), at lineament intersections in the central SRP (along the Banbury-Hagerman trend NW of Twin Falls, and along the northern margin of the Mt Bennett Hills-Camas Prairie area), and along the margins of the eastern SRP. Additional high temperature resources are likely associated with rhyolite domes and crypto-domes in the eastern SRP, but are masked by shallow groundwater flow leading to low upper crustal heat flow values. These blind resources may be exploitable with existing deep drilling technology. Groundwater modeling planned for later phases of the PFA project will address whether temperatures at viable producing depths are sufficient to support electricity production.

1. INTRODUCTION

The Snake River volcanic province in southern Idaho (Figure 1) formed in response to movement of the continental lithosphere over a deep-seated mantle thermal anomaly ("hotspot") that has thinned the lithosphere and fueled the intrusion of hot basaltic magma into the lower and middle crust, forming a layer over 10 km thick (*Shervais et al., 2006a, 2006b*). The heat from these intrusions drives the high heat flow and geothermal gradients observed in deep drill holes throughout the Snake River Plain (SRP: *Blackwell, 1980, 1989; Brott et al., 1978, 1981; Lewis and Young, 1989*). The SRP is one of the highest heat flow regions in the United States. Idaho was ranked third among western states for potential geothermal power production, with 855 MW of near-term economic potential resources, by the Geothermal Task Force of the Western Governors' Association (*Western Governors' Association, 2006).* Identification of blind resources should spur commercial development (*Nielson et al., 2012; Nielson and Shervais, 2014*) in this undeveloped area.

Play Fairway Analysis is an approach to exploration pioneered by the petroleum industry that integrates data at the regional or basin scale in order to define exploration targets (*plays*) in a systematic fashion. It then interrogates these data to highlight which plays have the highest likelihood of success (*prospects*). *Play Fairway Analysis* provides greater technical rigor than traditional exploration approaches, and facilitates quantitative risk-based decisions even when data are sparse or incomplete (*Shell Exploration and Production, 2013*).

Play Fairway Analysis is a mature science in petroleum, but it is a new exploration technique for the geothermal industry. Past techniques were based on conceptual models of systems as a whole, or targeted individual sites, and current exploration methodologies address those conceptual models *(Ward et al., 1981)*. The geothermal industry has evolved from drilling hot spring occurrences to blind exploration of known or inferred geothermal trends, and has identified distinct geothermal play types (*e.g., Moeck, 2014*), but has not adopted Fairway analysis. This represents a new approach that we believe will aid in the discovery of buried or blind geothermal systems. A key challenge is to adapt this analysis in a way that provides meaningful results and measurable return on investment *(Nielson et al., 2015)*.

Our goals for Phase 1 study were to: (1) adapt the methodology of *Play Fairway Analysis* for geothermal exploration by creating a formal basis for its application to geothermal systems, (2) assemble relevant data for the SRP volcanic province from publicly available and private sources, and (3) build a geothermal play fairway model for the Snake River Plain that will allow us to identify the most promising plays, using software tools that are standard in the petroleum industry. Our specific objectives include defining the critical elements that characterize a viable geothermal system (heat source, reservoir, and seal), integration of the diverse data sets that may be used to characterize these critical elements within a single analytical platform (Arc GIS), and interrogation of these data to produce *Common Risk Segment* maps and *Composite Common Risk Segment* maps *(e.g., Shell Exploration and Production, 2013)*.

2. METHODOLOGY

Our approach is to analyze direct and indirect indicators of geothermal potential in order to identify the three critical geothermal resource parameters: *heat source, reservoir,* and *seal (Nielson et al., 2015)*. The project is divided into three phases: Phase 1 will assess the distribution and viability of plays throughout the SRP region using existing data sources; Phase 2 (if selected) will focus on detailed analyses of specific promising plays, including collection of new field data where needed; Phase 3 (if selected) will focus on a specific prospect identified in Phase 2, which may include drilling of a exploration slimhole to confirm its geothermal potential. Preliminary results of Phase 1 work are documented here.

