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A Geophysical Characterization of the Structural Framework of the Camas Prairie Geothermal System, Southcentral Idaho

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Keywords

Camas Prairie, Idaho, geothermal, hydrothermal, hot springs, faulting, structure, seismic reflection, magnetotellurics (MT), gravity, magnetics, potential field modeling, Play Fairway Analysis

ABSTRACT

Play Fairway Analysis methods, utilizing existing geologic, thermal, geochemical, and geophysical data were employed in an initial assessment of geothermal resources in the Snake River Plain. These efforts identified the Camas Prairie in southcentral Idaho as a region with elevated resource potential. Subsequent efforts included structural and geophysical data collection to identify the most favorable structural settings for exploiting resources in the valley. The present work involved high-resolution gravity, magnetic, magnetotellurics (MT), field mapping, and seismic surveys to further characterize the system and target sites for exploration drilling around Barron's Hot Springs (BHS) in the southwest part of the valley.

Geophysical mapping and modeling reveal that the BHS coincides with a complex intersection of two major fault systems: a prominent NW-trending system that includes the Pothole fault, and EW-trending basin-bounding faults that control NS-extension. This complex zone includes a dense network of EW-oriented faults and a right stepover in the Pothole fault which, given the dominant dextral-normal to normal slip inferred for this fault, would promote extension in the immediate vicinity of the BHS.

Surface faulting in this region indicate Pleistocene or younger slip, and seismic imaging documents offsets of shallow strata that suggest ongoing activity on these structures. MT modeling results show that this zone also coincides with a prominent conductive anomaly, characteristic of the presence of hydrothermal alteration or hydrothermal fluids. These results

point to the importance of these structures in maintaining current and long-lived shallow hydrothermal activity around the BHS.

The detailed structural mapping and conceptual framework developed from this study provide critical constraints for siting a drill hole aimed at documenting reservoir characteristics and informing potential future development of these geothermal resources.

1. INTRODUCTION

Play Fairway Analysis (PFA) methods, utilizing existing geologic, thermal, geochemical, and geophysical data were employed (Shervais et al., 2016) in an initial (Phase 1) assessment of geothermal resource potential in the Snake River Plain (SRP). This work revealed that the western SRP and surroundings represent a region of high geothermal potential (Shervais et al., 2016, 2017; DeAngelo et al., 2016), based on the presence of extensive early to mid-Pleistocene basaltic volcanism (as young as ~200ka), recent faulting, high groundwater temperatures, and regional high heat flow. Subsequent efforts (Phase 2) of the project included structural and geophysical data collection to identify the most favorable structural settings for exploiting resources in the Camas Prairie.

