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Geothermal Play Fairway Analysis of the Snake River Plain, Idaho

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ABSTRACT

Play Fairway Analysis is a systematic approach to exploration that integrates data at the regional or basin scale in order to define exploration targets (*plays*), and then interrogates these data to highlight plays that have the highest likelihood of success. Play Fairway Analysis provides greater technical rigor than traditional geothermal exploration approaches, and facilitates quantification of play risks even when data are sparse or incomplete. It is a mature practice in petroleum, but represents a new approach for geothermal that we believe will aid in the discovery of buried or blind systems. A key challenge will be adapting fairway analysis to geothermal exploration in a way that provides both meaningful results and measurable return on investment. In this project, we focus on the Snake River Plain where, during Project HOTSPOT, our team discovered a blind hydrothermal system at Mountain Home Air Force Base in Idaho. From that discovery we are able to define key parameters that characterize the elements necessary for a geothermal reservoir based on basaltic (plume-related) magmatism, fracturing that defines a reservoir volume, seals that are provided by lake beds, hyaloclastics, and highly altered clay-rich basalts, and fluid recharge that is controlled by faulting and the primary permeability of basalt flows. Project Hotspot identified three different play types in the SRP (a) high thermal gradients along the volcanic axis beneath the SRP aquifer, (b) extremely large low temperature systems, and (c) blind high-temperature systems like that discovered at Mountain Home. Phase 1 of this project will assess the distribution and viability of these plays throughout the SRP region; Phase 2 will focus on detailed analyses of specific plays as we move from a Regional/Basin focus to a Play/Prospect focus. Our approach is to analyze direct and indirect methodologies for identifying critical reservoir parameters: heat source, reservoir permeability, seal and recharge.

1. INTRODUCTION

Exploration for natural resources is a high-risk venture where a large amount of funds can be committed without a certain return. It is imperative that the process be systematized and be based on sound understanding of resource characteristics. The search for buried geothermal systems, those with no surface manifestations, adds to the complexity because we must rely on geophysical detection or inferences based on geological evidence. It is safe to say that, in the United States, areas with direct evidence such as hot springs and acid altered ground have been explored by geophysical techniques or drilling, or have been written off for one reason or another. However, there are also situations where buried systems have been drilled by accident in areas where there is no surface evidence of hydrothermal activity.

Case studies are critical in defining both the geologic models of geothermal systems and demonstrating exploration techniques that are useful for the detection of geothermal phenomena versus those that do not. Certainly drilling and direct measurements of temperature and fluid flow provide the most precise information. Ward *et al.* (1981) reviewed the exploration techniques used by a number of companies on a variety of Basin & Range geothermal systems under DOE's Industry Coupled Program. Their preferred exploration strategy applied less expensive techniques to focus the search on the most prospective ground and formulate conceptual models that could be tested by more detailed geophysical techniques and drilling, from regional exploration to prospect evaluation.

Play Fairway Analysis (PFA) 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, and then interrogates these data to highlight which plays have the highest likelihood of success (*prospects*). PFA 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)*. PFA can also be effectively used to evaluate mature plays where there is extensive geophysical, petrophysical and well data (BeicipFranlab, 2011).

PFA is a new technique for the geothermal industry which has evolved from drilling hot spring occurrences to blind exploration of known or inferred geothermal trends. It represents a new approach that we believe will aid in the discovery of buried or blind geothermal systems. It also has the potential to improve the effectiveness of exploitation of producing geothermal systems. A key challenge will be adapting fairway analysis to geothermal exploration in a way that provides meaningful results and measurable return on investment.