Our workflow is modified from the petroleum industry, using industry-standard tools for data integration and modeling where appropriate. We used *ArcGIS,* with extensions for spatial and geostatisical analysis, 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. *IHS Kingdom* and *Petra* suites of software are used for 3D stratigraphic models based on well logs. Other software tools include *Oasis Montaj*®, which integrates 3D geophysical and geologic data modeling with ArcGIS layers; 3DStress, which analyzes fault dilation tendency and fault slip tendency based on interpolations of the regional stress field and fault orientation; *Team-GIS* from Exprodat, a set of petroleum industry extensions to ArcGIS for play fairway analysis; Google Earth Pro®, used to "field check" data such as volcanic vent locations, and to review ArcGIS shape files by team members.

Data are assembled from a range of public and private sources, both published and unpublished, and imported into ArcGIS to create a series of evidence layers for later analysis. Significant data types and sources include:

1. Heat flow and thermal gradient drillhole data compiled by the USGS and the SMU Geothermal Lab (*e.g., Williams and DeAngelo, 2008; 2011; Blackwell et al., 1989; Blackwell and Richards, 2004*), plus data from the National Geothermal Data System (Figure 2).
2. Geologic maps published by the USGS and Idaho Geological Survey, and unpublished maps; most available as GIS shape files (Figure 3a). Publicly available. *http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html*
3. Quaternary faults and lineaments from the USGS fault database and from geologic maps (Figure 3b). Publicly available. *http://earthquake.usgs.gov/hazards/qfaults/, http://mrdata.usgs.gov/, http://web2.nbmg.unr.edu/arcgis/rest/services/ID_Data/IDActiveFaults/MapServer*
4. Geophysical data: gravity and magnetic potentials, resistivity, MT and regional stress data compiled by the USGS, including new high-resolution gravity and magnetic data produced by Project Hotspot and the distribution of subsurface lineaments derived from maximum horizontal gradients in gravity and magnetic data. Publicly available: *http://research.utep.edu/Default.aspx?tabid=37229, http://crustal.usgs.gov/projects/namad/the_project.html, http://pubs.usgs.gov/of/1999/ofr-99-0371/idaho.html, http://pubs.usgs.gov/of/1999/ofr-99-0557/html/id_1st.htm.*
5. Seismic reflection and refraction lines, mostly in the western SRP, including publicly available lines shot by Chevron in the 1980's. Publicly available, owned by participants, or for sale by the Seismic Data Exchange.
6. Location and age of volcanic vents, as well as petrology, geochemistry and age of the lavas, and petrologic models of their thermal budgets (Figure 3c). Primary data from published and unpublished databases (*e.g., North American Volcanic and Intrusive Rock Database - NAVDAT*). Publicly available.
7. Lithologic and bore hole geophysical logs of deep wells, e.g., test wells at the INL site, USGS water resource and geothermal test wells, passive geothermal wells (Boise, Twin Falls districts), and wildcat petroleum exploration wells. These data are maintained by USGS, Idaho Geological Survey and Idaho Land Commission (Oil & Gas wells). Publicly available.
8. Geochemistry and geothermometry of geothermal well and thermal spring waters, from USGS and NGDS databases and other available data. Includes integration of recently developed multi-component geothermometry with more classical methods (*e.g., Peiffer et al., 2014; Palmer, 2014*). Publicly available, and contributed by collaborators from other GTO-funded projects at INL-University of Idaho *(Neupane et al., 2014)*, and LBNL *(Dobson et al., 2015)*.

9. Groundwater temperature distribution, which reflects thermal flux from below (Figure 3d). *http://resources.usgin.org/uri-gin/idwr/.*
10. Rock mechanical properties of core, correlated with borehole geophysical logs *(Kessler, 2015)*.
11. Data for land access analysis: GIS Shape files publically available from various Federal (USGS, BLM and USFS) and State agencies, and private sources. Available thru NREL. *https://maps.nrel.gov/geothermal-prospector/#/?aL=nBy5Q_%255Bv%255D%3Dt&bL=groad&cE=0&lR=0&mC=40.21244%2C-91.625976&zL=4*
12. NREL comprehensive worldwide database of geothermal reservoir properties for the development of geothermal occurrence models. Available through NREL. *https://maps.nrel.gov/geothermal-prospector/#/?aL=nBy5Q_%255Bv%255D%3Dt&bL=groad&cE=0&lR=0&mC=40.21244%2C-91.625976&zL=4*

