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Geophysical Investigations and Structural Framework of Geothermal Systems in West and Southcentral Idaho; Camas Prairie to Mountain Home

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ABSTRACT

A recent study of the geothermal potential of the Snake River Plain (SRP) region, which adapts play fairway methodology to assess geothermal resources (Shervais et al., 2016), identified several areas in southcentral Idaho, including a broad swath from Mountain Home to the Camas Prairie in the western SRP, as regions with elevated resource potential. The present work was undertaken to better characterize these resources through detailed geophysical exploration. We focus on three areas from the western SRP that range from high to low-temperature systems, span magmatic (basaltic sill), amagmatic (Basin-and-Range), and basement related play types, and have resource potential favorable for development of direct use, conventional, and EGS resources.

We performed geophysical studies of three areas (Mountain Home, Bostic, Camas Prairie), collecting high-resolution gravity and ground magnetic data, magnetotelluric data, and seismic reflection data to (1) characterize intra-basin and basin-bounding faults, (2) constrain basin geometry, (3) study fault interactions, (4) identify areas favorable to hydrothermal flow, and ultimately (5) guide exploration of the area's geothermal system. As part of this work, we collected 1659 gravity stations, over 725 line-km of ground magnetic data, more than 50 km of seismic reflection data, and 102 MT stations. Additionally, we integrated ground water well logs into our analyses, and collected hundreds of rock-property measurements on outcrops and samples (including susceptibility, density, and magnetic remanence) to constrain potential field modeling. Assessment of surficial geology and structure has encompassed detailed review of existing geologic mapping, new structure mapping based on aerial imagery, and new boots-on-the-ground structure mapping.

These data resolve key structural features that appear to be responsible for promoting permeability and facilitating hydrothermal flow. The structural and conceptual framework developed from this study provide important information relevant to future development of these geothermal resources in the western SRP.

1. INTRODUCTION

A recent study of the geothermal resources of the Snake River Plain (SRP) revealed that the western SRP is a region of high geothermal potential (Shervais et al., 2016; DeAngelo et al., 2016), based on the presence of extensive early to mid-Pleistocene basalt volcanism (as young as ~200,000 Ma), recent faulting, high groundwater temperatures, and regional high heat flow. In this paper we focus on three areas from the western SRP where we have performed geophysical studies involving potential field (gravity and magnetic), magnetotelluric, and seismic reflection surveys, to characterize subsurface structures (faults, contacts, fracture zones), study fault interactions, constrain formation and reservoir geometries, constrain heat sources and fluid pathways, and help guide future exploration and development in these areas. The three study areas encompass high to low-temperature geothermal systems, with potential for direct use applications and for electric power production from both conventional and EGS resources (Figures 1, 2). These systems also likely span a range of resource types from magmatic (basaltic sill), amagmatic (Basin-and-Range), and basement related plays.

1.1 Study Areas

1.1.1 Mountain Home

The Mountain Home study area represents a blind high-temperature geothermal system that is not associated with any mapped faults or surface geothermal manifestations. Initial investigations of the resource were prompted by elevated geothermal gradient estimates (59ºC/km) determined from a wildcat oil well (Bostic 1A, 2949m) drilled in 1973 at a location 20km southeast of the town of Mountain Home (Figure 1). A deep (1342m) geothermal exploratory well (MH-1) was drilled in 1986 as part of an effort to assess resources at the Mountain Home Air Force Base (MHAFB). A temperature of 93ºC logged at a depth of 1207m (Lewis and Stone, 1988), and an estimated thermal gradient of 69ºC/km, suggests that temperatures at depths in the range of 1500–1800m are high enough to support binary cycle power generation that could meet the base's present maximum electrical power requirements of 14 megawatts (Breckenridge et al., 2012), and potentially provide power to the town of Mountain Home or supply power to the grid. Subsequently, a second deep (1821m) well (MH-2), drilled on the base as part of an effort to study the tectono-volcanic history of the SRP in relation to the Yellowstone hotspot (Shervais et al., 2012), documented artesian flow and logged 135-140ºC water (Nielson et al., 2012) at a depth of 1745m.

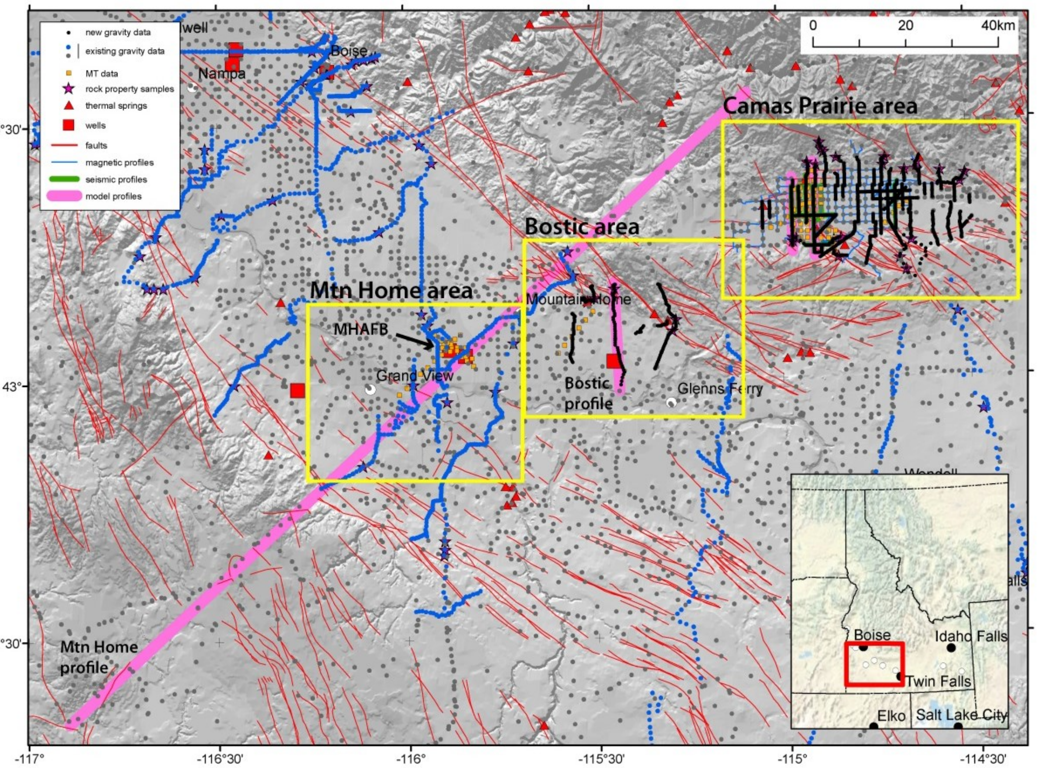

Figure 1) Shaded topographic index maps of the western SRP showing the three focus areas (outlined with yellow boxes; Mountain Home, Bostic, and Camas Prairie). Also shown are seismic reflection profiles, MT stations, gravity stations, magnetic traverses, modeled profiles, rock property sample locations Also shown are modeled profiles, faults and thermal springs.

The stratigraphy at Mountain Home, revealed by core from the MH-2 drill hole, consists of an upper section of basalt (>200m thick) overlying ~600m of fine-grained lake sediments, and a basal sequence of basalts with minor sedimentary layers. The sequence of low permeability lake sediments that overly the geothermal system at Mountain Home likely help maintain the resource by insulating the reservoir, preventing upward migration of the thermal fluids, and inhibiting mixing with cold meteoric water that could degrade the resource (Shervais et al., 2016). MHAFB has had a longstanding commitment to supporting research of the base's geothermal resources that would make them an ideal partner in future exploration and eventual development of this resource.

