

Geothermal Play Fairway Analysis of the Snake River Plain: Phase 1

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ABSTRACT

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 the analysis of stress orientations and magnitudes, post-Miocene faults, and subsurface structural lineaments based on maximum horizontal gradients of 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 tracks.

Our Phase 1 assessment indicates that important undiscovered geothermal resources may be located in several areas of the Snake River Plain (SRP). Our results identify eight areas with multiple prospects, each of which may contain resources that equal or exceed the system associated with the 10 MWe Raft River geothermal plant. 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. Our training site in the WSRP (on Mountain Home Air Force Base) is a blind resource similar in temperature to Raft River. Our identified prospects exhibit higher favorability and broader regional extents on CRS and CCRS maps than either of our training sites (Mountain Home, Raft River).

1. INTRODUCTION

The Snake River Plain (SRP) volcanic province overlies a thermal anomaly that extends deep into the mantle; it represents one of the highest heat flow provinces in North America. The Yellowstone hotspot continues to feed a magma system that underlies southern Idaho and has produced basaltic volcanism as young as 2000 years old. It has been estimated to host up to 855 MW of near term potential geothermal power production, most of which is associated with the Snake River Plain volcanic province (*Fleischmann, 2006*). Additional resources reside in surrounding regions, tied to elevated heat flow associated with Basin-and-Range type plays (*e.g., Welhan, 2016*).

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 favorable trends for exploration 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 methodology 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 exploration of blind systems within known or inferred geothermal trends, and has identified distinct geothermal play types (e.g., *Moeck, 2014*), but has not adopted Play 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 this Phase 1 study were 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 we have developed from standards in the petroleum industry, and tailored to geothermal exploration. Our ultimate goals are to lower the risk and cost of geothermal exploration throughout geothermal industry, and to stimulate the development of new geothermal power resources in Idaho.

Our study area encompasses almost all of southern Idaho, spanning 6° of longitude (~500 km EW) and over 2.5° of latitude (~300 km NS), or about 150,000 km² (Fig. 1). Most of the study area is underlain by a basaltic volcanic province that overlies a mid-crustal intrusive complex, which in turn provides the long-term heat flux needed to sustain geothermal systems. This represents a new conceptual model for geothermal systems that includes aspects of volcano-hosted systems and structurally controlled Basin-and-Range systems. Basin-and-Range systems underlie part of the study area; rhyolite domes and granite batholith systems are also present but were not evaluated quantitatively in this study, although our methodology can easily be adapted to other play types.

2. APPROACH

We analyze 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*). The Snake River Plain was divided into three main regions based on differences in tectonic and volcanic setting, which differ in their stratigraphy and structure. The main regions are (1) the eastern SRP, including Craters of the Moon-Great Rift along its western margin, (2) the central SRP, comprising the axial portion of the plain between Craters of the Moon-Great Rift on the east and Hagerman-Bliss on the west, as well as the Bruneau-Jarbridge eruptive center, the Mount Bennett Hills, and the Camas Prairie, and (3) the western SRP graben and adjacent regions. Subregions comprise areas of interest adjacent to the margins of the plain include Basin-and-Range areas north and south of the ESRP, the Idaho Batholith, which lies largely north of the WSRP and CSR, and the Owyhee Plateau, which lies south of the WSRP.

A *resource attribute worksheet* was created to summarize important properties (heat, permeability, seal) and the types of data needed to identify them (e.g., heat flow, volcanic vents, faults, gravity and magnetic lineations, etc). The *resource attribute worksheet* also included data sources and links where known, or ideas on where appropriate data might be found. This worksheet was expanded as work progressed, but the basic data elements laid out in this worksheet remained the dominant factors in our analysis throughout Phase 1. Critical element risk matrices were produced for several play types and attributes that assess model favorability against data confidence, or assess an attribute for model favorability. The primary foci for these risk matrices are heat source and reservoir quality (permeability). The critical element risk matrices were based in part on the resource attribute worksheet, which defined many of the critical elements of source, reservoir and seal, and in part on our evaluation of the uncertainty expected within each data type. Reservoir seal is more difficult to assess, since it consists of either impermeable sediments, whose distribution is relatively well known, or alteration self-seal, which is difficult to predict, but may be inferred from resistivity studies (e.g., *Lindholm, 1996*).