2. THE EXPLORATION PLAY

The term *Play* is imprecisely defined in petroleum exploration, but there is "...general agreement that the play describes groups of accumulations and prospects that resemble each other closely geologically..." (Doust, 2010). These similarities include reservoir rocks, source rock maturity, migration paths and traps. Importantly, the play has a requirement that petroleum be economically recoverable (Norwegian Petroleum Directorate, 2003). Fugelli and Olsen (2005) state that an exploration play is validated when at least one economic discovery is made. In petroleum, plays are often defined by stratigraphy, and, for instance, one well may intersect more than one play. The *Play Fairway* is the area of maximum possible extent of reservoir rocks in the play (Fugelli and Olsen, 2005). For geothermal, we propose that the Play Fairway be defined by the *maximum possible extent of potential heat sources*, in our case, the Snake River Plain volcanic province.

Play Risk is defined by the confidence in 1) the geological model and 2) the database available (Fugelli and Olsen, 2005). These are conveniently depicted as a confidence matrix with confidence ranked as low, medium and high (Fig. 1). Within a fairway, there can be a dramatic difference in data availability and quality (for instance seismic data absent, 2D or 3D). This type of analysis also provides a basis for identifying areas where additional data collection is necessary to reduce exploration risk.

Common Risk Segment (CRS) maps define areas that contain the same general probability for success for individual model components, based on our Level of Knowledge for these components. Each map indicates high, medium and low risk areas for each element being present. In petroleum exploration, there are risk elements of the reservoir, source, charge and trap. For geothermal systems, we consider risk elements to be the heat source, reservoir volume, recharge and seal. *Composite Common Risk Segment Maps (CCRS)* incorporate the information from the individual CRS maps and define the "sweet spots" that will lead to prospect definition.

In petroleum assessment, the CRS maps lead to a volumetric potential evaluation that is based on reservoir size *versus* probability of occurrence. In general, small systems have a much higher probability of occurrence than large systems, and the number and size of these systems may be estimated using log-normal plots of cumulative probability versus field size (e.g., *Shell Exploration and Production, 2013).*

There is a lack of comparable data for most geothermal areas. Brook *et al.* (1979) noted a relationship between characteristic temperature of a hydrothermal system and size where higher temperature systems were larger. This relationship was confirmed by Nielson (1993). In contrast, the warm water district centered on Twin Falls, Idaho, appears to represent an extremely large low temperature system (Nielson *et al.*, 2012); although, it may repreent an entirely different play type.

3. GEOLOGICAL MODEL

Basaltic terrains are not generally considered to be viable exploration targets for high-temperature geothermal systems since conventional wisdom is that basalt is channeled rapidly from depth to the surface through fractures, forming dikes that cool rapidly. However, important geothermal systems in basaltic terrains include the Puna geothermal district in Hawaii, the Reykjanes peninsula in Iceland, and the submarine hydrothermal systems related to mid-ocean ridges. The geothermal systems of the Imperial Valley also reflect the thermal input from basaltic magmatism. Although the Snake River Plain is part of the highest heat flow anomaly in the US, it has seen relatively little geothermal exploration. We believe that this results from the lack of obvious high temperature manifestations (due in part to the influence of the extensive Snake River Aquifer in the eastern SRP) and the basaltic nature of the province.

In our PFA, we will focus on the Snake River Plain (SRP) where, on a previous DOE project, our team discovered a blind hydrothermal system at Mountain Home Air Force Base in Idaho. From that discovery we are able to define key parameters that we believe characterize the elements necessary for a geothermal reservoir based on basaltic (plume-related) magmatism, fracturing that defines a reservoir volume, seals that are provided by lake beds, hyaloclastics, and highly altered clay-rich basalts, and fluid recharge that is controlled by fracture networks, faults, and the primary permeability of basalt flows (Nielson and Shervais, 2014).