GIS specialists at the USGS geothermal program prepared Python scripts to automate the process of risk segmenting using ArcGIS functions and custom processing. Kernel density functions assess data density (e.g., vents, fault segments) by counting all instances of a data point within a specified radius of a single point and dividing by the area of the search radius. This density is then distributed from a maximum at the location of the data point to zero at the full radius of the search area using a quadratic function. Data points may be weighted prior to counting. In our workflow, volcanic vents are weighted by age (1.0 for the youngest to 0.1 for the oldest) and size (1.0 for large shield vents or hydrovolcanoes, to 0.1 for small spatter vents satellite to a larger vent). Fault segments are weighted by both dilation tendency and slip tendency, as determined by the 3DStress software, on a scale from zero to 1.0 (Figure 4).

Data interpolation for point or line sources is carried out with either a radial basis function (RBF), inverse distance weighted (IDW), or by kriging, depending on data density and desired result. The RBF and IDW functions are exact interpolators, so no variance or standard errors are predicted.

Data uncertainties are assessed using a combination of fuzzy logic (user assigned uncertainty weights for non-interpolated data) and kriging standard error (a Bayesian method for interpolated data). Examples of non-interpolated data include data derived from geologic mapping, which are weighted based on published map scale (high certainty for 1:24,000 scale, lower certainty for 1:250,000 scale). This includes volcanic vent locations and faults. Examples of interpolated data are heat flow and groundwater temperatures, which are interpolated across the study area from a finite number of well locations. Risk maps for each primary evidence layer are produced by combining the evidence layer (which shows likelihood of a resource characteristic being present) with the data uncertainty maps (which assesses likelihood of data being reliable or complete).

3. RESULTS

A Resource Attribute worksheet was created to summarize important properties and what types of data can be used to establish them. The Snake River Plain was divided into regions based on differences in tectonic and volcanic setting, which are likely to have distinct play types, and subregions for areas of interest adjacent to the margins of the plain (Figure 2).

The data collected include geologic maps at scales from 1:24,000 to 1:250,000, structural features (faults, lineaments), vent locations, ages, and types from geologic maps and other sources, heat flow from the USGS and SMU databases, groundwater temperatures (USGS, IDWR), existing regional gravity data as well as newly collected high resolution profile data, and processed potential field data yielding depth to source and curie temperature, passive seismic velocity, magnetotelluric and crustal thickness data from Earthscope, regional EM data from USGS reports, the location of 56 commercially-available active source seismic lines and other public domain seismic lines, distribution, thickness and age of lacustrine sediment seals, the distribution and temperatures of thermal springs and wells from IDWR and NGDS, water chemistry and stable isotope chemistry from USGS and from partner GTO-funded projects, and He isotopes from partner GTO-funded projects. Boise State completed the analog to digital conversion of about 210 km of seismic lines from the western SRP, including six lines from the Seismic Data Exchange inventory of seismic profiles from the WSRP (160 km) and seven digital profiles from other sources (50 km). This inventory does not include many of the short profiles collected by Boise State projects.

Four play-types have been defined in Idaho: (a) SRP basaltic sill-complexes: fault-controlled permeability; volcanic sill heat source; lake sediment seal in the west, clay alteration of basalt in the east; a subset of this type: Craters of the Moon – very young basaltic rift setting; (b) shallow silicic intrusions and domes, which may create their own permeability during intrusion, *e.g.*, Big Southern Butte and other silicic domes (Cedar Buttes); (c) Basin-and-Range systems: fault-controlled permeability, deep heat source (e.g., Raft River); and (d) granite-based systems – Idaho Batholith (e.g., Young, 1985). Types (a) and (b) are associated with the SRP, while (c) and (d) are outside the study area and/or are studied by other projects (c.f., Faulds et al., 2013).

Critical element risk matrices were produced for play types (a) and (b) that assess model favorability against data confidence (Figure 5). The primary focus for these risk matrices was on heat source and reservoir quality (permeability). Reservoir seal consists of either impermeable sediments, whose distribution is relatively well known, or alteration self-seal, which is more difficult to assess.