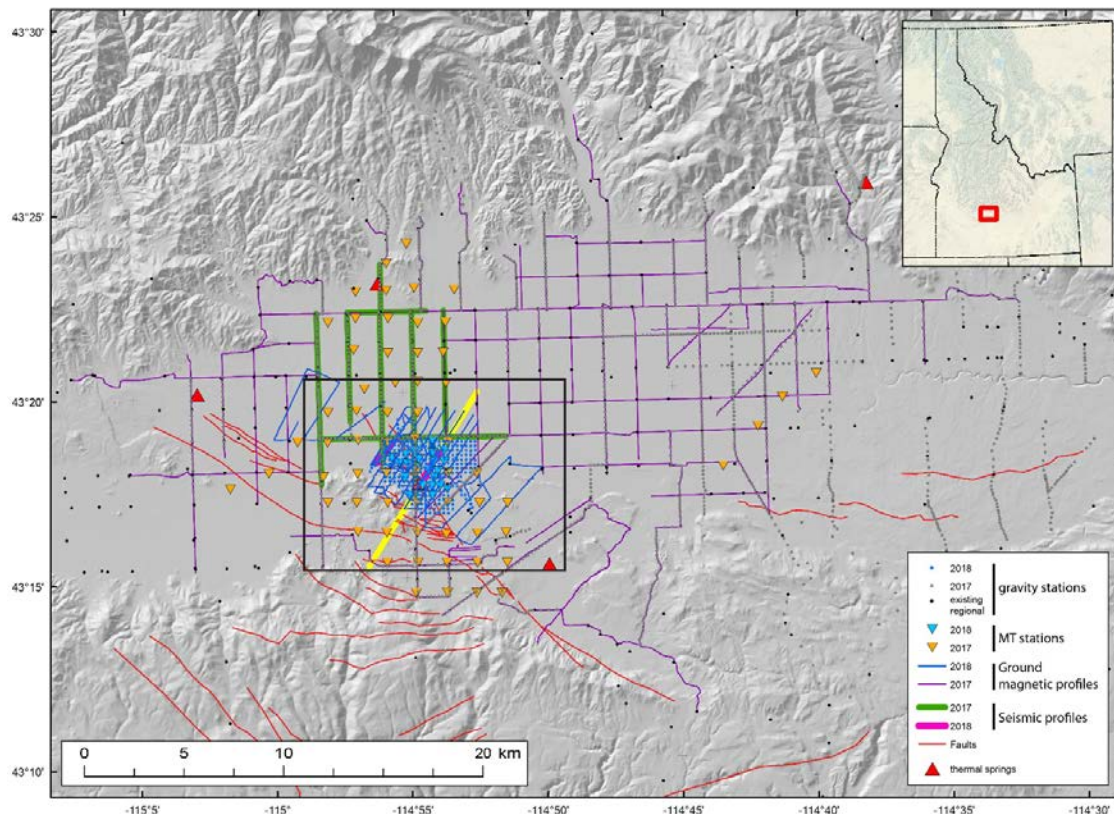


Figure 1: Regional shaded topographic index map of the Camas Prairie study area showing existing and newly collected seismic reflection profiles, MT stations, gravity stations, and magnetic traverses. Modeled profile shown in Figure 7 is depicted with yellow line. Faults are from USGS (2006) and Glen et al. (2017). The black box shows the extent of the Barron's Hot Springs area of Figures 2, 4-6.

In this paper we focus on an area within the Camas Prairie, southcentral Idaho where we have performed additional detailed geophysical investigations (Phase 3) involving potential field (gravity and magnetic), magnetotellurics (MT), and seismic reflection surveys, to characterize subsurface structures (e.g., faults, contacts, and fracture zones), study fault interactions, constrain formation and reservoir geometries, constrain heat sources and fluid pathways, and help guide future exploration and development, including temperature gradient drilling that will take place this year.

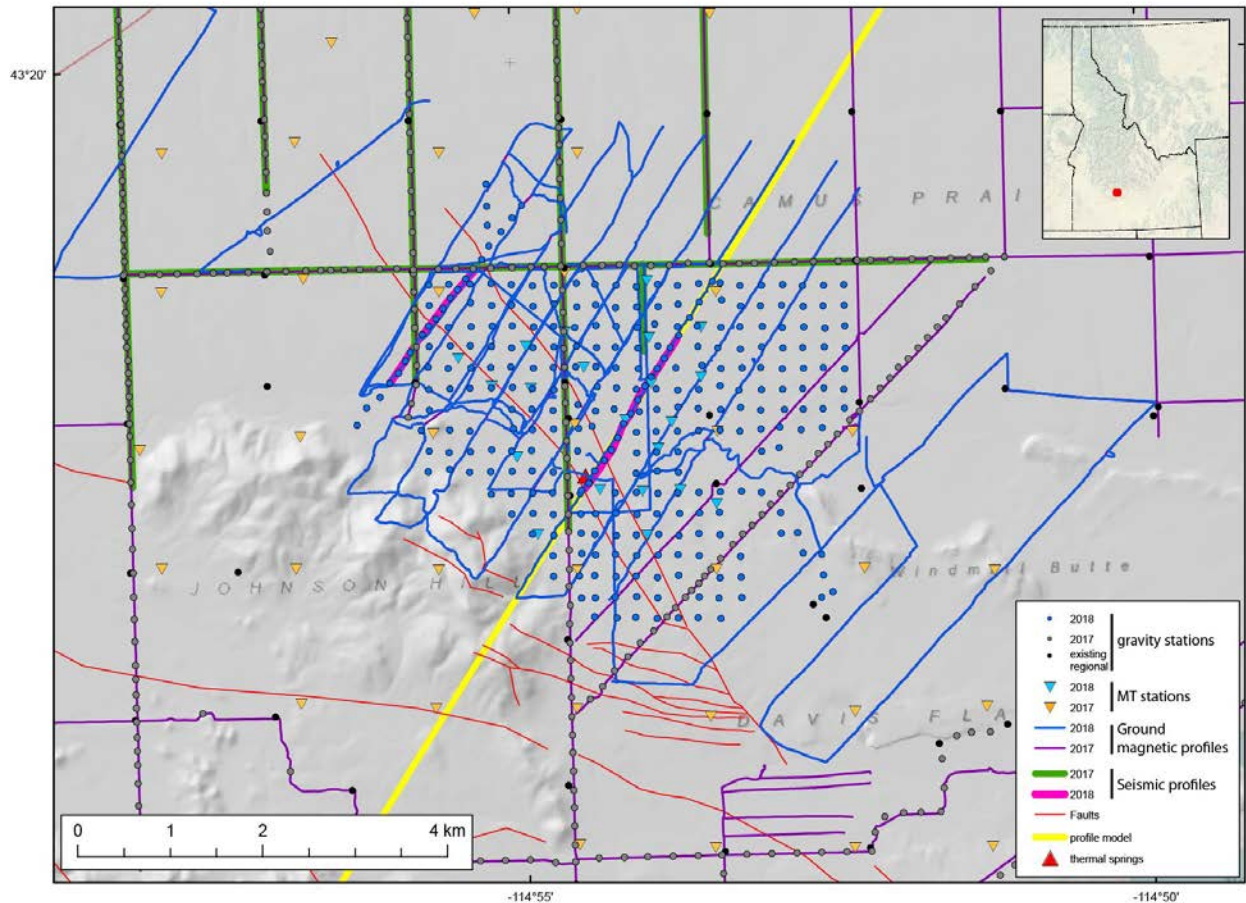


Figure 2: Shaded topographic index map of the Barron's Hot Springs focus area showing locations of gravity, magnetic, seismic and MT data. Barron's Hot Springs is shown by the red triangle at the center of the map.