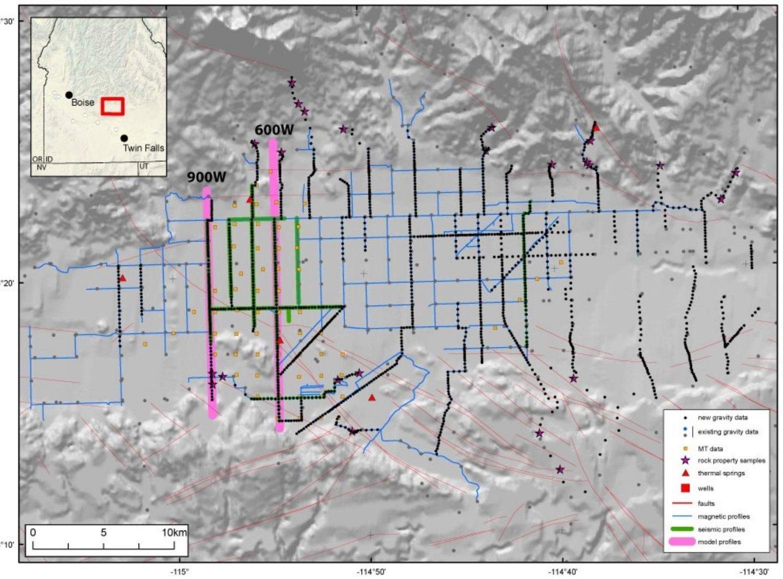

Figure 2) Shaded topographic index maps of the Camas Prairie study area showing newly collected seismic reflection profiles, MT stations, gravity stations, magnetic traverses, and rock property sample locations. Also shown are existing gravity data, modeled profiles, faults, and thermal springs.

1.1.2 Bostic (Glenns Ferry- Mount Bennett Hills)

A region ~20km east of Mountain Home, between Glenns Ferry and the Mount Bennett Hills was first identified as an area with elevated geothermal potential based on findings from the Bostic 1A exploratory oil well that yielded a measured bottom hole temperature (at 2931m) of 195℃ (Arney et al., 1984). The Bostic well spans a stratigraphy consisting of Quaternary alluvial deposits overlying a sequence of interbedded basalts and sediments of the Plio-Pleistocene Idaho Group (including the Banbury Basalt, Glenns Ferry Formation, and Bruneau Formation), and late Miocene to early Pliocene rhyolites of the Idavada Volcanics. The well extends below the high-permeability active groundwater system and into a region of low-permeability basement in silicic volcanics.

These findings motivated subsequent studies of the area, including a hot dry rock investigation (Arney 1982; Arney et al, 1982). Although this area has estimated potential for development of high-grade enhanced geothermal system (EGS) resources, with predicted temperatures exceeding 200-250°C at a depths of 4-6 km (Tester et al., 2006; Williams and DeAngelo 2011), no further exploration of this resource has taken place since the efforts in the 1980s. This region immediately surrounding the Bostic well is considered largely unfaulted (aside from minor displacements affecting the shallow subsurface) and consist of rhyolite, granite and inferred crystalline intrusive basement that would be suitable EGS reservoir (see area outlined by black polygon, Figure 3). In addition to its potential as an EGS resource, the broader region, extending from the Danskin Mountains and Mount Bennett Hills into the Plain (as far as highway 84) may represent viable targets for development of conventional hydrothermal resources (see areas outlined by yellow polygons, Figure 3). This region encompasses local structural zones consisting of numerous intersecting faults of late Pleistocene and younger age faults, and Pleistocene (≤300 ka) basaltic vents (Shervais et al, 2002). In addition, surface hydrothermal springs manifest at areas east of Mountain Home along the Danskin and Mount Bennett foothills (Figure 3). Hot springs in this region yield multicomponent geothermometry temperatures of 175-200℃ (Neupane et al., 2014).

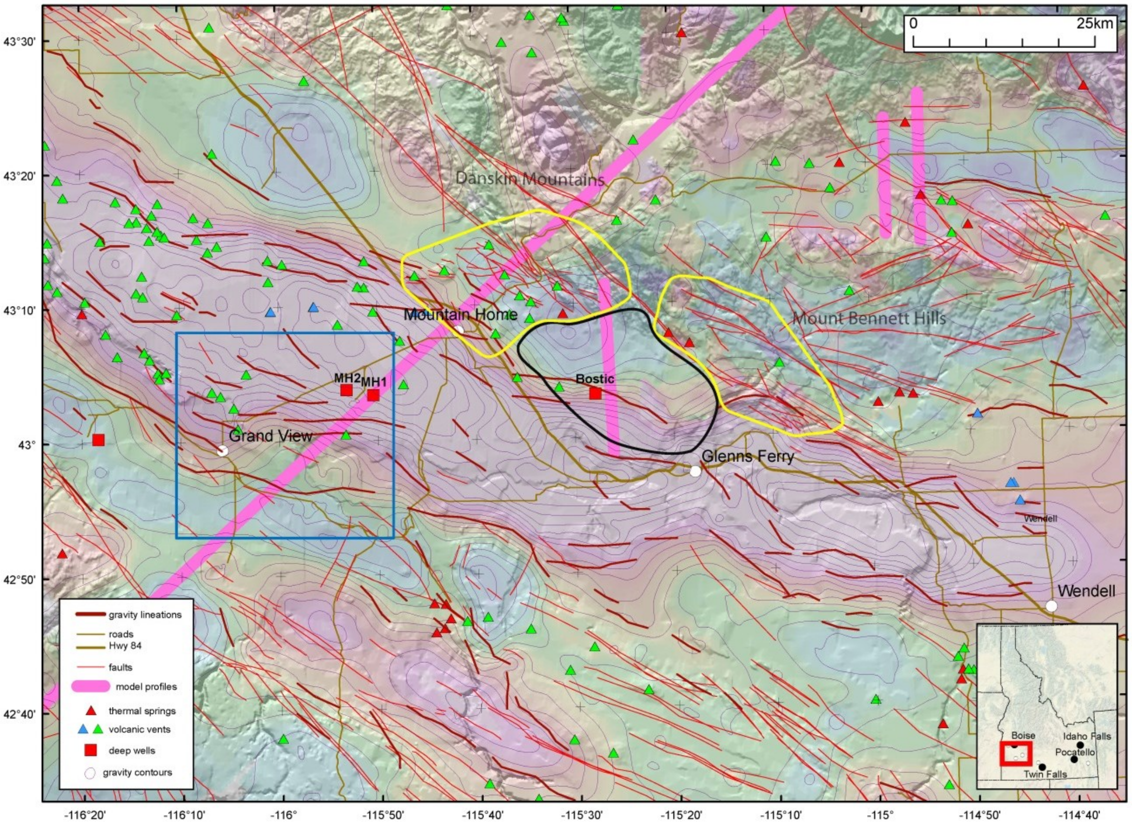

Figure 3) Colored residual isostatic gravity and shaded topographic relief map of the western SRP showing volcanic vents, thermal springs, and deep drill holes. Also shown are geophysically-inferred structural features (gravity lineations) based on maximum horizontal gradients of residual isostatic gravity. Geophysical grids are superimposed on a topographic base map. Blue triangles indicate young volcanic vents. See text for description of colored polygons.

1.1.3 Camas Prairie

The geothermal play fairway analysis (PFA) methodology employed by Shervais et al. (2016) identified the Camas Prairie in southcentral Idaho (Figures 1,2,4,5) as a region with a potential commercial resource (e.g., capable of supporting 10 MW or more of electric power generation) based on its presumed heat, permeability, and presence of basin filling sediments. It was chosen for this study 1) based on these initial estimates of moderate-high geothermal potential, 2) because it represents a unique play type among resources found in the western SRP, and 3) because it presented an opportunity to address a relatively under-characterized geothermal system. In addition, as a Basin-and-Range style hydrothermal system, the Camas area was the most amenable to geophysical study, including shallow penetrating seismic reflection methods, that could reveal important structural features.