3.1 Source (Heat)

There are three potential indicators of heat source: heat flow, volcanic vent distribution, and hot springs or wells. Heat flow is uniformly high across the SRP (~110 mW/m^2), except in the eastern SRP, where shallow thermal flux is masked by advective transport of heat through the immense Snake River Aquifer (Figure 2). The influence of the aquifer on the heat flow pattern is demonstrated by comparing heat flow determined using all thermal gradient wells (Figure 2a) with heat flow determined using only those wells deep enough to penetrate the aquifer in the east (Figure 2b). The effect of the aquifer is to suppress conductive gradients above and within the aquifer, so that temperatures greater than 150ºC require wells deeper than 2.5 to 3.0 km (i.e., up to 1 km deeper in the eastern SRP). In contrast, areas of the central and western SRP lie outside the influence of the aquifer and are characterized by high thermal gradients (~75ºC/km) and high heat flow (~110 mW/m^2).

Because the recent transmission of lava to land surface is indicative of subsurface emplacement of magma (heat source), an alternate measure of potential heat is the distribution of young volcanic vents (Figure 3c). These vents are generally younger (<780 ka) and more common in the eastern SRP; however young vent clusters also occur in the western SRP, where they are characterized by primitive compositions and high mantle potential temperatures (*Shervais and Vetter, 2009*). The youngest vents (≤50 ka) are found in the Craters of the Moon-Great Rift cluster (Figures 2a, c); however, almost all of these vents lie within the expanded Craters of the Moon National Monument, and are thus off-limits to geothermal development.

The third set of potential indicators of heat source, hot springs and thermal wells, are most commonly located on the margins of the SRP, e.g., the Boise Thermal District and the Twin Falls Thermal District, both of which are characterized by moderate fluid temperatures (30-40ºC) and have been used for district space heat for decades (*e.g., Street and DeTar, 1987*). The most prominent hot spring districts are

Banbury-Miracle (on the Snake River west of Twin Falls) and Magic-Camas (along the northern front of the Mount Bennett Hills). Both areas are associated with regional-scale fault intersections (see permeability discussion below), and are characterized by high reservoir temperatures calculated using multicomponent geothermometers (*Neupane et al., 2014*) and high $^{3}He/^{4}He$ ratios (*Dobson et al., 2015*). In particular, the high $^{3}He/^{4}He$ isotope ratios imply recent heat source emplacement (magmatic input) from great depth along faults which penetrate the crust. High temperature thermal fluids (~150ºC) were also encountered in an exploration well in the western SRP on Mountain Home Air Force Base (*Shervais et al., 2012; Lachmar et al., 2012; Nielson et al., 2012*), indicating a previously unidentified permeable zone at depth.

3.2 Reservoir (Permeability)

Faulds et al. (2013) have shown that 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. The scale of mapping in southern Idaho is generally not sufficient to document these locally, but regional trends (Figures 1, 3b) suggest three major areas of fault interactions: (a) the Banbury-Miracle trend, where NW-trending faults of the western SRP refract into N-trending Basin and Range faults through intermediate faults which intersect both; (b) the western Camas Prairie region, where the N-dipping Danskin Mountains (to the west) and S-dipping Mount Bennett Hills (to the east) intersect in a major accommodation zone, and (c) along the northern margin of the Mount Bennett Hills, where the multiple NW- and NE-trending faults within the mountains intersect the main range front faults that form the Camas Prairie rift (*Cluer and Cluer, 1986*).

A proxy for fault intersections is fault density, where high fault densities tend to favor multiple intersections. In order to select areas in which faults create permeability, we weight the faults by dilation tendency and slip tendency, as described in Methods. Fault density maps (e.g., Figure 4) generally are restricted to the margins of the SPR, but (outside of the Basin and Range regions) show high densities in the three areas discussed above, as well as along the borders of the western SRP and within the Owyhee Plateau. A similar exercise carried out for buried structures using high horizontal gradients in the gravity and magnetic anomalies 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 (*Nielson and Shervais, 2014*), which encountered an artesian hydrothermal system at 1745 m depth, characterized by <50% core recovery, suggesting high permeability and large apertures.