2.1 Methodology

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*. Because different data types have different uncertainties associated with their collection, each *evidence layer* has its own *confidence layer*, which reflects geographic variations in these uncertainties. *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 analysis of undiscovered geothermal resources. The CCRS map identifies several priority targets for future, focused study during the next phase of our research. A detailed description of our methodology is presented in a companion paper at this meeting (*DeAngelo et al., 2016*).

2.2 Data Compilation

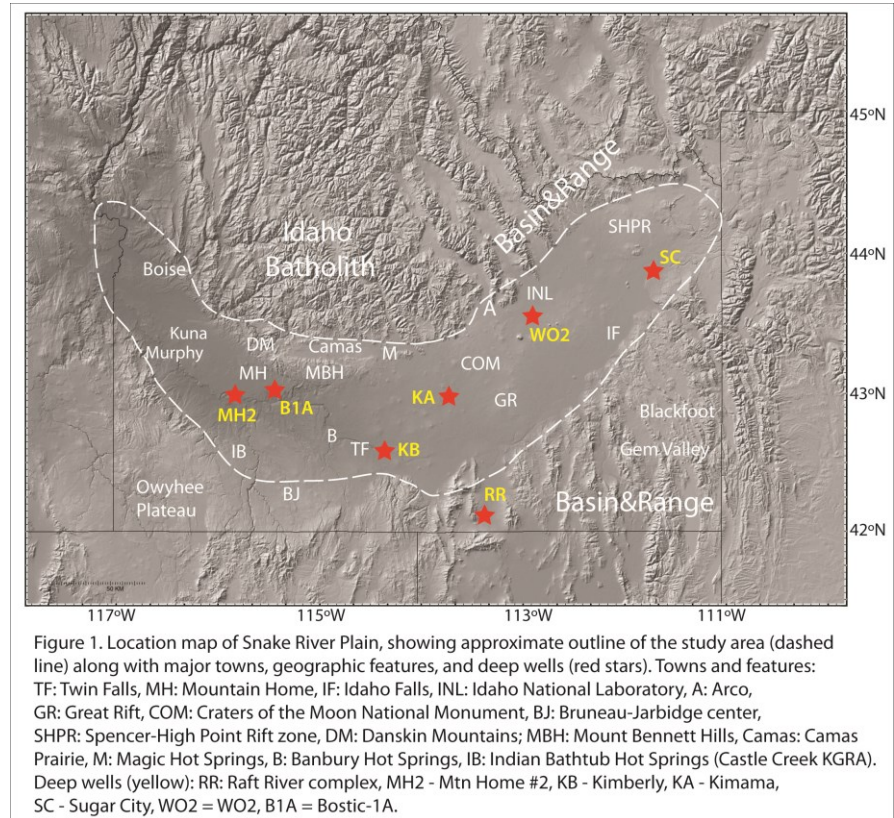
Data were compiled from a range of public and private sources, both published and unpublished, and imported into ArcGIS to create a series of data layers for later analysis. The data collected include geologic maps at scales from 1:24,000 to 1:250,000, structural features (faults, lineaments), vent locations, ages, and types from geologic maps and other sources, heat flow from the U.S. Geological Survey (USGS) and Southern Methodist University (SMU) Geothermal Laboratory databases, groundwater temperatures from the USGS and Idaho Department of Water Resources (IDWR), aeromagnetic data, existing regional gravity data as well as newly collected high resolution profile data, and processed potential field (gravity and magnetic) data yielding subsurface structural interpretations, 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.

3. RESULTS

3.1 Distribution of Heat

The distribution of heat throughout the SRP volcanic province was assessed using measured thermal gradients, interpolated heat flow values, groundwater temperatures, the distribution of volcanic vents (weighted by age, size, and composition), measured temperatures of thermal waters from springs and wells, calculated ionic and multicomponent temperatures of thermal waters from springs and wells, and the distribution of high $^3\text{He}/^4\text{He}$ in thermal waters. 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 $^3\text{He}/^4\text{He}$ ratios found in thermal waters from Camas Prairie, Banbury, Arco, and the Blackfoot area (Dobson *et al.*, 2015).

The *Common Risk Segment map for Heat Source* (Fig. 2A) 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 Air Force Base (AFB)), the Castle Creek-Bruneau KGRA, and part of Bruneau-Jarbridge 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 (adjacent to the INL FORGE site), and the Spencer-High Point rift, which trends EW and intersects the margin of Island Park caldera. Heat flow is relatively high in SE Idaho, coincident with Basin-and-Range structures, although the volcanic fields around Blackfoot are not as high as the Raft River area farther south. Heat flow is somewhat elevated in the southeastern part of the Idaho Batholith (90-100 mW/m²), which supports a number of thermal springs and pools in the Salmon River drainage.