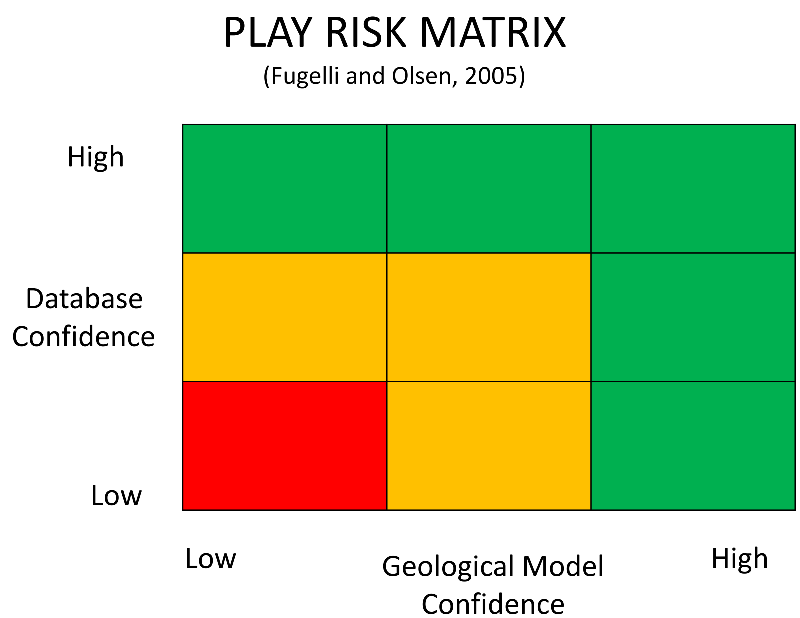

Figure 1: Play Risk Matrix

3.1 Heat Source

A high-level heat source is the principal requirement for a high-temperature geothermal system that is within economically accessible drilling depths. The SRP is one of the highest heat flow provinces in North America. Within that province, we are looking for areas where temperatures are enhanced by repeated or high-level magmatism. Using the Mountain Home corehole as an example, although there are no intrusive rocks identified in the core hole, there are hydrothermal breccias that are probably formed at temperatures >350^{o} C and indicate proximity to an intrusive (Nielson *et al.*, 2012).

Nielson and Shervais (2014) argued that the likely heat source for the Mountain Home system is a complex of *Layered Mafic Intrusions* (LMI) located in the lower part of the upper crust. This hypothesis is supported by fractionation and recharge cycles in basalts recovered by slim hole coring (Shervais *et al*., 2006), by the presence of cumulate xenoliths in basalts of the central SRP and by an exposed sill complex at the western edge of the western SRP (White, 2007). Although individual sills are on the order of 100-200 m thick (White, 2007), gravity and seismic imaging have identified a 10-km thick mid-crustal sill complex that extends under the entire SRP, and represents the aggregation of dozens of individual sills (Peng and Humphreys 1998; Hill and Pakiser 1969; DeNosaquo *et al*., 2009). We believe that the heat sources for high-temperature systems are shallow magma chambers that lie at intermediate depths (8 to 12 km). The most recent basalt flows in the SRP are only 2000 years old, indicating that magmatism is still active, and young (<200 ka) vents are found across the western, central, and eastern SRP.

In order to identify areas underlain by these complexes and associated heat sources, we anticipate using the petrochemistry age, and distribution of basaltic vents, gravity, magnetics, magnetotellurics (MT), seismic, regional heat flow data, groundwater temperatures, and estimates of deep reservoir temperatures derived from isotopic, cation, and multicomponent geothermometers. Rhyolite domes and lavas are less common (e.g., Big Southern Butte), but may also form an important heat source if they are underlain by relatively shallow magma chambers. In some areas, heat appears to come from circulation within the crust (e.g., Twin Falls area), in settings that resemble traditional Basin and Range systems.

3.2 Reservoir Volume

Geothermal reservoirs are defined by fracture permeability, associated with fracturing related to tectonic and magmatic processes. Fractures are difficult to characterize in the subsurface, but their presence can be predicted by steep gravity and magnetic gradients, alignment of volcanic vents, petrophysical analyses of wireline log data, and an understanding of the relationships between lithology and mechanical properties/lithostratigraphy. Analysis of fault trace maps and quantitative structure/stress analysis will be used to help locate permeability associated with large, mapped structures. It has been shown (Faulds *et al*., 2013) that geothermal permeability is typically highest within step-overs (transfer zones), accommodation zones, and fault intersections; these will be high priority targets for identification and mapping. MT and magnetics are useful tools in identifying zones of alteration produced by interaction of geothermal fluids with the host rock. Geothermal reservoirs also discharge fluids that are often detectable by fluid geochemical methods, enhanced groundwater temperatures, or hot springs.