The Camas Prairie forms an E-W elongate valley situated between the Idaho Batholith and the central SRP that is thought to have formed as a rift basin, under north-south extension, in response to passage of the Yellowstone hotspot and subsequent downwarping in the SRP (Cluer and Cluer, 1986). The Soldier Mountains, which bound the Prairie to the north, are comprised mostly of late Cretaceous to early Tertiary granodiorite and related intrusives associated with the Idaho Batholith, as well as younger extrusive rocks, including the Eocene Challis volcanics. This range essentially represents the southern extent of the Idaho Batholith, although the valley is thought to be floored by batholith rocks and some granitic outcrops occur along the southern margin of the valley. The valley fill consists of poorly sorted Pliocene and Holocene age sediments derived mainly from the Soldier Mountains to the north and, to a lesser degree, volcanics from the Mount Bennett Hills to the south. Interbedded with these sediments are young volcanic units that flowed out onto the Prairie from eruptive centers in the Mount Bennett Hills. The Mount Bennett Hills are comprised of mafic Miocene volcanic rocks, largely derived locally from vents in the southeastern part of the basin. Rifting and basin development is loosely constrained to between 5 and 1.8Ma (Cluer and Cluer, 1986) based on limited age control on rifted silicic and basin-filling basalts.

The Camas Prairie is characterized as a rift basin resembling other extensional basin-and-range systems, like those in the Great Basin. These systems generally involve amagmatic, moderate temperature resources associated with the circulation of geothermal fluids along deep crustal structures that tap a region of high crustal heat flow. In the Camas Prairie, however, direct surface evidence for major basin-controlling and intra-basin structures is limited, and little is known about the nature of the resource. While the valley resides in an area of elevated heatflow associated with the SRP and is underlain by granitic basement (a potential radiogenic heat source), the geothermal system may involve contributions from a magmatic sources, given the presence of Quaternary volcanism in the southern part of the basin. In the western Prairie, where this research is focused, the youngest flows are associated with The Pothole – a Pleistocene basaltic vent and associated flows that are cut by a northwest-trending fault. This recent volcanic activity offers the possibility for a magmatic heat source underlying the western Camas Prairie geothermal system.

The Prairie hosts several hot springs that are exploited for direct use applications and display high measured temperatures, and high multicomponent geothermometry temperatures. This includes Barron's Hot Springs, which displays measured surface temperatures of 72°C, and yielded a maximum measured temperature of 91℃ at a depth of 300 feet below surface from a well located near the hot springs (Mink, 2010, Camas Creek Assessment). Geochemistry of Barron's Hot springs yields predicted reservoir temperatures suggestive of low to moderate temperature systems (Neupane et al., 2014)]. Although this suggests it may be able to support electric power generation using binary cycle technology, more is needed to demonstrate adequate flows and production temperatures. While Barron's Hot Springs is located on private property, much of the surrounding area near the hot springs is managed by the BLM. This, and the close proximity of the resource to power transmission infrastructure along U.S. Highway 20, would help facilitate development of the resource.

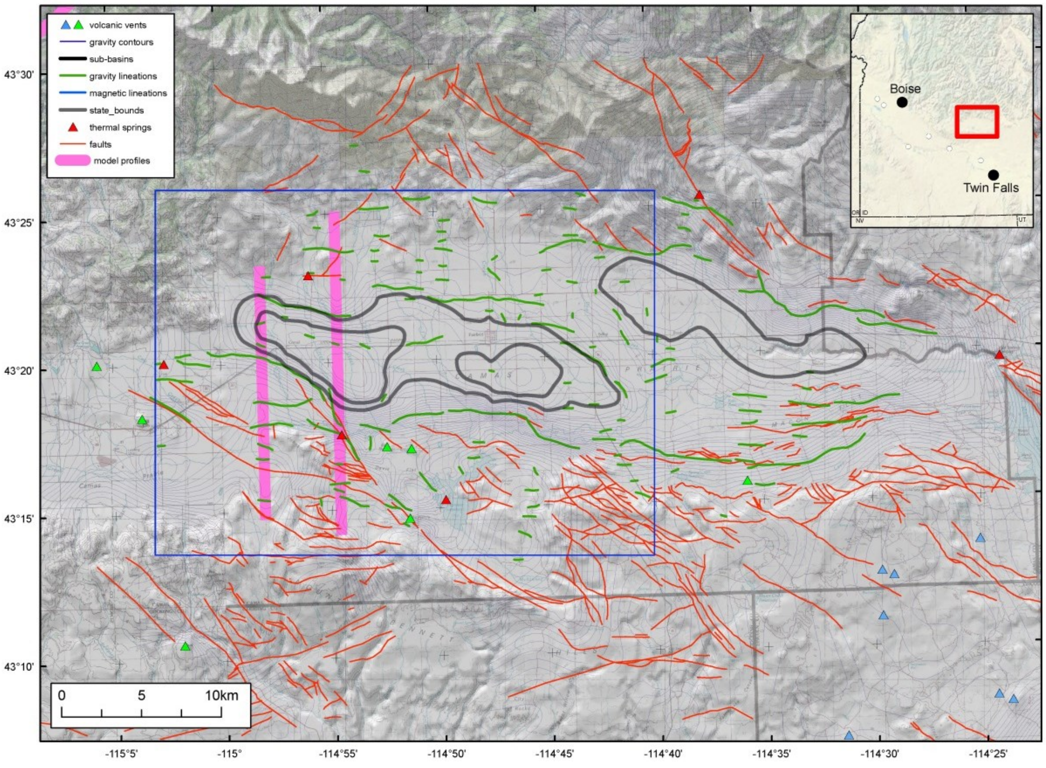

Figure 4) Topographic map of the Camas Prairie study area showing contours of the residual isostatic gravity, volcanic vents, thermal springs, deep drill holes, and profile model locations. Geophysically inferred structural features (gravity lineations) based on maximum horizontal gradients of residual isostatic gravity are shown in green. Faults (red) are derived from a number of sources including Garwood et al. (2014) and new mapping performed as part of this study. Also shown are outlines of sub-basins (thick grey lines) interpreted from the gravity data. Blue triangles indicate young volcanic vents. Blue box indicates area shown in figure 5.

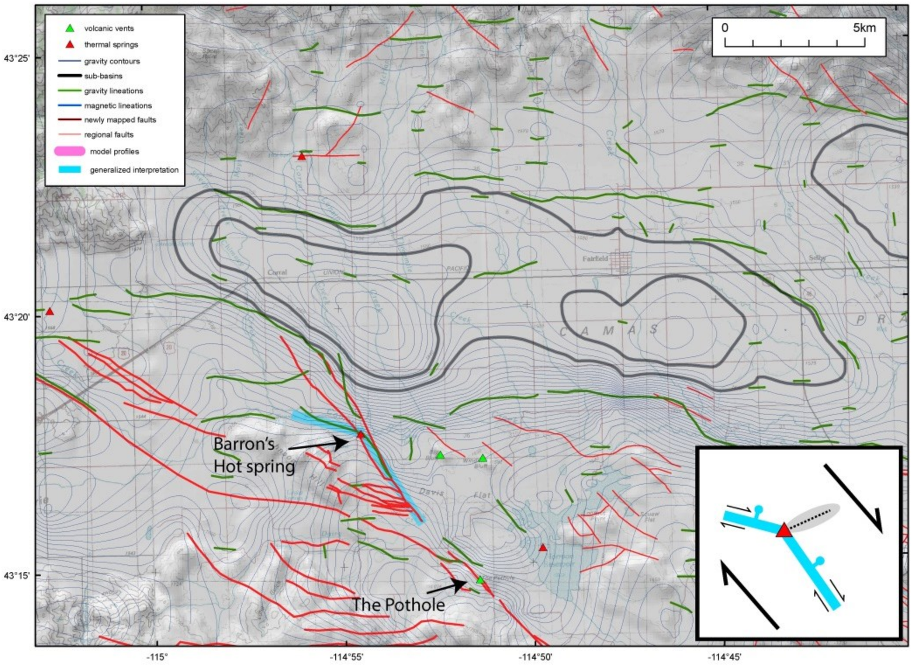

Figure 5) Topographic map of the Camas Prairie study area. Inset shows a regional interpretation of the structural setting responsible for controlling the location of Barron's Hot springs (see figure 4 and text for explanation).