3.2 Distribution of Permeability (Reservoir/Recharge)

Reservoir and recharge permeability was assessed using the weighted sum of mapped faults, magnetic lineaments, upper to mid-crustal gravity lineaments, and deep crustal gravity lineaments, each processed for both slip tendency and dilation tendency. Risk maps for the deepest lineaments are weighted more heavily than those for shallow (magnetic) or surface features (mapped faults), which reflect the difficulty in imaging deeper structures and their correlation with large structural offsets in the basement. It also reflects the fact that surface faults are mapped with great precision in some areas, resulting in high fault densities in places where there may be little structural offset. Weights were adjusted empirically to ensure that known subsurface structures (*e.g.*, the seismically imaged central gravity high in the WSRP) appear on the CRS maps as favorable structures. *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.*, accommodation zones, fault intersections, and step-overs). A proxy for fault and lineament intersections at the regional scale of this study is fault density, where high fault (or lineament) densities tend to favor multiple intersections.

Faults are restricted to the margins of the SRP (due to the ubiquitous presence of young volcanic rocks in the plain that tend to obscure older structures), with high densities in three areas (outside of the Basin and Range regions). Buried structures and lineaments, defined by high horizontal gradients in the gravity and magnetic anomalies, suggest significant permeability along the northern and southern margins of a major gravity anomaly in the WSRP. The *Common Risk Segment map for Permeability* (Fig. 2B) 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.

3.3 Distribution of Seals

The SRP geothermal system has 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*). The first is relatively easy to map; the second much more difficult. The distribution of lake sediments is well known in the WSRP, where regional formations consisting largely of lacustrine sediments are widespread, deposited by paleo-Lake Idaho (*Wood and Clemens, 2002*). These formations gradually pinch out from west to east. The *Common Risk Segment map for Seal* shows that the distribution of seal is extensive, with most areas having either significant thicknesses of lacustrine sediments (WSRP, Camas Prairie, Burley area) 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.

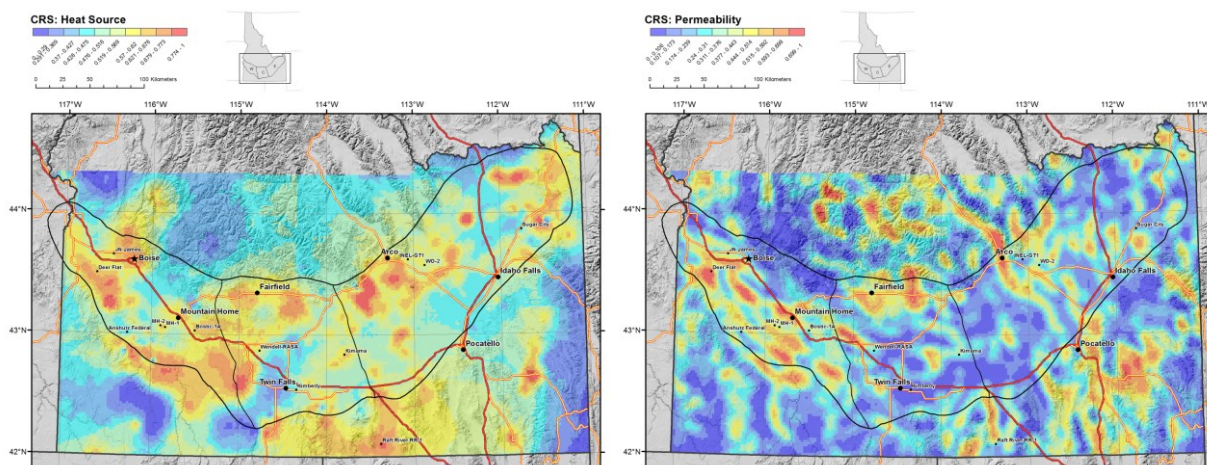


Fig. 2. Common Risk Segment (CRS) maps for (A) Heat Source and (B) Permeability. Hot colors indicate regions with (A) high potential heat or (B) high potential for permeability. Labeled small dots (e.g., MH-2) indicate the names and locations of deep wells within the study area.