1.1 Geologic Background

The geothermal PFA methodology employed by Shervais et al. (2016) identified the Camas Prairie in southcentral Idaho (Figure 1) 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 sedimentary caps. 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 reveal important structural features.

The Camas Prairie forms an E-W elongate valley situated between the Idaho Batholith and the central SRP/Mount Bennet Hills. The valley 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, largely comprise late Cretaceous to early Tertiary granodiorite and related intrusive rocks associated with the Idaho Batholith, as well as younger extrusive rocks, including the Eocene Challis volcanic rocks. 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 and western margins of the valley. The valley fill consists of poorly sorted Pliocene, Pleistocene and Holocene age sediments derived mainly from the Soldier Mountains to the north and, to a lesser degree, volcanic rocks from the Mount Bennett Hills to the south. Interbedded with these sediments are Tertiary and Quaternary volcanic rocks that flowed out onto the Prairie from eruptive centers in the Mount Bennett Hills and Magic Reservoir areas. The Mount Bennett Hills are comprised of Oligocene through late Pleistocene 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 1.8 Ma (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 was known about the nature of the resource prior to the present investigations. While the valley resides in an area of elevated heatflow associated with the SRP (Blackwell and Richards, 2004; Williams and DeAngelo, 2011) and is underlain by granitic basement (a potential radiogenic heat source), the geothermal system may involve, given the presence of Quaternary volcanism in the southern part of the basin, contributions from magmatic sources. In the western Prairie, where this research is focused, the youngest flows are associated with The Pothole – a ~700 ka basaltic vent and associated flows that are cut by the northwest-trending Pothole fault. This recent volcanic activity offers the possibility for a present-day magmatic heat source underlying the western Camas Prairie geothermal system.

The Prairie hosts several hot springs and thermal wells that have been exploited for direct use applications. The hottest surface manifestation was Barron's Hot Springs, which displayed measured surface temperatures of 72°C, but is no longer active due to changing hydrologic conditions linked to irrigation. A well drilled close to this feature yielded a maximum measured temperature of 91°C at a depth of 300 feet (90 m) below surface (Mink, 2010, Camas Creek Assessment).

Combined geochemical and isotopic analyses of water samples from hot springs and wells with elevated temperatures were made to assess their geothermal potential (Neupane et al. 2017). Multicomponent geothermometry results indicate estimated reservoir temperatures at Barron's

Hot Springs ranging from 100-140 °C, suggestive of a low to moderate temperature system. δD and $\delta^{18}O$ of water samples from Barron's Hot Springs yield isotopic compositions that generally indicate a meteoric origin. He Rc/Ra values of samples from the Barron Well are elevated (2.36), suggestive of a potential magmatic component. Helium results from Elk Creek and Wardrop/Wolf Hot Springs samples, located on the north side of the valley, show relatively lower (0.85-1.33) Rc/Ra values, though not low enough to be consistent with a basement-derived resource associated with radiogenic heating and deep circulation within granitic Idaho Batholith basement rocks. These helium data suggest that geothermal fluids throughout Camas Prairie have a component of mantle-derived fluids. This may be related to young, shallow crustal magmatism, a tectonic connection to mantle derived fluids, or a combination of both (e.g., Kennedy and Van Soest, 2007; Siler and Kennedy, 2016). The high (2.36) value measured in the Barron Well and similarly elevated values for several nearby features strongly suggests a heat source for Barron's Hot Springs originating from Quaternary volcanism and related intrusions.

2. STRUCTURE

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 analysis of aerial photos 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 (~285-295°) and NNW (~325°). 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

3.1 Methods and data collection

Magnetotellurics (MT) is a passive electromagnetic geophysical method that measures the Earth's electrical response to natural time-varying magnetic fields that diffuse into the Earth and induce electrical currents in the subsurface [see Vozoff, (1991) for a description of MT methods]. Depth of penetration of the diffusing magnetic field depends on subsurface resistivity and the frequency of the inducing magnetic field, where more resistive rocks and lower frequencies allow for deeper penetration. Typical depths are from 10's of meters to 10's of kilometers.

MT measurements in the field are done by using induction coils to measure the time-varying magnetic field for frequencies between 1000–0.001 Hz, and electric dipoles to measure the Earth's electrical response. A total of 63 MT stations were occupied in the Camas Prairie during Phase 2, and an additional 21 stations were added during Phase 3 characterization of the focus area around the Barron's Hot Springs (Figures 1-3, 6).