2. STRUCTURE

The availability of high resolution structure data is critical to developing and validating reliable resource models, particularly when assessing under-characterized or blind geothermal systems. Structural data is limited for much of the western SRP to the scale of existing geologic mapping (100k). Efforts to map active structures is hindered by the fact that much of the plain and foothills are blanketed by young sediments and volcanics. Mapping efforts, as part of this study, have involved reconnaissance mapping in the Camas Prairie along the southwestern foothills close to the Barron's Hot springs and the Pothole, and to aerial photo analysis of the broader Mount Bennett Hills in the Camas and Bostic areas.

Surface faulting in the Barron's Hot Springs-Pothole area consists of two distinct structural trends NW (~318°), and NNW (~341°). Faults of both domains dip predominantly NE. Both structural domains pervasively cut the Pleistocene Pothole and other basalts, indicating that the faulting is Pleistocene or younger in age. Striated surfaces and relative offset of contacts and marker beds indicate that the dominant sense of slip is dextral-normal to normal.

3. MAGNETOTELLURICS

Magnetotelluric (MT) data acquired by EarthScope provide information about a deep heat source, while a regional MT survey provides information about distribution of impermeable lake sediments and clay-seal associated with hydrothermal alteration below the regional aquifer that would be considered as a sufficient seal for a potential geothermal reservoir. A total of 102 MT stations were collected from the three study areas (63 in the Camas Prairie, 33 in the Mountain Home area, and 6 from the Bostic area; Figures 1, 2).

4. SEISMIC STUDIES

A total of five 7-10 km long south-north seismic profiles and two 5-8 km long west-east profiles were acquired along section roads (one mile spaced) within the Camas Prairie (Figure 2). The focus of the seismic profiling effort was to identify permeable faults and to characterize the sedimentary cover that overlies basement. Data were acquired using the Boise State seismic land streamer and accelerated weight drop system that allowed production rates of five km per day at four meter source spacing. Data were processed and interpreted with standard industry-standard seismic processing software (ProMAX, Kingdom), where reflectors on cross lines were utilized to map key stratigraphic and structural boundaries.

Legacy seismic reflection data within the western SRP region are of varying quality, but the bulk of data were acquired for oil/gas exploration in the deep sedimentary basin locations to the west of Mountain Home and to the south of Boise, Idaho (Figure 1). These data define bedrock depth, volcanic rock interbeds, and offset strata and related faults. Geothermal and groundwater focused seismic profiling related to the Bostic 1A borehole (Arney, 1982), the Mountain Home exploration well (Liberty et al., 2015), and the Boise geothermal system (Liberty, 1998) also provide key insights into stratigraphy and structures for the upper few km beneath the western SRP margins. US Array lithospheric-scale seismic tomography and receiver function data also provide context of crustal and mantle heat sources, crustal thickness, and plume-related geometries.

5. POTENTIAL FIELDS

Potential field methods are used in geothermal exploration to facilitate imaging of subsurface structures (faults, fractures, contacts) that may provide conduits or barriers to fluid flow. Variations in gravity and magnetic fields occur due to lateral contrasts in rock density and magnetic properties (magnetic susceptibility and remanent magnetization), respectively, and can be used to resolve the geometry and origin of buried sources, particularly when combined with other geologic constraints.

In the western SRP, the physical properties of mafic igneous rocks contrast strongly with the surrounding tuffaceous, sedimentary, and silicic intrusive and extrusive rocks to produce prominent gravity and magnetic anomalies. As a result, potential field methods are particularly well-suited for mapping and modeling subsurface geologic structures such as faults and contacts that juxtapose these contrasting rock types and lead to distinct gravity and magnetic anomalies. Important constraints for potential field modeling typically come from other geophysical data (seismic, MT), regional geologic mapping, borehole logs from wells, and rock-property measurements.

As part of the present study, a total of 1659 (240 in the Bostic area, 1329 in Camas Prairie) new gravity data were collected to improve regional coverage in areas of sparse control and provide detailed coverage (100-200m station spacing) along a series of profile lines in the study area (Figures 1, 2). Additional data were derived from a high-resolution data set recently collected under an earlier study of the SRP (Shervais et al., 2012), and from a regional data of southern Idaho acquired through the PACES database (PACES, 2016). Gravity data were reduced using standard gravity reduction methods (Dobrin and Savit, 1988; Blakely, 1995), in order to produce a gravity map reflecting lateral variations in density in the crust that are used to map and model faults and contacts.

A variety of new and existing magnetic data were used in the potential field modeling. The Idaho state aeromagnetic map compilation (McCafferty et al., 1999) was used to model the regional profile through Mountain Home. Data digitized from a 1982 aeromagnetic survey of the Mountain Home Known Geothermal Resource Area (KGRA) southeast of Mountain Home (U.S. Geological Survey, 1982) was used to model the Bostic profile. In the Camas Prairie, over 1000 line-km of new high-resolution ground magnetic data (~725km of unique lines) were collected on foot along off-road profile lines, and using ATV-magnetometer systems (Athens et al., 2011) to collect data along roads and in agricultural fields (Figure 2).

Rock-property [density (dry bulk, grain and saturated bulk densities) and magnetic (magnetic susceptibility and remanence)] measurements were performed on outcrops, hand samples, and paleomagnetic cores taken from the three study areas in order to constrain the potential field models. Model rock properties are based on these measurements, which include all of the principal rock units from the study areas, as well as data derived from a national database (unpublished data, D. Ponce, USGS, 2016) consisting of over 19,000 measurements made on similar lithologies.

We applied a variety of derivative and filtering methods to the magnetic and gravity data to help delineate structures, such as intra-basin or basin-bounding faults or contacts, and to constrain their geometry. Residual maps, produced by upward-continuing the observed anomalies and subtracting the result from the original grid, are useful for removing the contribution of deeper sources, and emphasizing surface and near-surface sources. The pseudogravity (or magnetic potential) transformation (Blakely, 1995), converts a magnetic anomaly into one that would be observed if the magnetic distribution of the body were replaced by an identical density distribution. Although there are significant assumptions that can limit its effectiveness, this method can be useful for simplifying the interpretation of magnetic sources by centering magnetic anomalies over their sources. Maximum horizontal gradients (MHG; Blakely and Simpson, 1986) of gravity and pseudogravity, which reflect abrupt lateral changes in the density or magnetization in the subsurface, and tend to lie over the edges of bodies with near vertical boundaries, are used to estimate the extent of buried sources (Grauch and Cordell, 1987; Cordell and McCafferty, 1989).

6. PROFILES AND MODELING

Two-dimensional potential field models were constructed along profiles (figures 1, 2) across the study areas. Where possible, potential field, seismic and MT data collection was coordinated to facilitate modeling and interpretations (figures 6-9). In the 2D modeling, subsurface geology is approximated by horizontal tabular prisms or blocks that vary in the ± Y directions (commonly referred to as 2¾D modeling). The surface extents of model blocks were initially informed by geologic mapping, MT and seismic cross sections. The geometries of the model bodies were adjusted iteratively through a series of forward and inverse calculations to match model anomalies with observed anomalies within the limits imposed by surface geology, seismic, rock property, and MT data.

7. DISCUSSION

The geophysical mapping and modeling methods employed in this study were used to resolve subsurface structures that have little or no surface manifestation. Key goals of this work were to help delineate deep-seated features that likely represent important permeable pathways for hydrothermal fluid flow, constrain basin geometry, study fault interactions, and identify areas favorable to hydrothermal flow. Below we describe results and interpretations of our investigations of the geothermal systems at Mountain Home, Bostic and Camas Prairie study areas.