3.3 Seal

According to our model *(Nielson and Shervais, 2014)*, the SRP geothermal system has two potential seals: (a) fine-grained lacustrine sediments, which are largely impermeable and (b) self-seal of volcanic rocks by hydrothermal alteration. The first is relatively easy to map; the second much more difficult. The distribution of lake sediments in well known in the western SRP, where regional formations consisting largely of lacustrine sediments are widespread (e.g., Bruneau, Glens Ferry, and Chalk Hills Formations). These formations were deposited by paleo- Lake Idaho, which filled the western SRP for much of its existence, and provide an impermeable seal 0.5-1.6 km thick (Wood and Clemens, 2002). These formations continue into the central SRP, but gradually pinch out from west to east (e.g., Jean et al., 2013). In the eastern SRP, there are two areas with lake deposits: the Burley area, with up to 100 m of sediment attested in well logs, and paleo-Lake Terreton, along the northern margin of the northeastern SRP.

For a traditional geothermal reservoir within volcanic deposits at depth, a permeable zone needs to be capped by a zone of alteration. Because volcanic deposits are highly heterogeneous, and the thermal resource is at great depth, self-seal by alteration is difficult to ascertain without core data. Sant (2012) has documented that the base of the Snake River Aquifer is controlled by the onset of clay alteration in basalt groundmass. Rocks in the MH-2 well are self-sealed by smectite alteration below ~950 meters depth. Predicting self-seal in blind systems will require more geophysical data.

3.4 Plays and Prospects

A preliminary assessment of plays and potential prospects based on the results discussed above suggests several areas where undiscovered geothermal resources may be found based on indicators of sufficient heat source and probable sufficient permeability below a sealed zone. Systems with dispersed surface indicators include: (a) the Banbury-Miracle hot springs areas, which lie 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 high $^{3}He/^{4}He$ ratios. (b) The Magic Hot Spring-Camas Prairie area, characterized by complex fault interaction zones at both the western and eastern ends (major accommodation zone with the Danskin Mountains in the west, range front fault intersections in the east). Camas Prairie is underlain be relatively young volcanic rocks, and surface manifestations include hot springs with high calculated reservoir temperatures and high $^{3}He/^{4}He$ ratios (*Dobson et al., 2015*). Blind systems, which lack surface indicators, include (c) those parts of the western SRP underlain by steep horizontal gradients along the northern and southern margins of the major gravity anomaly, and (d) areas along the margins of the eastern SRP characterized by high heat flow and young volcanism, but which lack significant indicators of subsurface permeability; these areas are not good prospects for hydrothermal systems but may be viable EGS sites.

3.5 Future Work

Future work planned for Phase 2 of this project will focus on refining our methodology and data products, and on the collection of critical new data in selected areas of interest to help validate this method. New data we deem critical to a robust evaluation of potential geothermal prospects include magnetotelluric surveys of the most promising areas to delineate regions of enhanced permeability and seals, limited seismic imaging to constrain stratigraphy, new Ar-Ar ages for volcanic rocks to establish the age of youngest volcanism, targeted water chemistry with full spectrum elemental analyses, stable isotope analyses, He-isotope analyses, LIDAR surveys to confirm active fault distributions, and a campaign of field investigations to verify and enhance existing field data.

4. SUMMARY AND CONCLUSIONS

We present an approach to Play Fairway Analysis that is adapted for use in geothermal exploration, and based on previously discussed conceptual models (e.g., Nielson and Shervais, 2014; Nielson et al., 2015). We have developed a systematic workflow by creating custom Python scripts that use ArcGIS functions and Python processing to automate data analysis. ArcGIS may use either raw data or synthetic data products (e.g., fault dilation and slip tendency) derived from other programs for primary evidence layers. Density calculations are carried out using ArcMap's weighted kernel density function and data interpolation maps will be built using ArcMap's Geostatistical Analyst tools, such radial basis function (RBF), inverse distance weighted (IDW), or Kriging, depending on data density and desired result.

Our preliminary assessment of the data suggests that important undiscovered geothermal resources exist in several areas of the Snake River Plain, including the western SRP (associated with buried lineaments defined by gravity or magnetic anomalies, and capped by extensive deposits of lacustrine sediment), at lineament intersections in the central SRP (along the Banbury-Hagerman trend NW of Twin Falls, and along the northern margin of the Mt Bennett Hills-Camas Prairie area), and along the margins of the eastern SRP. Additional resources may be associated with rhyolite domes and crypto-domes in the eastern SRP, but many of these may be chilled in the shallow subsurface by groundwater.