3.2 Inverse modeling

MT response functions were modeled in three-dimensions (3-D) using the code ModEM developed by Egbert and Kelbert (2012) and Kelbert et al. (2014). Input data were edited using the EDI editor in MTpy (Krieger and Peacock, 2014) to remove obvious outliers in the data and suppress bias in the modeling. All data was interpolated onto 23 frequencies in the range of 500-0.001 Hz. Resistivity models were developed in two steps, one for the regional data, and another for the focus area around the BHS. The regional model had dimensions of 117 x 102 x 49 cells (280 km x 280 km x 200 km), with cell size of 200 m x 200 m within the station area, increasing by a factor of 1.4 outside. A total of 59 stations were inverted for the regional model. The focus area around the BHS had dimensions of 66 x 66 x 49 cells (180 km x 180 km x 200 km), with cell size 100 m x 100 m within the station area, increasing by a factor of 1.4 outside. A total of 30 stations were inverted for the local model. The regional model was used as an a priori model for the focused model. The thickness of the first layer of the models was set to 10 m and increased logarithmically downwards. Inversions were run on NASA's high-end computing capability (HECC) Pleiades super computer, where average run times were on the order of 60 hours.

4. SEISMIC STUDIES

A total of ~53.3 km of seismic reflection data was acquired on section roads (one mile spaced) along seven profiles within the Camas Prairie during Phase 2 and ~3.5 km of data were collected in Phase 3 along two NE-trending profiles across the focus area (Figures 1 and 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 industry-standard seismic processing software (ProMAX, Kingdom), where reflectors on cross lines were utilized to map key stratigraphic and structural boundaries.

5. POTENTIAL FIELDS

Potential field methods are used in geothermal exploration to facilitate imaging of subsurface structures (e.g., faults, fractures, and 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 Camas Prairie, 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 (e.g., seismic reflection and MT), regional geologic mapping, borehole logs from wells, and rock-property measurements.

As part of this study, rock-property measurements were performed on outcrops, hand samples, and paleomagnetic cores taken from the study area in order to constrain the potential field models (this includes 50 density [dry bulk, grain and saturated bulk densities] measurements, 253 outcrop magnetic susceptibility measurements on 28 individual sites, and 26 remanence measurements made on Macon Flat and Pothole basalt flows). Model rock properties are based on these measurements, which include all the principal rock units from the study areas, as well as data derived from published and unpublished databases involving similar lithologies.

5.1 Gravity

As part of the present study, a total of 1612 (1329 during Phase 2, 293 during Phase 3) new gravity data were collected in Camas Prairie 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). These were combined with existing data (Glen et al., 2017; Shervais et al., 2012; PACES, 2016). Gravity data were reduced using standard gravity reduction methods (Dobrin and Savit, 1988; Blakely, 1995), in order to produce a gravity grid reflecting lateral variations in density in the crust that is used to map faults and contacts, perform 2D modeling of subsurface structure, and perform a regional gravity inversion of the basement surface.

5.2 Magnetics

In the Camas Prairie, over 850 line-km of new high-resolution ground magnetic data (~725km in 2017 and ~130km in 2018) 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 (Figures 1 and 2).

6. MAPPING

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 geometries. Residual maps (Figures 3-5), 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.

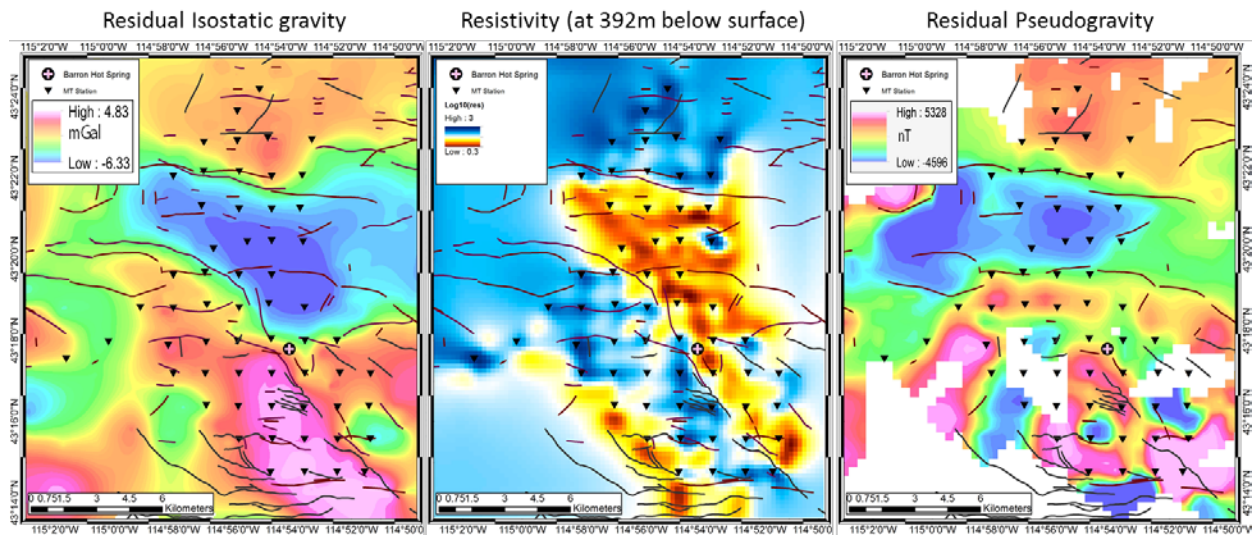


Figure 3: Regional maps of the western Camas Prairie of gravity (residual isostatic, left), resistivity (at 392m below the surface, middle), and magnetics (residual pseudogravity, right), showing geophysical lineations derived from maximum horizontal gradients of gravity (plotted on gravity and resistivity maps) and pseudogravity (plotted on the magnetic map).