4.0 POTENTIAL PROSPECTS: AN ASSESSMENT

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. In this section we present an overview of geothermal potential within specific regions of the SRP, and conclude with a discussion of the sites that we believe have significant potential for exploitation. The following discussion is based on the *CRS maps for Heat, Permeability, and Seal*, and on the *Composite CRS map* (Fig. 3), which sums the contributions of each CRS map across the entire study area.

4.1 Western Snake River Plain (WSRP)

The WSRP presents numerous opportunities for geothermal exploration. It is characterized by relatively high heat, based on its heat flow, high groundwater temperatures, and the extensive distribution of early to mid-Pleistocene basalt volcanoes, with some vents as young as ~200,000 years. Volcanic vents form clusters that follow the southern margin of the axial gravity high, and parallel the northern margin, with a dense cluster at its western end. The vent distribution corresponds to subsurface lineaments highlighted in the permeability CRS map, which combine to make an excellent exploration target. The viability of these prospects is attested by our training site, Project Hotspot well MH-2, which was located on the southern margin of this gravity high and encountered hot (~150°C) water at 1745m depth. Thermal modeling (*Garg et al., 2016*) show that this is a large regional thermal anomaly associated with multiple prospects.

4.2 Central Snake River Plain (CSRP)

The CSRP is characterized by a low density of young volcanic vents compared to the eastern SRP. Basalt vents in the CSRP are typically 100-400 ka along the Axial Volcanic Zone, and older (up to 2-3 Ma) along the margins. The Holocene Shoshone flow erupted on the northern margin of the plain, and other Holocene to late Pleistocene vents are found nearby in the Mount Bennett Hills (e.g., *Shervais et al, 2005*). Thermal resources are indicated by the presence of numerous hot springs throughout the region, typically along the margins of the plain (e.g., the Banbury-Miracle HS area, the Magic Reservoir-Camas Prairie HS area, and Latty HS on the SW edge of the Mount Bennett Hills) and by the widespread warm water of the Twin Falls thermal district (*Street and deTar, 1987; Street, 1990; Baker and Castelin, 1990*).

4.3 Eastern Snake River Plain (ESRP)

The ESRP is characterized by dense clusters of vents in the EW-trending Spencer-High Point rift and along the Axial Volcanic Zone. Although there are some Holocene vents, most volcanic activity was late Pleistocene (Brunhes normal epoch, ≤780,000 years). The Axial Volcanic Zone contains three rhyolite domes (<700 ka) that post-date basalt, an older rhyolite cryptodome, and an evolved dacite volcano (Cedar Butte). There are two rhyolite cryptodomes on the southern margin (McCurry et al., 2008). As with the COM-Great Rift, deep heat flow is high, but heat flow based on shallow wells is much lower, and groundwater temperatures are low. The Snake

River aquifer extends over much of the eastern SRP and masks the deeper geothermal resource (Smith, 2004); there is no surface faulting except along the margins, and there is little indication of buried permeability from gravity or magnetics. Payne et al. (2008, 2012) present GPS strain data that document extension in the Basin and Range regions north and south of the SRP, whereas the SRP itself moves as a coherent block with uniform velocity. This implies relative motion along the interface between the SRP and the adjoining mountain areas, but at this time there is no indication of faulting or earthquakes along these boundaries. Due to the effects of shallow groundwater flow, temperatures needed for energy production are likely too deep to make resources viable at this time.

4.4 Basin-and-Range Plays

There are two Basin-and-Range plays that may represent potential prospects (not counting our training site at Raft River): the Arco Rift-Big Lost River Valley in central Idaho, and the Blackfoot-Gem Valley region of SE Idaho. The Blackfoot-Gem Valley region has been studied extensively by McCurry and colleagues (McCurry et al., 2011, 2015; McCurry and Welhan, 2012; Welhan et al., 2014; Welhan, 2016). A test well drilled by Unocal in the 1980s encountered a major flow of cold water moving towards Blackfoot reservoir. However, a 3-km deep well drilled NE of the reservoir in 1979 by Conoco measured a bottom hole temperature of 190°C – similar to the Bostic 1A well in the WSRP (Fleischmann, 2006). Welhan et al. (2014; Welhan, 2016) suggest that this resource comprises a large area with high heat flow (~100-220 mW/m²) that is masked by structural relations in the SE Idaho fold and thrust belt.