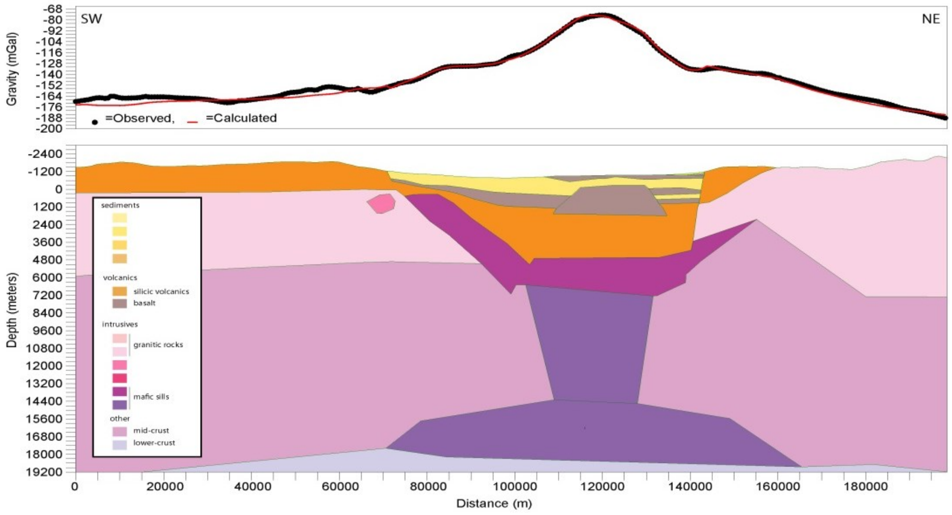

Figure 6) Two-dimensional geophysical model along across the western SPR. The top panel show observed (black circles) and model (black line) anomalies for gravity. The bottom panel shows the potential field model with individual model bodies colored by rock unit. Location shown on Figure 1 (labeled Mtn Home profile).

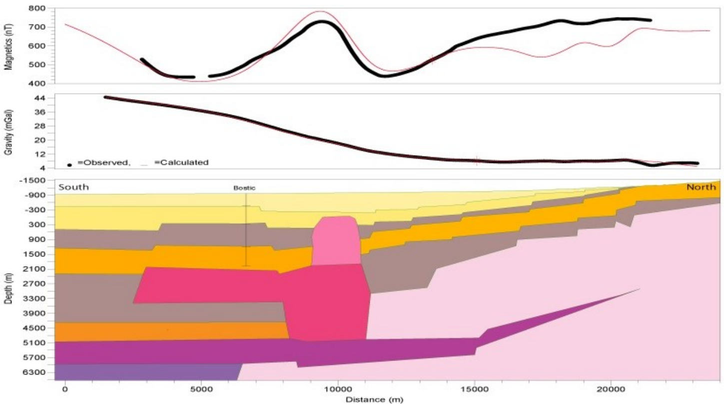

Figure 7) Two-dimensional geophysical model along across the Bostic study area. Panels show observed (black circles) and model (black line) anomalies for magnetic (top) and gravity (middle) fields, and potential field model with individual model bodies colored by rock unit (bottom). Location shown on Figure 1 (labeled Bostic profile).

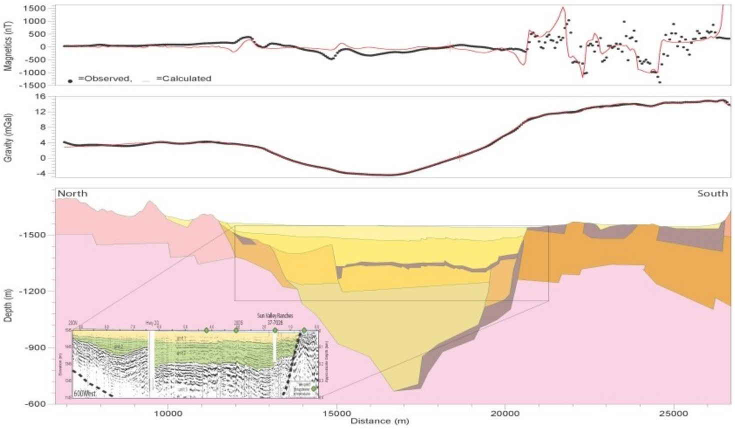

Figure 8) Two-dimensional geophysical model of the Camas Prairie along road 600W. Panels show observed (black circles) and model (black line) anomalies for magnetic (top) and gravity (middle) fields, and potential field model with individual model bodies colored by rock unit (bottom). Location shown on Figure 2.

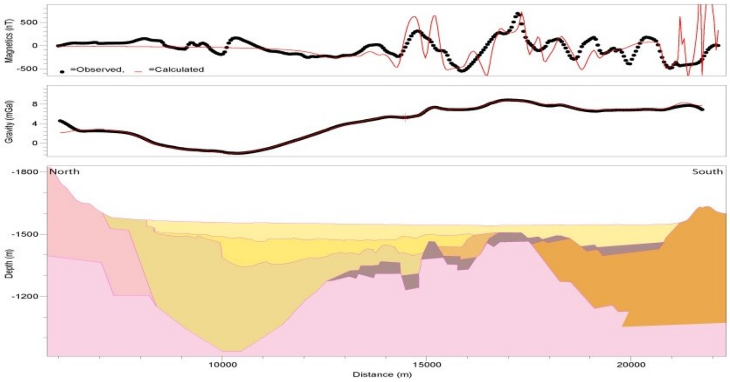

Figure 9) Two-dimensional geophysical model of the Camas Prairie along road 900W. Panels show observed (black circles) and model (black line) anomalies for magnetic (top) and gravity (middle) fields, and potential field model with individual model bodies colored by rock unit (bottom). The lower panel shows the interpreted geologic cross section. Location shown on Figure 2.

7.1 Mountain Home

A regional potential field model was developed for the western SRP that extends through the Mountain Home resource area (Figure 6, see figures 1 and 3 for profile location) largely based on high-resolution gravity data collected across the plain. Regional lithospheric structure of the model was constrained by a N-S-trending deep seismic refraction line, extending from Boise to Elko NV that crosses the profile at Mountain Home (Hill and Pakiser, 1967; Prodehl, 1970). In addition, seismic reflection results associated with the MH2 borehole (Liberty et al., 2015) and 33 new MT data, collected as part of this study across the MHAFB and extending 20km along the profile (Figure 1), were used to inform the interpretation of structures around the base.

The dominant feature along the profile is a prominent gravity high that extends nearly the full length of the western SRP (Figures 3, 6). This high is primarily modeled as a dense mafic root and sill complex intruded into the lower and middle crust. Also contributing to the high, however, is a horst block in the upper crust consisting largely of dense mafic lavas. Both wells (MH1 and MH2) drilled at the MHAFB are located over the prominent gravity high (Figure 3) and extend into basalts interpreted to mark the top of the horst.

The primary heat source for the resource, interpreted to derive from layered basaltic sills (Nielson and Shervis, 2014), is modeled as an extensive sill complex emplaced in the middle to upper crust. In the model, the sill complex extends to shallow crustal levels on the southwest side of the Plain to account for prominent long linear magnetic anomalies that bound the gravity high to the south (not shown). In a conceptual model of the geothermal system (Figure 10), heat derives from an intrusive complex feeding young (~200ka) volcanism north and west of Mountain Home (see vents shown in Figure 3) and drives circulation of thermal fluids in the reservoir. Structural features bounding the horst represent deep crustal structures extending into the underlying silicic volcanics that may provide important conduits for reservoir fluids to circulate to shallower crustal levels. Indeed, evidence such as shallow crustal faulting (e.g., near King Hill, Rosevear Gulch, Strike Reservoir, Bruneau Valley), the manifestation of hot springs (near Thomas Flats and the Bruneau Valley), and the distribution of young volcanic vents (north and west of Mountain Home that appear to flank the central high), that occurs at places along the central gravity high and along ancillary highs within the plain, suggest that deep crustal features related to the gravity anomaly are active and influence faulting, permeability and fluid flow. A particularly interesting area for the focus of future study is a region southwest of the study area that marks a nexus of geophysically-inferred faults that are concentrated over a major step-over of the gravity high (outlined in blue square, Figure 3). This area likely represents a profound zone crustal complexity that may promote permeability at significant depths.