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Figures

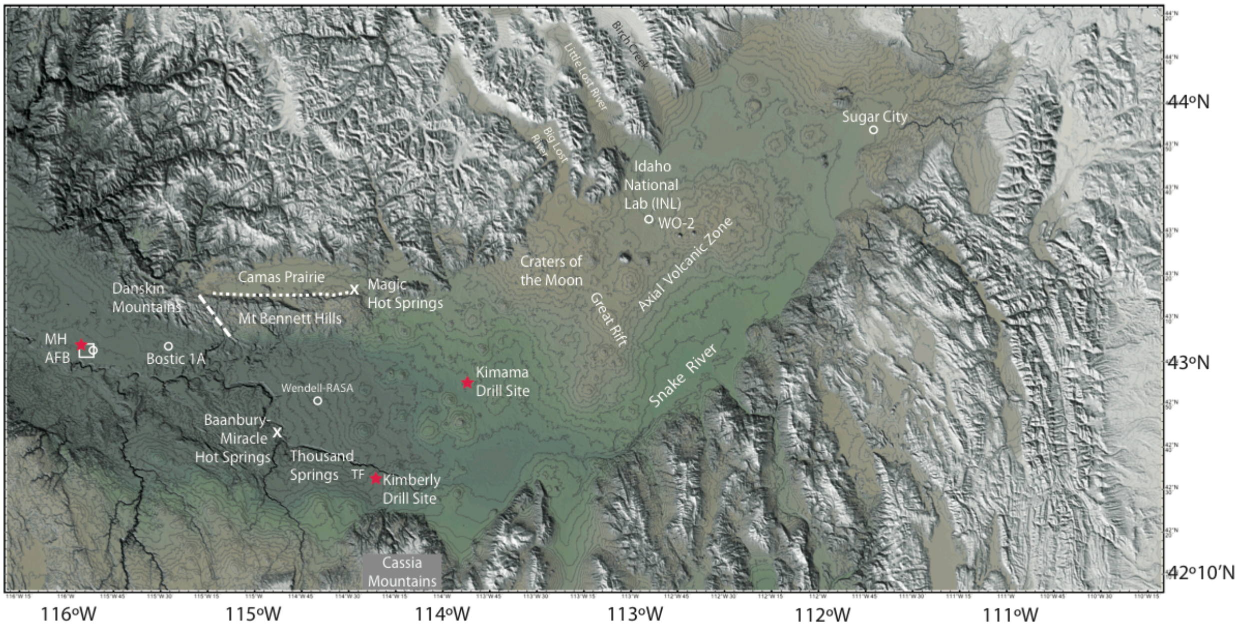

Figure 1. Shaded relief-topographic map of Snake River Plain, derived from NASA 10 m DEM data and contoured at 30 m intervals in GeoMap App; lowest elevations are green, highest are white. Major features discussed in text are labeled. Project Hotspot drill sites = red stars; other drill sites = white circles. Hot springs shown with small x. Accommodation zone between the NE-dipping Danskin Mountains and S-dipping Mount Bennett Hills indicated with white dashed line; Camas Prairie-Magic Hot Springs zone indicated with white dotted line.