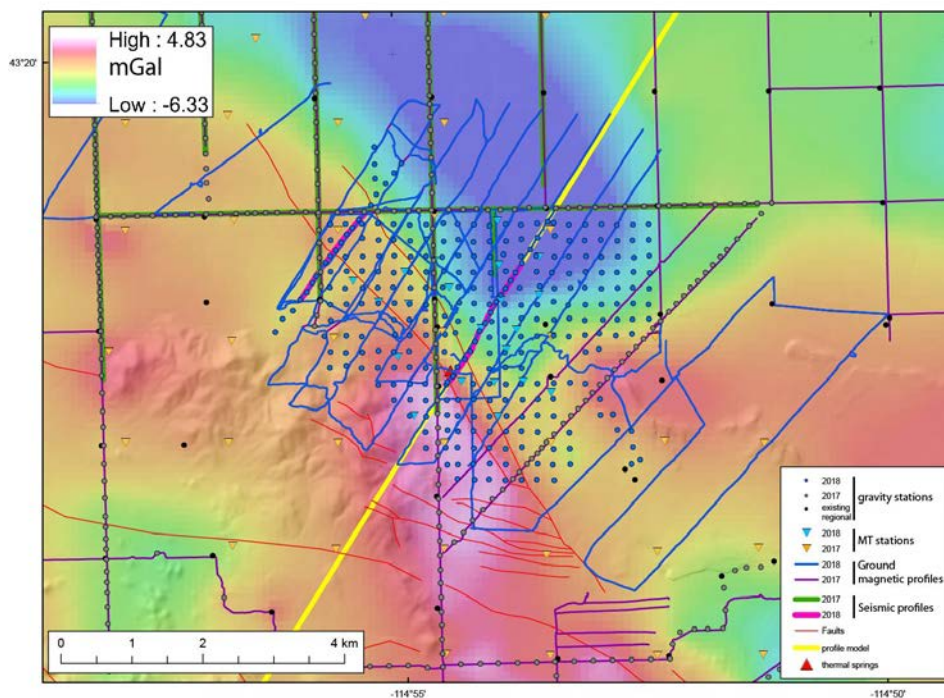


Figure 4: Colored residual isostatic gravity on shaded topographic relief map of the focus area around Barron's Hot Springs.

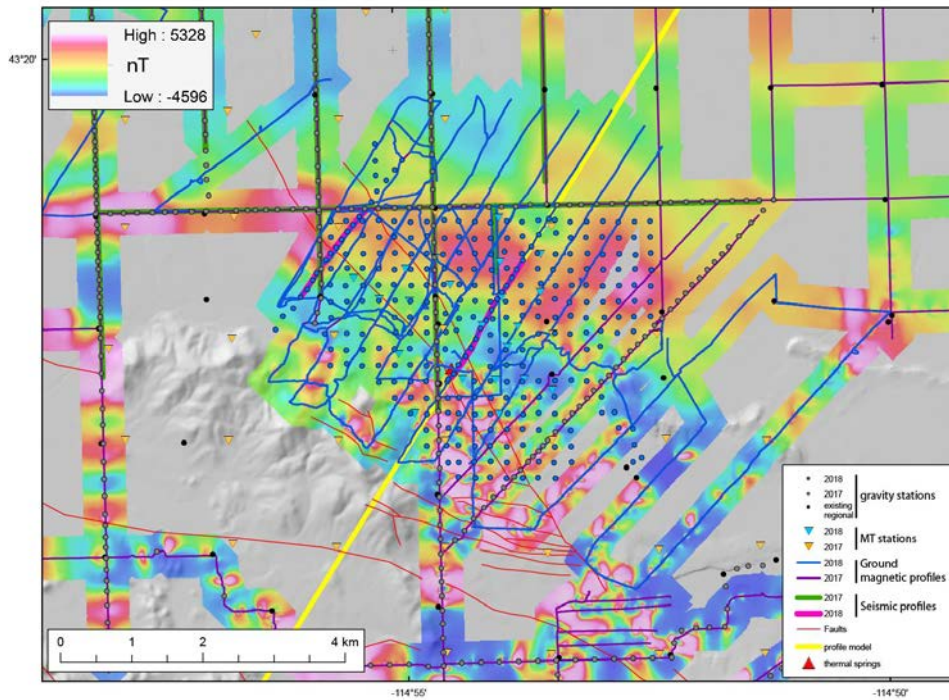


Figure 5: Colored reduced to pole magnetic field on shaded topographic relief map of the focus area around Barron's Hot Springs.