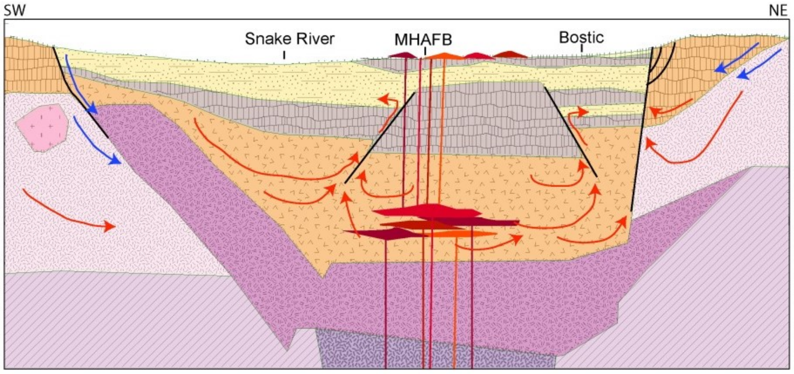

Figure 10) Cartoon illustrating our conceptual model of the structure and geothermal system of the western SRP relevant to the Mountain Home and Bostic study areas.

7.2 Bostic (Glenns Ferry- Mount Bennett Hills)

The potential field model of the Bostic area (Figure 7) was derived from detailed gravity data collected along a line extending from the Bostic 1A well northwards to the Danskin Mountains (Figures 1,3) and from an aeromagnetic survey of the Mountain Home KGRA (U.S. Geological Survey, 1982). In addition, legacy seismic data and new MT data, collected as part of this study along a NE-trending line situated northwest of the modeled profile, were used to inform the interpretation of modeled structures.

The profile is characterized by a prominent gravity anomaly on its southern end, which corresponds with the central SRP gravity high. The Bostic 1A drillhole is situated along of the northern shoulder of this high, presumably within the structural horst. The model indicates the presence of two distinct intrusive bodies emplaced in the upper crust (extending to within 1km of the surface) that were modeled to account for several 100 nT anomalies observed along the profile. This feature corresponds with a roughly 3x7km wide anomaly seen in the aeromagnetic map (not shown).

The potential field model reflects minor faulting following the interpretive schematic cross sections of Arney et al. (1984). This is primarily intended to illustrate the regional presence of such structures (note that a complex of faults occurs off-axis of the profile to the northeast of Mountain Home), whereas along this particular profile, the potential field data suggest that only a couple of the illustrated structures within the region north of the Bostic well have any significant geophysical expression that might suggest they involve appreciable offset and extend into basement.

A conceptual model of the geothermal system (Figure 10) indicates deep circulation of fluids through the silicic volcanic basement. Heat may be derived from intrusives related to young (~200ka) volcanism occurring to the northwest. However due to proximity to the rangefront, additional heat might involve fluids originating from the basement beneath the Danskin Mountains.

7.3 Camas Prairie

Gravity and magnetic maps were gridded from a combination of new and existing data collected throughout the Camas Prairie valley and surrounding regions (Figure 2). Analyses of MHG of residual isostatic gravity and magnetic grids delineate a number of intrabasin structures that have little or no surface manifestation (Figures 4, 5, 8, 9). These structures reflect two dominant sets of trends, W to WNW-trending structures that likely reflect the major basin-bound structural grain, and a NW-trending set that appears to control the major subbasin geometry of the valley.

Potential field modeling was performed along two profiles at the western end of the valley (lines 600Wand 900W, Figure 2, 8, 9). Seismic data collected along these lines constrain the upper several hundred meters of the models. The models reveal a deep (500-1000m) structurally controlled sedimentary basin that displays offsets along numerous structures imaged in the seismic profiles and reflected in the potential field data. MT results support structures identified by gravity or seismic, and provide depths to the base of basin sediments to constrain gravity inversions. The modeled basin is floored by crystalline basement that is, at least partly, capped with volcanic flows presumably derived from sources in the Mount Bennett Hills. The model also reveals that the basin stratigraphy includes interbedded volcanic flows that are offset along the same structures identified in the seismic profiles.

Regional gravity mapping indicates the valleys subsurface consists of several NW-elongate sub-basins characterized by isolated gravity lows (Figures 4, 5). The deepest of these inferred sub-basins, which resides on the western end of the Prairie just north of Barron's Hot springs, reflects the deepest part of the basin (up to 1km). This area coincides with anomalously high groundwater temperatures and may represent the primary geothermal reservoir for fluids that feed the springs. A steep gradient bounding the southwest side of the gravity low likely reflects the more structurally active part of the basin. Seismic results show diminishing offsets of shallow strata from southeast to northwest away from Barron's Hot springs, intersecting fault systems beneath the central basin region, and offset of the shallowest reflectors that support ongoing NW-trending basin extension.

The steep gradient bounding the sub-basin in the western end of the valley is aligned with inferred NW-trending structures that extend through Barron's Hot spring. The location of hot springs appears to be related to the intersection of this NW-trending structure with more easterly-oriented basin-bounding structures that delineate the southern edge of the valley.

Analyses of new and existing geologic and structural mapping support the importance of these faults in controlling basin geometry and possibly influencing hydrothermal fluid flow. The two dominant fault sets south of Barron's Hot Springs (WNW- and NNW-striking, E-dipping with dextral-normal to normal slip), though based on a limited dataset (a total of 37 fault surface measurements), are consistent with the trends of the major subsurface intra-basin features inferred from the geophysics. Under right lateral transtension, conditions conducive for dilation and fluid flow would be expected at releasing steps along intersections of these structural trends (Figure 5, inset).

A conceptual model of the basin (Figure 11) illustrates the likely source and circulation of thermal fluids. This involves recharge from the Soldier Mountains to the north of the valley, and deep circulation of fluids through the underlying granitic basement driven by the regional topographic head between the valley and the adjacent highlands. Aside from deep basement circulation within a region characterized by elevated geothermal gradients, thermal fluids may also derive their heat from a possible magmatic source that is suggested by the presence of relatively young volcanic rocks emplaced within and around the valley.

This conceptual model also indicates that surface discharge of thermal fluids involves upflow along basin controlling structures. We suggest that key intersections between W-to-WNW-trending basin-bounding structures and prominent NW-trending faults provide conduits for upward convection of thermal fluids at the southern margin of the valley adjacent to the deep structural subbasin. This, together with active faulting along these structures, could stimulate and maintain zones of permeability that allow for upflow of thermal fluids and discharge at the Barron's Hot springs.

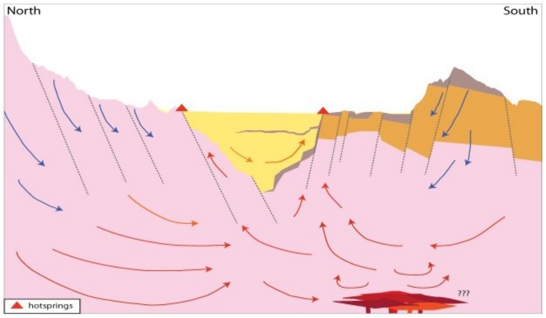

Figure 11) Cartoon illustrating our conceptual model of the structure and geothermal system of the Camas Prairie study areas.

8. CONCLUSIONS

We performed detailed geophysical studies of three distinct resource areas in southcentral Idaho to characterize their geothermal resource and guide future exploration and possible development of these systems. We employed high-resolution gravity, magnetic, magnetotelluric (MT), seismic reflection surveying, and structural mapping, with the aim of characterizing intra-basin and basin-bounding faults, resolving fault interactions, modeling basin geometries, and identifying areas favorable to hydrothermal flow.

Together, the three study areas encompass high to low-temperature geothermal systems, with potential for direct use applications and for electric power production from both conventional and EGS resources. These systems also likely span a range of resource types from magmatic (basaltic sill), amagmatic (basin-and-range), and basement related plays.