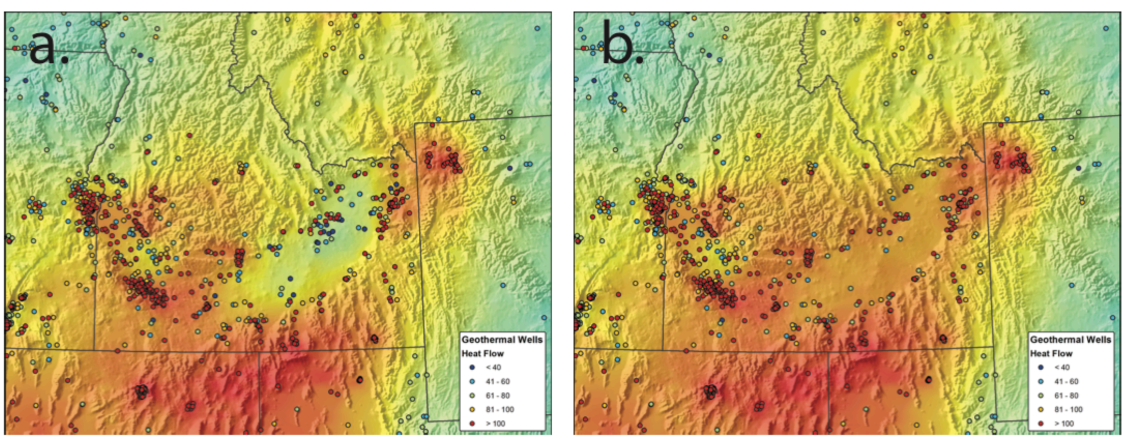

Figure 2. Heat flow maps with well locations, from Williams and DeAngelo, 2008: (a) heat flow interpolated from all well data, including shallow wells in the eastern SRP affected by the Snake River Aquifer; (b) heat flow interpolated from deep wells that penetrate the Snake River Aquifer or lie outside bounds of the aquifer.

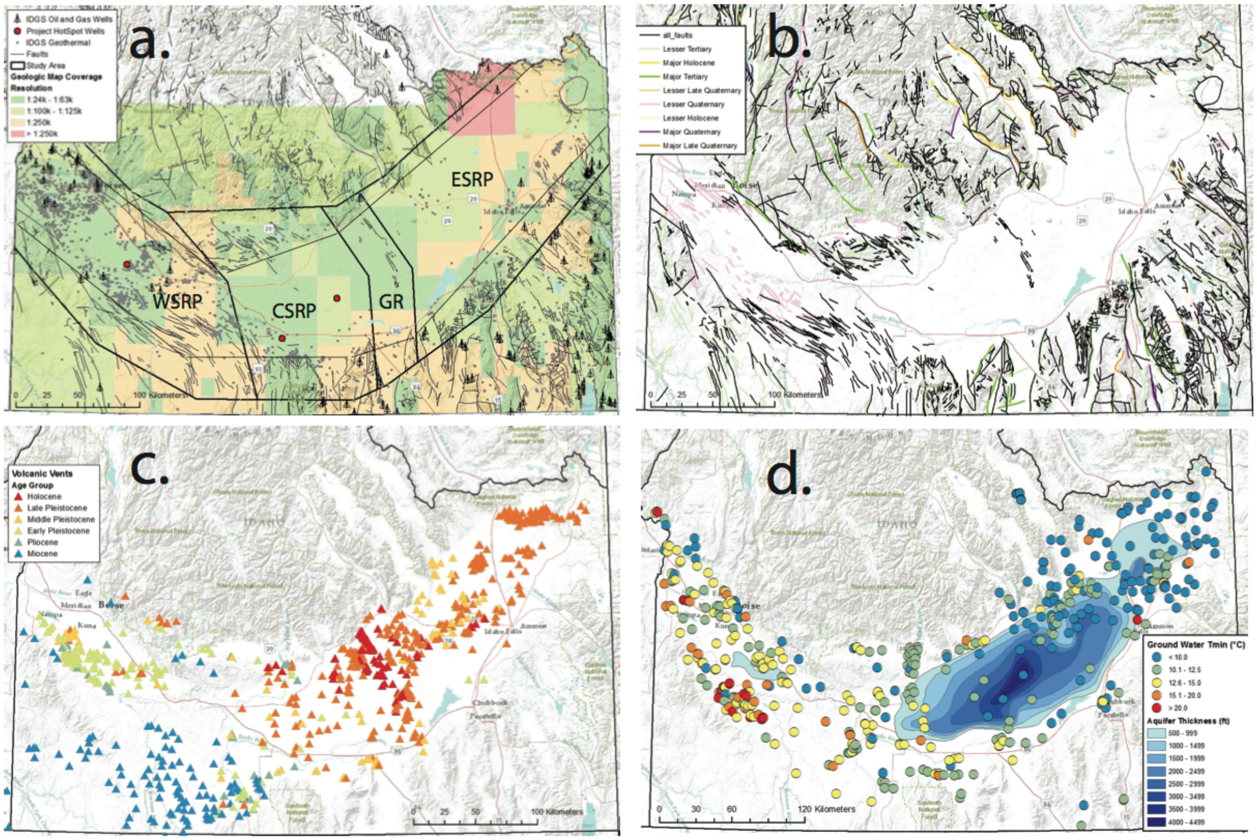

Figure 3. Evidence layers for Snake River Plain. (a) map showing division of SRP into four regions (western, central, eastern, and Great Rift-Craters of the Moon) and eight subregions (areas to north and south of each region), along with geologic map coverage, oil and gas wells, Project Hotspot wells, and faults; (b) map showing distribution of surface mapped faults and lineaments; (c) map showing distribution of volcanic vents by age; (d) map showing groundwater temperatures and thickness of the Snake River Aquifer.