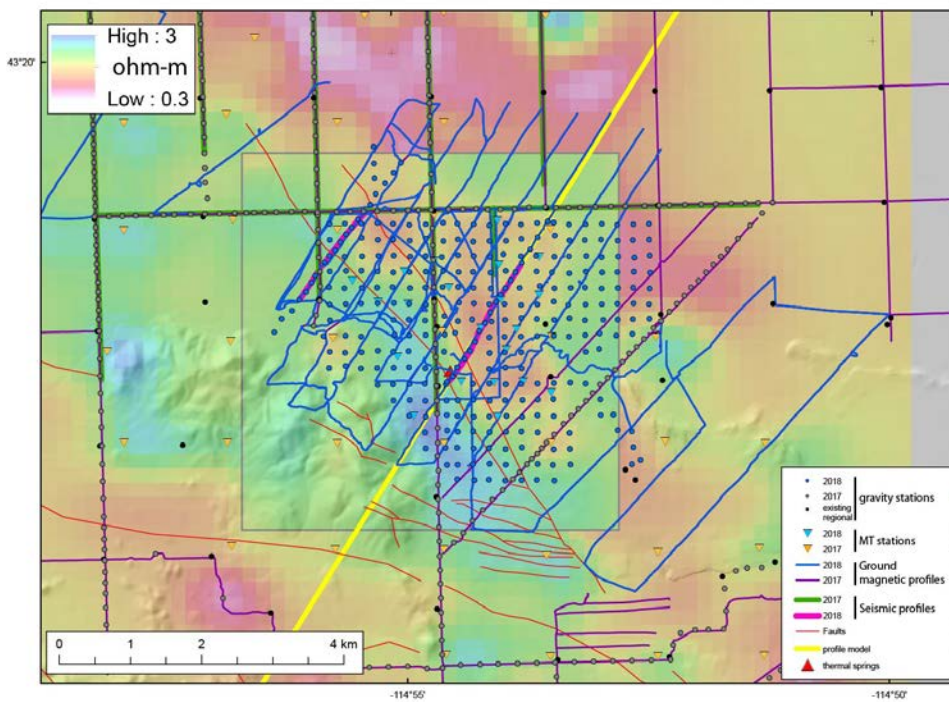


Figure 6: Colored MT resistivity (at ~500m depth) on shaded topographic relief map of the focus area around Barron's Hot Springs. The MT grid inside and outside the area indicated by the grey box reflect modeling results based on coarse- and fine-mesh inversions of the data, respectively.

7. PROFILES AND MODELING

Two-dimensional potential field models were constructed along profiles (Figures 1 and 2) across the study area. Where possible, potential field, seismic and MT data collection was coordinated to facilitate modeling and interpretations (Figures 6-8). In the 2D modeling, subsurface geology is approximated by horizontal tabular prisms or blocks that vary in the $\pm Y$ directions (commonly referred to as 2³/₄D 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. In addition, a 3D inversion of gravity was performed, using methods described by Jachens and Moring (1990), to yield an estimate of the depth to sediment-basement interface within the basin.

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).

Maps of the regional field across the western Camas Prairie are shown in Figure 3. Detailed geophysical maps of the Barron's Hot Springs area are shown in Figures 4-6.8.

8. 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 fluid flow.

Gravity and magnetic maps were gridded from a combination of new and existing data collected throughout the Camas Prairie valley and surrounding regions (Figures 1 and 2). Analyses of MHG of residual isostatic gravity and pseudogravity grids delineate a number of intrabasin structures that have little or no surface manifestation (Figures 3, 7). These structures represent two dominant fault trends; W to WNW-trending structures that likely reflect the major basin-bounding faults, and a NW-trending set that appears to control the major sub-basin geometry of the valley.

Potential field modeling was performed along several profiles at the western end of the valley (Figure 7, and Glen et al., 2017). Seismic data collected along these lines constrain the upper several hundred meters of the models. The models reveal a deep (500-1000 m) 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.

