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Geophysical Imaging of Geothermal Systems Spanning Various Geologic Settings

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ABSTRACT

Despite the wide range of geologic settings in which geothermal systems reside, many systems share characteristics that can be targeted by geophysical techniques. Over the last few years, the authors have used potential field and magnetotelluric (MT) methods to jointly image and characterize numerous geothermal systems in various geologic and tectonic settings. This includes systems in the Basin and Range, Washington Cascade Range, Northeastern Oregon, and the Snake River Plain. The principal geothermal targets are areas of elevated temperatures near fault interactions that promote permeability and fluid flow. Gravity, magnetic, and MT data are all sensitive to different physical parameters that together form a complementary set of tools for characterizing subsurface structure and identifying favorable geothermal targets. In general, potential fields delineate important geologic structures and MT locates fluids and zones of hydrothermal alteration. Joint interpretation of these complementary methods, along with other geologic information, provides a robust framework for geothermal prospecting and understanding a hydrothermal system. Specifically, common geothermal targets lie along potential field gradients and are associated with an electrically conductive anomaly that resides in the less-dense, less-magnetic material.

1. INTRODUCTION

The risk of drilling a non-productive geothermal well can be reduced by jointly interpreting various geophysical data sets to identify optimal sites to drilling (e.g. Forson et al. 2017). Geophysical methods help 1) increase likelihood of identifying requisite temperatures and permeability necessary to meet energy needs, whether for electricity generation or direct-use applications, 2) improve drilling success, and 3) reduce exploration and development costs.

The three geophysical methods used in this study are gravity, magnetics, and magnetotellurics (MT), which are mutually complementary because they are sensitive to different physical properties. Gravity measurements are sensitive to density contrasts in the subsurface and are useful for detecting lateral geological boundaries that could control flow of hydrothermal fluids (ex. Bouligand et al., 2014). Similarly, magnetic data are sensitive to variations in subsurface magnetic susceptibility and magnetic remanence and are useful for locating lateral geologic structures, lithologic contacts, and areas of hydrothermal alteration (ex. Glen et al., 2017). MT is sensitive to subsurface electrical resistivity and is useful for locating clay caps, zones of hydrothermal alteration, hydrothermal fluids, and thermally enhanced zones (ex. Munoz, 2014). Notwithstanding, to interpret these geophysical data sets and subsequent models, other information needs to be incorporated, including geological mapping, rock property information, and other geophysical constraints, like seismic reflection data and earthquake locations.

Here we describe multiple examples of using the three aforementioned geophysical data sets to develop conceptual geological and hydrogeologic models of various geothermal systems in different geologic settings. This includes the Basin and Range, Eastern Oregon, Cascade Range, and the Snake River Plain. Geothermal targets in the Basin and Range are amagmatic and associated with circulation of fluids along deep faults where the temperature is in enhanced due to a thin lithosphere (Faulds et al., 2011). In Eastern Oregon, also an amagmatic region, the targets are deep-seated faults where the natural thermal gradient can generate enough heat for direct-use or energy production. Volcanic settings along the Cascade Range provide viable heat sources, however volcanic hazards can make exploiting those heat sources difficult. Recent volcanism along the Snake River Plain implies magmatic sources for geothermal potential. Regardless of the geologic setting, the geothermal target is always a zone of enhanced permeability and temperature with associated fluids.

Table 1: Geophysical data collected by U.S. Geological Survey for geothermal exploration

Site	**Gravity Stations**	**Magnetic Data**	**MT Stations**
Mount St. Helens, WA	297	Existing Aeromagnetics	36
Pendleton, OR	1379	34,524 line km of aeromagnetics	36
Gabbs Valley, NV	400	300 line km	24
Camas, ID	1500	1000 line km	20

2. STUDY AREAS

Though numerous areas have been studied, here focus is on examples from each distinct geologic setting including volcanic, Basin and Range, and amagmatic systems. Each study area includes an introduction to the geologic setting, a brief summary of key observations from the geophysical data and models, and finally a brief description of a potential conceptual model. Table 1 summarizes statistics on the geophysical data collected for each study area.

2.1 Mount Saint Helens, WA

Mount St. Helens (MSH) is the most active volcano in the Cascade Arc (Evarts et al. 1987) and would presumably be a good target for geothermal prospecting. Unfortunately, due to hazards, one cannot simply poke a hole in the volcano; therefore exploration sites were chosen 12 km to the north and south of MSH (Forson et al. 2017). Here, the focus is on the northern exploration location, which is located over the MSH seismic zone (SHZ). The SHZ is a structurally complex region where northwest-trending Eocene metasediments are sandwiched between Miocene plutons, namely the Spud Mountain Pluton to the west and the Spirit Lake Pluton to the east. The highly altered, carbonaceous Eocene metasediments are structurally weaker than the surrounding plutons (Johnson and Stanley, 1995). This weakness accommodates strain associated with clockwise rotation of the North American plate (McCaffery et al., 2009) leading to focused seismicity along the boundary between the metasediments and the plutons at 5-12 km depth, forming the northern part of the SHZ. Soda Spring, located at the northern end of the exploration area above the SHZ, has elevated temperatures (~30° C) suggesting that hydrothermal fluids may be present in the area.