The reservoir volume must be of adequate size to warrant commercial production. In addition, due to the high cost of drilling geothermal production wells (Mansure and Blankenship, 2013), we are proposing for this study that the system must be accessible by wells no deeper than 3000 m. Commercial production is also dependent on production rate of wells and their thermal decline, which reflect on the sustainability of the resource.

3.3 Seal

An impermeable seal is critical for the preservation of an active geothermal system. In the absence of seal, thermal fluids will escape to form surface hot springs, or will mix with cold waters in shallower aquifers. *Project Hotspot* demonstrated that lake sediments, hyaloclastites (glassy volcanic sediments), and altered basalts may serve as effective reservoir seals. The distribution of lake sediments in the SRP is documented by surface exposure and well logs. Hydrothermally altered basalts and hyaloclastites may be mapped using magnetics and MT. This information will be used to establish a seal overlay for the fairway analysis.

3.4 Recharge

Recharge by the migration of water into the geothermal system is critical to maintaining a long-lived resource. The hydrology of the SRP is complex. In the central-eastern SRP, the upper parts of the Snake River Regional Aquifer (SRRA) are reasonably well known; however, the deeper parts are understood only from deep holes, such as the Kimama hole drilled in the Hotspot project (Nielson *et al.*, 2012*)*, and from electromagnetic (EM) and magnetotelluric (MT) data. Deep groundwater circulation is even less well known in the western SRP, where lake sediments dominate. Important recharge paths will be provided by tectonic faulting that will allow fluids to penetrate beneath lake beds and into geothermal reservoirs.

3.5 Fluid Flow and Reactive Transport Modeling

Conceptual models for seals and temperature distributions will be tested quantitatively using coupled thermal-hydrological-chemical models (THC) that incorporate heat flow, recharge, and mineral-water reactions over a range of temperatures. Recent 2D and 3D modeling of geothermal systems has shown the ability to capture high-temperature permeability changes and alteration mineral distributions (Sonnenthal *et al*., 2012; Spycher *et al*., 2014), and spring compositions and temperatures, in addition to heat and fluid flow along faults (Wanner *et al*., 2014). Assessment of potential geothermal areas can be tested through modeling of temperatures and fluid flow in existing boreholes, and calibration to surface heat flow measurements. The newly parallelized THC code TOUGHREACT–V3-OMP (Xu *et al*., 2011) will be used to model a 1-D section of the SRP system, considering different heat flux models, timing of intrusives, and conceptual models of the geothermal plays.

4. DATABASE

The data available for the analysis are limited to that available in the public domain. Most of these data are available for the entire study area, however some data are limited geographically (for example, seismic reflection data are largely restricted to sedimentary basins associated with the western SRP). The following list is not comprehensive, but includes the most important data and data sources.

4.1 Geology

1. Geologic Maps published by the USGS and Idaho Geological Survey, and unpublished maps. Most of these maps are available as GIS shape files from the USGS and IGS web sites.

2. Petrology, geochemistry and age of the lavas, and petrologic models of their thermal budgets; primary data from published and unpublished data bases (e.g., North American Volcanic and Intrusive Rock Database - NAVDAT). Publicly available from the database websites. Pertinent references include Bonnichsen *et al*., 2008; Hughes *et al*., 1999; 2002; Kuntz, 1992; Kuntz *et al*., 1986a, b; 1992; 2002; Leeman, 1982a, b; Leeman *et al*., 2008; 2009; McCurry *et al*., 1999; Morgan *et al*., 1984; Morgan and McIntosh, 2005; Shervais *et al*., 2002; 2005; 2006b; Wood and Clemens, 2002.

3. 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.