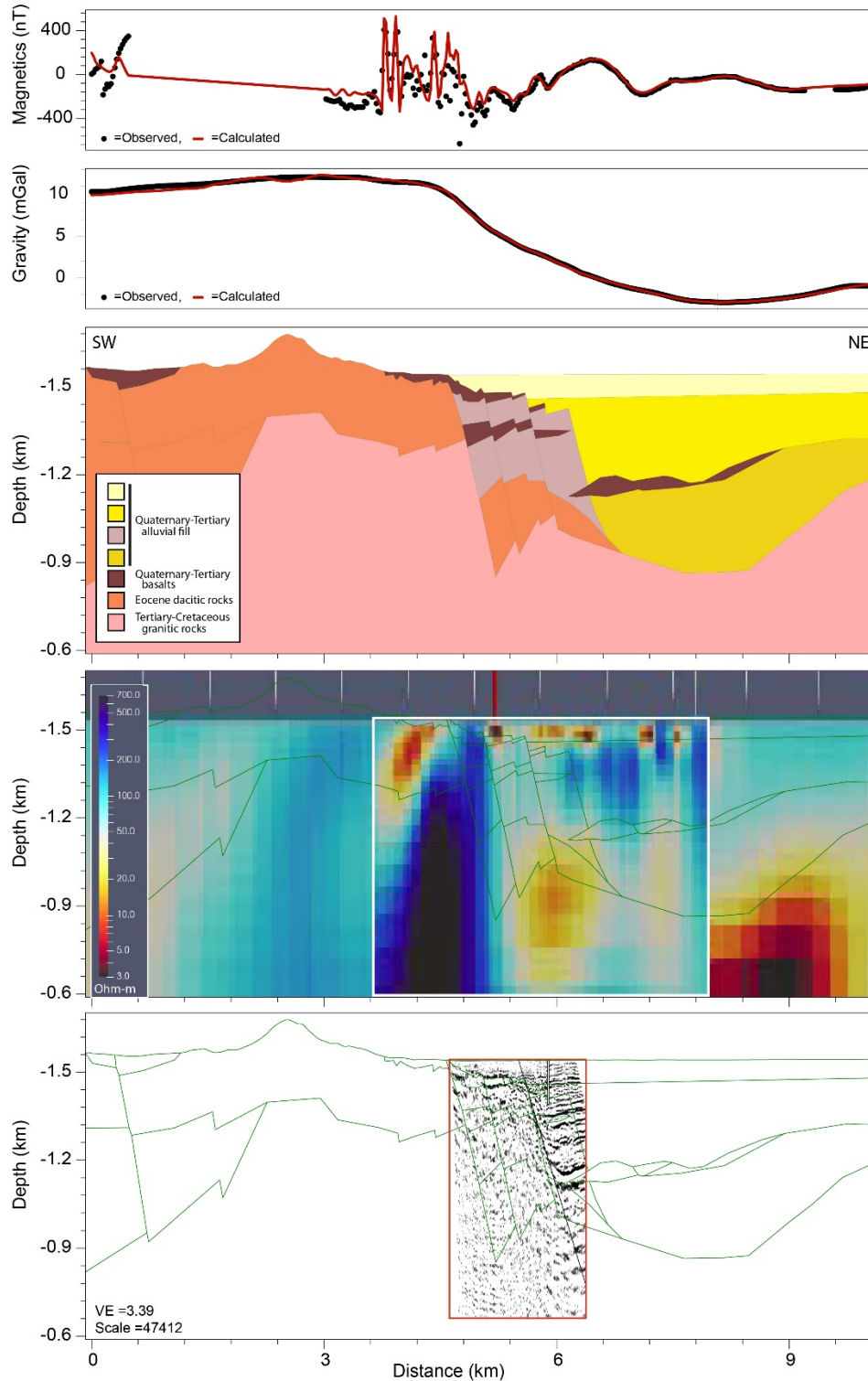


Figure 7: Two-dimensional geophysical model of the Camas Prairie along the Barron profile (see Figure 2 for location). Panels show (from top to bottom) magnetic field, gravity field, potential field model with individual model bodies colored by rock unit, MT resistivity model, and a seismic image with interpretation. Magnetic and gravity profiles show observed (black circles) and model (red line) anomalies. The MT cross-section inside and outside the area indicated by the white box reflect modeling results based on based on coarse- and fine-mesh inversions of the data, respectively.

Regional gravity mapping indicates the valleys subsurface consists of several NW-elongate sub-basins characterized by isolated gravity lows (Glen et al., 2017). The inferred sub-basin that resides on the western end of the Prairie just north of Barron's Hot Springs reflects the deepest part of the basin (up to 1 km). 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 Springs. 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 8, and inset).

A conceptual model of the basin (Glen et al., 2017) illustrates the likely source and circulation of thermal fluids and involves 1) recharge from the Soldier Mountains to the north of the valley and Mount Bennett Hills to the south, and 2) deep circulation of fluids through the underlying granitic basement driven by the regional topographic head between the valley and the adjacent highlands. The system likely derives its heat from a magmatic source that is suggested by the presence of relatively young volcanic rocks emplaced within and around the valley (Shervais et al., 2018), but may also involve heat from deep basement circulation within a region characterized by elevated geothermal gradients.

This conceptual model also indicates that surface discharge of thermal fluids involves upflow along basin-controlling structures. We suggest that key intersections between ~EW-trending basin-bounding structures and prominent NW-trending faults associated with the Pothole fault system, and the apparent dilational right stepover in the dextral-normal Pothole fault, provide conduits for upward convection of thermal fluids at the southern margin of the valley adjacent to the deep structural subbasin (Figure 8). Active faulting along these structures, could stimulate and maintain zones of permeability that allow for upflow of thermal fluids at the Barron's Hot Springs. New high-resolution geophysical studies around Barron's Hot Springs reveal structural complexity at the intersection of the basin-bounding and Pothole fault systems. This is characterized by numerous fault segments that involve a prominent right-stepover in the Pothole fault.