Each of these sites is favorable for future development from the perspective of the resource potential, local demands for a cheap reliable energy resource, and basic logistical considerations. They are all proximal to major transportation and power transmission corridors, and to population centers that would benefit from a local geothermal resource that could provide for direct-use and electricity needs. There is also a long history of geothermal resource use in the western SRP that has established a culture supportive of geothermal development. This is reflected in active efforts from private, municipal, and federal parties to promote the resource in this region.

Mountain Home area:

The Mountain Home study area represents a blind high-temperature geothermal system that is not associated with any mapped faults or surface geothermal manifestations, A sequence of low permeability lake sediments capping the geothermal system at Mountain Home likely maintains the resource by insulating the reservoir, preventing upward migration of the thermal fluids, and inhibiting mixing with cold meteoric water that could degrade the resource. The area is situated over a prominent gravity high, the edges of which coincide with steep gradients that are inferred to reflect deep crustal structures. Active faulting, geothermal manifestation, and the distribution of young volcanic vents that appear to be spatially correlated with the edges of the gravity high suggest that this deep crustal features may influence faulting, permeability and fluid flow and offer a target for exploration. A particularly interesting area for the focus of future study is a region southwest of the study area that marks a nexus of geophysically-inferred faults that are concentrated over a major step-over of the gravity high. This area likely represents a profound zone of crustal complexity that may promote permeability at significant depths.

Bostic area:

The Bostic and Mountain Home systems have similarly high geothermal gradients and likely shares a common stratigraphy and heat source. Due to the lack of significant permeability in the area around the Bostic well and the presence of extensive silicic volcanic rocks flooring the western SRP, a significant part of this resource area seems favorable for EGS stimulation. Adjacent to this however (such as between the town of Mountain Home and the Danskin Mountains) are local structural zones consisting of numerous intersecting faults, and where surface geothermal features are manifest. This suggests that focused research within a relatively limited area could assess viable prospects with permeabilities favorable for both conventional geothermal resource development and both EGS that otherwise share many similar characteristics.

Camas Prairie area:

Geophysical investigations of the Camas Prairie geothermal system reveal several previously unidentified hydrothermal and structural features that have led to a new conceptual model for the geothermal reservoir and pathways for fluid flow. Potential field mapping indicates the Camas Prairie actually consists of several NW-elongate sub-basins characterized by isolated gravity lows. The deepest of these inferred sub-basins resides on the western end of the valley just north of Barron's Hot Springs, where potential field models reveal a deep (500-1000m) structurally controlled sedimentary basin that displays offsets along numerous structures imaged in the seismic profiles and reflected in the potential field data. This sub-basin coincides with anomalously high groundwater temperatures that may represent the primary geothermal reservoir for fluids that feed the springs. A steep gradient bounding the southwest side of the gravity low likely reflects the more structurally active part of the basin. Seismic results document offsets of shallow strata that support ongoing

NW-trending basin extension. This active NW-trending structural zone appears to extend through Barron's Hot Springs where it intersects more easterly-oriented basin-bounding structures that delineate the southern edge of the valley. Structural mapping support the importance of these faults in controlling basin geometry and possibly influencing hydrothermal fluid flow. Fault exposures near Barron's Hot Springs reveals two dominant fault sets (WNW- and NNW-striking) with fault striations that indicate predominantly E-NE-dipping dextral-normal slip. These orientations are consistent with the trends of the major subsurface intra-basin features inferred from the geophysics. Under right-lateral transtension, conditions conducive for dilation and fluid flow would be expected at releasing steps along intersections of these structural trends. These fault systems have been active as recently as the Pleistocene, but may be even younger. Our conceptual model of the basin involves deep circulation of fluids through the underlying granitic basement (with the possible input of heat from a magmatic source), and the upflow and surface discharge of thermal fluids occurring within favorable structural intersections. We suggest that key intersections between W-to-WNW-trending basin-bounding structures and prominent NW-trending faults provide the conduits for thermal fluids manifesting at Barron's Hot Springs.

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REFERENCES

Armstrong, R.L., Harakal, J.E., and Neill, W.M., 1980, K-Ar dating of the Snake River Plain (Idaho) volcanic rocks-new results. lsochron/West. no. 27, pp. 5-10.

Armstrong, R.L., Leeman, W.P., and Malde, H.E., 1975, K-Ar dating, Quaternary and Neogene volcanic rocks of the Snake River Plain, Idaho, American Journal of Science, v. 275, pp.225-251.

Arney, B., 1982, Evidence of Former Higher Temperatures from Alteration Minerals, Bostic 1-A Well, Mountain Home, Idaho, GRC Trans, 6 pp. 3-6.

Arney, B.H., Gardner, J.N., and Bellnomi, S.G., 1984, Petrographic analysis and correlation of volcanic rocks in Bostic 1-A well near Mountain Home, Idaho: Los Alamos National Laboratory Report LA-9966- HDR, 29 p.

Arney, B.H., Goff, F., and Harding Lawson Associates, 1982, Evaluation of the hot dry rock geothermal potential of an area near Mountain Home Idaho: Los Alamos National Laboratory Report LA-9365-HDR, 65 p.

Athens, N.D., Glen, J.M.G., Morin, R.L., and Klemperer, S.L., 2011, ATV magnetometer systems for efficient ground magnetic surveying, The Leading Edge, 30, 394-398.

Blakely, R.J., 1995, Potential theory in gravity and magnetic applications: New York, Cambridge University Press, 441 p.

Blakely, R.J., and Simpson, R.W., 1986, Approximating edges of source bodies from gravity or magnetic data: Geophysics, v. 51, p. 1494–1498, doi: 10.1190/1.1442197.

Blaney, H.F., and Criddle, W.D., 1962, Determining water requirements in irrigated areas from climatological and irrigation data, U.S. Department of Agriculture, Soil Conservation Service, Technical Paper 96.

Cluer, B.L., 1987, A gravity model of basement geometry and resulting hydrogeologic implications of the Camas Prairie, south central Idaho, Unpublished Northern Arizona University M.S. thesis.

Cluer, B.L., 1989, Storage Basin Volume and Drainage Basin Dynamics: Camas Prairie, South Central Idaho, Ground Water, 27, 3, 323-332.

Cluer, J.K., and Cluer, B.L., 1986, The late Cenozoic Camas Prairie Rift, south-central Idaho, Contributions to Geology, University of Wyoming, v. 24, no. 1, pp. 91-101.

Cluer, J.K., and Cluer, B.L., 1986, The late Cenozoic Camas Prairie rift, south-central Idaho, Geology, v. 24 p. 91-101.

Cordell, L., and McCafferty, A.E., 1989, A terracing operator for physical property mapping with potential field data: Geophysics, v. 54, p. 621–634, doi:10.1190/1.1442689.

Dansart, WJ, Kauffman, JD, and Mink, LL, 1994, Overview of Geothermal Investigations in Idaho 1980 to 1993: Idaho Water Resources Research Institute, University of Idaho Moscow ID, 79pp.

Davis, R.W., 1967, A geophysical investigation of hydrologic boundaries in the Tucson basin, Pima County, Arizona, Unpublished University of Arizona Ph.D. dissertation.

Davis, S.N., 1969, Porosity and permeability of natural materials, In DeWeist, R.J.M., ed., Flow Through Porous Media, Academic Press, New York, NY.

Deangelo, J., Shervais, J.W., Glen, J.M., Nielson, D., Garg, S., Dobson, P., Gasperikova, E., Sonnenthal, E., Visser, C., Liberty, L.M., Siler, D., Evans, J.P., and Santellanes, S., 2016, GIS Methodology for Geothermal Play Fairway Analysis: Example from the Snake River Plain Volcanic Province, Proceedings, 41st Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 22-24, 2016, SGP-TR-209.