4. Rock mechanical properties of core, correlated with borehole geophysical logs. Available from Hotspot collaborators.

5. Structural features and stress regime of the region that could lead to enhanced reservoir permeability. Pertinent reference include Anders et al. (1989); Parsons, 1998; Payne et al., 2008; 2012; Puskas *et al*., 2007; Rodgers *et al*., 2002.

4.2 Heat Flow

6. Database of heat flow and thermal gradient wells compiled by SMU Geothermal Lab (e.g., Blackwell, 1989; Brott *et al*., 1978; 1981), plus data from the National Geothermal Data System.

7. Groundwater temperature distribution, which reflects thermal flux from below. These data are available from several sources, including the USGS and Idaho National Laboratory.

4.3 Seismic

8. Seismic reflection and refraction lines, mostly in the western SRP, including publically available lines shot by Chevron in the 1980's. Seismic reflection and refraction data for SRP will be compiled, with interpretive synthesis, depth to basement, depth

of lacustrine sediments, and other enhancements where possible. There is more than 1,000 km of known seismic data within the SRP, much of which has not been compiled into a comprehensive, integrated database that enables geoscientists to investigate the data. Publicly available or owned by participants. Published studies include Smith *et al*., 1982; Greensfelder and Kovach, 1982.

4.4 Magnetotelluric and Electrical Resistivity

9. Magnetotelluric data with a 70 km station spacing are publically available from the Earthscope project; these data are most useful for deeper crustal studies (e.g. Zhdanov *et al.*, 2011; Kelbert *et al.*, 2012). More detailed regional data have been published by several research groups (e.g., Zohdy and Stanley, 1973; Stanley *et al*., 1977; Keller and Jacobson, 1983; Young and Lucas, 1988; DeGroot *et al.*, 2003; Kelbert *et al.*, 2012). Electrical and electromagnetic data will be compiled and used to constrain/support gravity and/or seismic models.

4.5 Gravity and Magnetics

10. Gravity and magnetic data include new high-resolution data collected by the USGS as well as publically available data derived from State and National compilations and individual surveys.

4.6 Geochemistry of Thermal Fluids

11. Geochemistry and geothermometry of geothermal well and thermal spring waters, from USGS database for Idaho and other available data. This will include the integration of recently developed geothermometry modeling approaches with more classical methods to assess available water chemistry data in an integral and comprehensive manner over the area of interest. Publicly available data sources include Baker and Castelin, 1990; Cannon *et al*., 2014; Lewis and Young, 1982; 1988; Mariner and Young, 1995; Mariner *et al*., 1991; 1997; McLing *et al*., 2002; 2014; Parliman and Young, 1992; Ross, 1970; Young and Lewis, 1982; Young and Mitchell, 1973; Young *et al*., 1988.

4.7 Land Use and Access

12. Data for land access analysis: GIS Shape files publically available from various Federal (USGS, BLM and USFS) and State agencies, and private sources. Publicly available.

13. NREL comprehensive worldwide database of geothermal reservoir properties for the development of geothermal occurrence models. Available thru NREL.

5. SUMMARY

The project will construct a conceptual model of the SRP constrained by the data elements examined. This comprehensive model will focus on the key elements of basalt-hosted geothermal systems described by Nielson and Shervais (2014), e.g., the key lithologic units of reservoirs and seals, the presence of faults that might enhance recharge or reservoir permeability, or pose a seal breach risk, depict the distribution of low-permeability seals, document the locations and quality of heat sources, the subsurface temperature and fluid pressure distributions, and likely sites of recharge.

The project will identify specific plays within SRP, and additional data requirements for developing 3D models of these plays. The final product of this work will be a series of Common Risk Segment (CRS) maps and Composite Common Risk Segment (CCRS) maps that together define Geothermal Plays. Quantitative risk assessment will be inherent in these maps, which will weigh the probabilities associated with each data set. These data will be used to assess the Geothermal Plays in order to identify the most likely prospects for development within the highest quality plays.

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