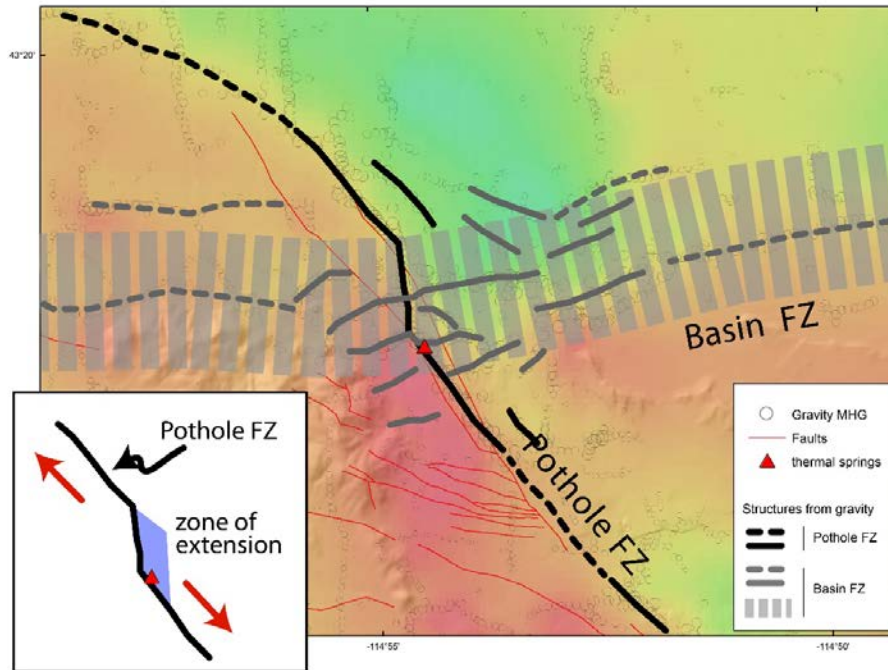


Figure 8: Conceptual model of the geophysical structural interpretation of the Barron's Hot Springs area showing geophysical lineations (faults) interpreted from Maximum Horizontal Gradients (MHG) of gravity, and illustrating the interaction of basin-bounding (Basin FZ) and Pothole (Pothole FZ) fault zones. The interpretation is superimposed on the residual gravity map. The Basin FZ is less well delineated where the fault zones intersect (in contrast to its expression in the central and eastern Camas Prairie), but is characterized by numerous roughly EW-trending geophysical lineations (highlighted here by a grey hatched area). The inset depicts an apparent right-stepped fault zone that results in interpreted extension across the zone where the two fault systems intersect and coincident with Barron's Hot Springs.

9. CONCLUSIONS

We performed high-resolution geophysical surveys of the southwestern Camas Prairie in southcentral Idaho to characterize the structural setting of Barron's Hot Springs (BHS) – a low-temperature geothermal system with the potential for both direct use applications and electric power production. We employed high-resolution gravity, magnetic, MT, seismic reflection surveying, and structural mapping, with the aim of modeling basin geometry, characterizing intra-basin and basin-bounding faults, resolving fault interactions, and identifying areas favorable to hydrothermal fluid flow.

Potential field mapping delineates a NW-elongate gravity low on the western end of the valley just north of BHS that reflects a deep (500-1000m) structurally controlled sedimentary sub-basin. A steep gradient bounding the southwest side of this low is interpreted as a major fault zone that likely reflects the more structurally active part of the basin. Seismic results document offsets of shallow strata that are consistent with potential field modeling and support ongoing extension across this fault zone. This NW-trending zone includes the Pothole fault, which cuts a Pleistocene basaltic vent and associated flows of the same name.

The BHS coincides with the intersection of the NW-trending Pothole fault system with an EW-trending fault zone that comprises basin-bounding faults delineating the southern extent of the valley and accommodating NS-extension. This intersection is characterized by a complex structural zone that is marked by numerous ~EW-trending geophysically-inferred faults, and a right stepover in the Pothole fault. We suspect that the dense faulting in this region plays a role in enhancing permeability and upflow. Furthermore, the dominant sense of dextral-normal to normal slip inferred for the Pothole fault, should result in extension across the stepover in the immediate vicinity of the BHS.

MT modeling results show that this zone also coincides with a prominent conductive anomaly, characteristic of the presence of hydrothermal alteration or hydrothermal fluids. These results point to the importance of the fault intersection in localizing stresses that promote permeability, focus hydrothermal fluid flow, and result in sustained hydrothermal activity around the BHS.

Based on these results, we have identified the fault intersection as the target for drilling scheduled later this year that will entail reservoir testing and geophysical logging intended to document reservoir characteristics. Measurements made on core samples and chips will be used to update potential field models during the next phase of investigations. It is anticipated that future work will entail 3D modeling which will fully integrate geologic and geophysical constraints, and better characterize the structures responsible for promoting permeability and facilitating hydrothermal fluid flow associated with the BHS system.

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