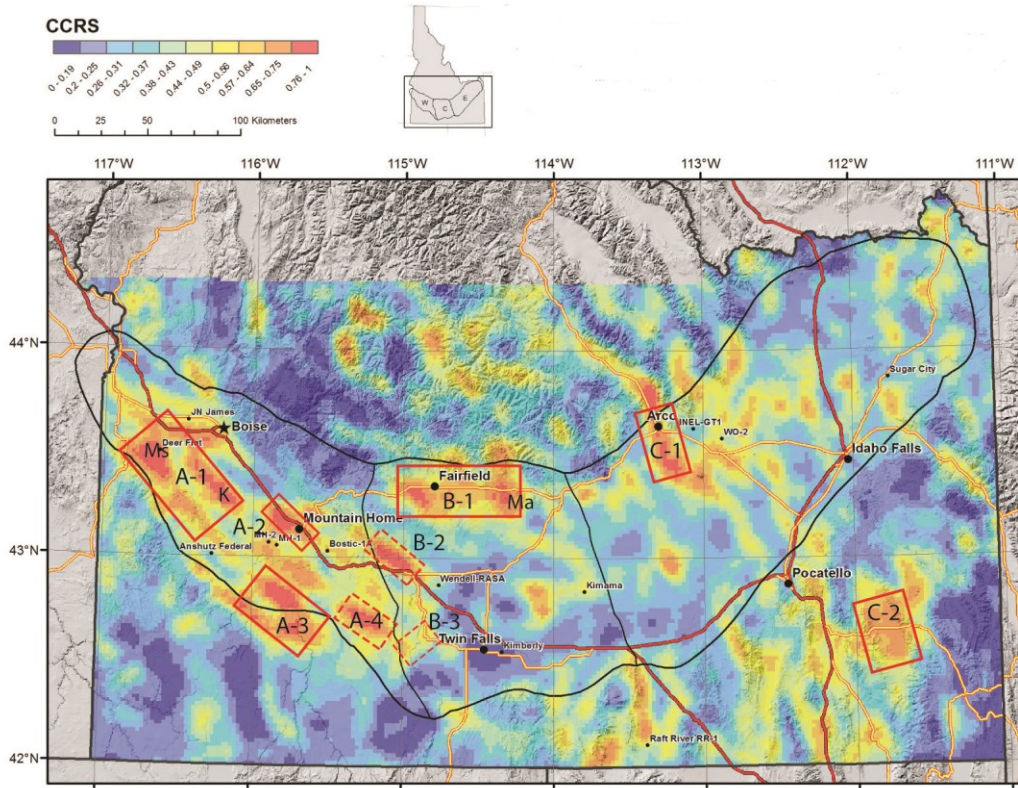


Fig. 3. Composite Common Risk Segment (CCRS) map for southern Idaho. Hot colors indicate regions with high favorability for geothermal resources. Labeled small dots (e.g., MH-2) indicate the names and locations of deep wells within the study area. Red rectangles indicate “areas of interest” for further exploration. A-1: Marsing-Kuna; A-2: Mountain Home; A-3 Castle Creek-Bruneau; A-4: Deadman Flat; B-1: Camas-Mt Bennett Hills; B-2: King Hill; B-3: Banbury; C-1: Arco; C-2 Blackfoot. Ms: Marsing; K: Kuna; Ma: Magic Hot Springs.

5.0 CONCLUSIONS

Our Phase 1 assessment suggests that important undiscovered geothermal resources may be located in several areas of the SRP. Our results identify eight areas with multiple prospects, each of which may contain resources that equal or exceed the 10 MW Raft River geothermal plant. 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. Our training site in the WSRP (on Mountain Home Air Force Base) has a confirmed resource that is at least 5 km long, parallel to a buried fault system. Our identified prospects exhibit higher favorability on *Common Risk Segment* and *Composite Common Risk Segment* maps than either of our training sites, and have regional extents that generally exceed both of our training sites. These data strongly support the conclusion that commercial geothermal resources exceeding 100 MW are present in southern Idaho.

The goal of our project was to reduce the risk for private developers and thus remove barriers to further exploration and development. The methodology and tools developed by this project have helped to identify where these resources are located, to estimate their volume, and in time, to locate the best places to drill in order to harness this resource. Furthermore, these methods and tools are transferable to other regions with different geothermal resources and may be used throughout the geothermal industry.

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