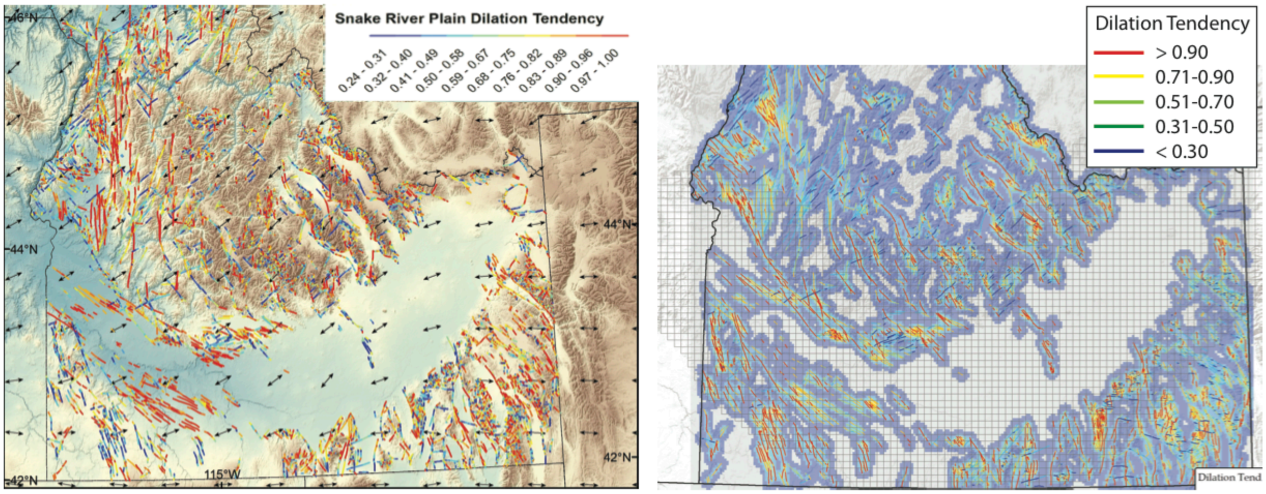

Figure 4. Example of fault-stress mapping. (a) Dilation tendency on mapped surface fault segments from 3DStress; red = high dilation tendency, blue = low dilation tendency. (b) kernel density function analysis, scaled from 0 to 1.0. Grey represents areas with no surface faulting (no data); six km grid overlay.

Model Quality **Data Confidence**	**No Faults 0-0.2 (0.1)**	**Simple Faults, No obvious Intersections 0.2-0.4 (0.3)**	**Complex Subparallel Faults 0.4-0.6 (0.5)**	**Intersections & Step-overs, Simple 0.6-0.8 (0.7)**	**Multiple Intersections, Step-overs, Accommodation Zones 0.8-1.0 (0.9)**
Extensive Mapped Surface Outcrops 0.8-1.0 (0.9)	0.09	0.27	0.45	0.63	0.81
Partly Mapped, or Inferred from basement offsets, GPS 0.6-0.8 (0.7)	0.07	0.21	0.35	0.49	0.63
Partly Covered, Inferred from surface otc 0.4-0.6 (0.5)	0.05	0.15	0.25	0.35	0.45
Largely Covered, Inferred 0.2-0.4 (0.3)	0.03	0.09	0.15	0.21	0.27
No Surface Exposures 0.1-0.4 (0.3)	0.03	0.09	0.15	0.21	0.27

Figure 5. Example of risk matrix that compares model quality (i.e., likelihood of characteristic being present; rows) with data uncertainty (likelihood that data are correct or complete; columns).