Dobrin, M.B., and Savit, C.H., 1988, Introduction to Geophysical Prospecting (4th ed.): New York, McGraw-Hill, 867 p. Dobson, P.F., Kennedy, B.M., Conrad, M.E., McLing, T., Mattson, E., Wood, T., Cannon, C., Spackman, R., van Soest, M., and Robertson, M., 2015, He isotopic evidence for undiscovered geothermal systems in the Snake River Plain. Proceedings, 40^{th} Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, 7 p.

Ferris, J.G., 1951, Ground water, chap. 7, In Wisler, C. O., and E. F., Bracer, eds., Hydrology, John Wiley and Sons, New York. pp. 198-272.

Finn, C.A., and Morgan, L.A., 2002, High-resolution aeromagnetic mapping of volcanic terrain, Yellowstone National Park, J. Volcanol. Geotherm. Res., 115, 207–231.

Garwood, D.L., Kauffman, J. D., Othberg, K.L., Lewis, R.S., Freed, J.S., Taylor, T.A., Bird, J.S., Gantenbein, C. and Stanford, L.R., 2014, Geologic Map of the Fairfield 30 x 60 Minute Quadrangle, Idaho, Idaho Geological Survey.

Grauch, V.J.S., and Cordell, L., 1987, Limitations of determining density or magnetic boundaries from the horizontal gradient of gravity or pseudogravity data: Geophysics, v. 52, p. 118–121, doi: 10.1190/1.1442236.

Hammer, S.I., l945, Estimating ore masses in gravity prospecting, Geophysics, v. 10, pp. 50-62.

Johnson, E.E., 1972, Ground Water and Wells, Johnson Division, Universal Oil Products Company, St. Paul, MN,

Kirkham, V.R.D, 1931, Snake River downwarp, Journal of Geology, v. 39, pp. 456-482.

Leeman, W.P., 1982, Geology of the Magic Reservoir area, Snake River Plain, Idaho, In Bonnichsen, B., and Breckenridge, R.M., eds., Cenozoic Geology of Idaho. Idaho Bureau of Mines and Geology, Bulletin 26. pp. 369-376.

Lewis, R.L., 1990, Geology and geochemistry and mineral potential of Cretaceous and Tertiary plutons in the eastern part of the Soldier Mountains, Idaho, Corvallis, Oregon, Oregon State University, PhD thesis, 214 p., 2 sheets, scale 1:62,500.

Lewis, R.S., 1991, Geologic map and geochemical data of the eastern part of the Soldier Mountains, Camas County, Idaho. Idaho Geological Survey Technical Report 91-1, 2 sheets, scale 1:62,500.

Liberty, L., 1998, Seismic reflection imaging of a geothermal aquifer in an urban setting, Geophysics, 63(4), pp.1285-1294.

Liberty, L.M., Schmitt, D.R. and Shervais, J.W., 2015, Seismic imaging through the volcanic rocks of the Snake River Plain: insights from Project Hotspot. Geophysical Prospecting, 63(4), pp.919-936.

McCafferty, A.E., Kucks, R.P., Hill, P.L., and Racey, S.D., 1999, Aeromagnetic Map For The State of Idaho: A Web Site for Distribution of Data, USGS Open-File-Report 99-371.

Mink, L.L., 2010, Camas Creek Ranch Geothermal Assessment Preliminary Report (unpublished).

Mitchell, J.C., 1976, Geothermal investigations in Idaho, Part 7, Geochemistry and geologic setting of the thermal waters of the Camas Prairie area, Blaine and Camas Counties, Idaho, Idaho Department of Water Resources, Water Information Bulletin, no. 30, 44 pp.

Mitchell, J.C., 1976, Geothermal Investigations in Idaho: Geochemistry and Geologic Setting of the Thermal waters of the Northern Cache Valley Area, Franklin County, Idaho: Idaho Department of Water Resources Water Information Bulletin 30, Part 5, 47 p.

Neupane, G., Smith, R. W., Palmer, C. D., and McLing, T. L., 2013, Multicomponent equilibrium geothermometry applied to the Raft River geothermal area, Idaho: preliminary results, Geological Society of America Abstracts with Programs, 45 (7).

Nielson, D.L., Delahunty, C., and Shervais, J.W., 2012, Geothermal systems in the Snake River Plain, Idaho, characterized by the Hotspot project, Geothermal Resources Council Transactions, 36, 727-730.

Oakley, W.L., Link, P.K., Long, S., Frommer, R., and Boyack, D., 2006, Geologic map of the Davis Mountain Quadrangle, Gooding and Camas Counties, Idaho. Idaho Geological Survey.

Pan-American Center for Earth and Environmental Studies (PACES), http://research.utep.edu/paces (accessed 2016).

Piper, A.M., 1926, Ground water for irrigation on Camas Prairie and Elmore Counties, Idaho, Idaho Bureau of Mines and Geology, Pamphlet 15, 46 pp.

Schmidt, D.W., 1962, Quaternary geology of the Bellevue area in Blaine and Camas counties, Idaho. U.S. Geological Survey Open File Report 62-120, 135 p., 2 sheets, scale 1:48,000.

Shervais, J.W., Nielson, D., Evans, J.P., Lachmar, T., Christiansen, E.H., Morgan, L., Shanks, W.C.P., Delahunty, C., Schmitt, D.R., Liberty, L.M., Blackwell, D.D., Glen, J.M., Kessler, J.A., Potter, K.E., Jean, M.M., Sant, C.J., and Freeman, T.G., 2011, Hotspot: The Snake River Geothermal Drilling Project — Initial Report, GRC Transactions, 36, 767-772.

Shervais, J.W., Glen, J.M., Nielson, D., Garg, S., Dobson, P., Gasperikova, E., Sonnenthal, E., Visser, C., Liberty, L.M., Deangelo, J., Siler, D., and Evans, J.P., 2016, Geothermal Play Fairway Analysis of the Snake River Plain: Phase 1, Proceedings, 41st Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 22-24, 2016, SGP-TR-209.

Sokolov, A.A., and Chapman, T.G., 1974, Methods for Water Balance Computations; An International Guide for Research and Practice, The Unesco Press.

Struhsacker, D.W., Jewell, P.W., Zcisloft, J., and Evans, S.H., 1982, The geology and geothermal setting of the Magic Reservoir area, Blaine and Camas Counties, Idaho, In Bonnichsen, B. and R. M. Breckenridge, eds., Cenozoic Geology of Idaho, Idaho Bureau of Mines and Geology , Bulletin 26. pp. 377-393.

Tester, J., 2006, The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century. Massachusetts Institute of Technology.

U.S. Department of Agriculture, 1987, Idaho cooperative river basin study, Camas Creek erosion and sediment study, 116 pp.

U.S. Geological Survey, 1982, Aeromagnetic map of an area east of Mountain Home, Idaho, Open-File Report 82-542, 1 map.

U.S. Geological Survey, Water Resources Division, 1985, Idaho water year 1984, Great Basin and Snake River Basin above King Hill, ID-84-l. v. 1.

Walton, W.C., 1962, Ground-water resources of Camas Prairie, Camas and Elmore Counties, Idaho, U.S. Geological Survey Water-Supply Paper 1609, 57 pp.

West, R.E., and Sumner, J.S., 1972, Ground-water volumes from anomalous mass determinations for alluvial basins, Ground Water, v. 10, no. 3, pp. 24-32.

Williams, C.F., and DeAngelo, J., 2011, Evaluation of Approaches and Associated Uncertainties in the Estimation of Temperatures in the Upper Crust of the Western United States, GRC Transactions, 35, 1599-1605

Wood, S.H., and Clemens, D.M., 2002, Geologic and tectonic history of the western Snake River Plain, Idaho and Oregon. Tecton ic and Magmatic Evolution of the Snake River Plain Volcanic Province: Idaho Geological Survey Bulletin, 30, 69-103.

Young, H.W., 1978, Water resources of Camas Prairie, south-central Idaho, U.S. Geological Survey, Water· Resources Investigations 78-82, Open File Report, 34 pp.