New gravity, ground-based magnetics, and MT data (2016) were collected in the area of interest to complement existing aeromagnetic data (Figure 1). All data sets image a contrast in physical properties between the SHZ and surrounding plutons. Gravity data indicate the SHZ follows a gradient on the eastern edge of a gravity low. Conversely, the SHZ follows a magnetic gradient along the eastern edge of a moderate aeromagnetic high. At depth the SHZ follows the eastern edge of a highly conductive zone. The low density, moderately magnetic, and highly conductive material on the western side of the SHZ is interpreted to be Eocene metasediments. These sediments have been highly fractured and likely contain hydrothermal fluids, as suggested by the high conductivity. The denser, less magnetic, and highly resistive body to the east of the SHZ is interpreted as the Spirit Lake Pluton. The magnetic low suggests hydrothermal alteration either coeval with emplacement or post-emplacement of the Spirit Lake Pluton (Iveson et al. 2016).

The thermal gradient near MSH is moderate, 30-50° C/km (Blackwell et al., 1990), considering proximity to active volcanism, suggesting geothermal potential for energy development is deeper than 3 km. The heat source could be a zone of partial melt at 20 km depth under the Spirit Lake Pluton (Bedrosian et al., 2018), though a thermal model is needed to confirm this conjecture. A likely conceptual model includes meteoric fluids penetrating the SHZ fault system and other deep-seated faults. Fluids percolate downwards to depths of 5 km or more where they might mix with existing formation fluids. As fluids heat up, buoyancy pushes them upwards creating a convection cell within the metasediments that results in a sustained geothermal system. Surface manifestations of hydrothermal fluids are minimal, which suggests the presence of a geologic cap, possibly an impermeable clay layer associated with past or present hydrothermal alteration. However, no distinct conductive layer is observed in the resistivity model, suggesting the cap is caused by young impermeable intrusive rocks (green units in Figure 1d). Soda Spring has a greater potential for geothermal development due to an electrically conductive connection to the surface from the deeper conductor associated with the SHZ.

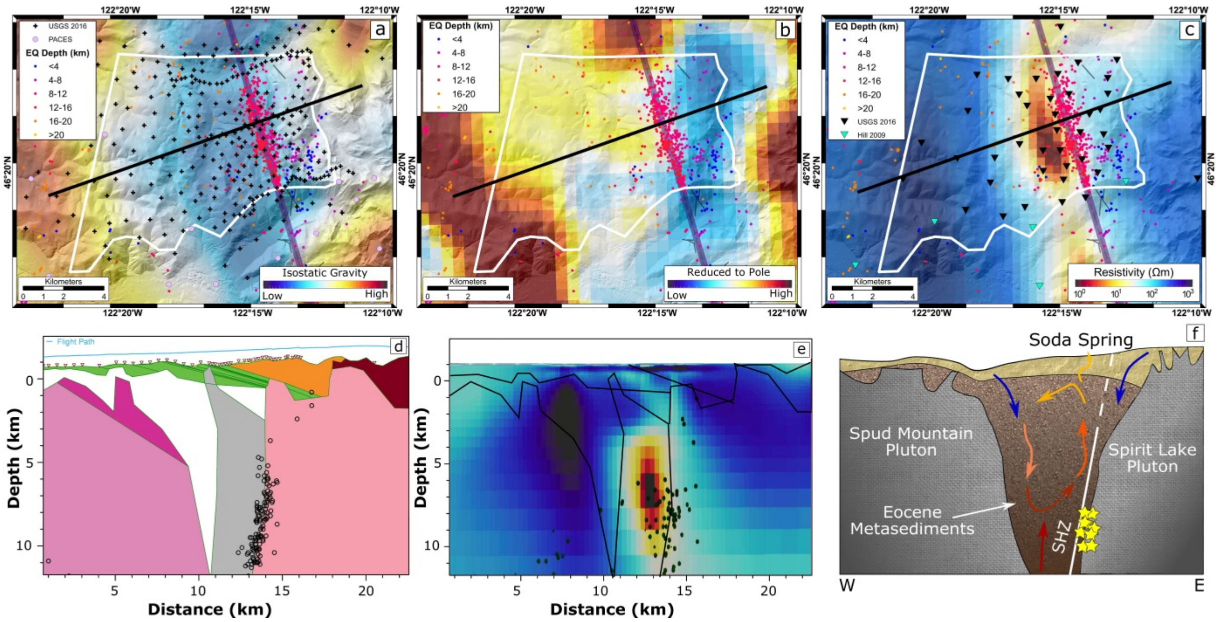

Figure 1: Mount St. Helens Geothermal Prospect, Washington. Top: map view of geophysical data, black line represents the profile line of models shown in d and e. Earthquake locations are represented by circles colored by depth. The study area is outlined in white. The SHZ is identified as the purple line. a) Isostatic gravity with station locations. b) Reduced-to-pole magnetic susceptibility. c) Depths slice of the 3D resistivity model at 7 km with MT station locations as triangles. d) Potential field 2D model with earthquake locations within 1 km of the profile line. e) Slice through the 3D resistivity model along the profile line, same color scale as c. f) Conceptual model of the system, arrows indicate potential fluid flow.

2.2 Pendleton, OR

The area near Pendleton, OR, is structurally complex as it is close the rotational pole of the North American plate (McCaffrey et al., 2007), and near the interaction of the northeast trending Klamath-Blue Mountain Lineament (KBL) and the northwest trending Olympic-Wallowa Lineament (OWL). This leads to complex interaction of regional and local fault systems. The geothermal focus here is on the Confederated Tribes of the Umatilla Indian Reservation (CTUIR), where multiple fault intersections occur and nearby hot springs exist. The two previously observable intersections are the Hite Fault zone and the Wilahatya Fault zone, and the Wilahatya Fault zone and the Hawtmi Fault zone (Figure 2).

The generic stratigraphic column in the area includes a thin veneer of alluvium and loess sediments sitting atop the Columbia River Basalt Group (CRBG) with Eocene sediments of the Herren formation below; and near the bottom are metamorphic rocks of the Blue Mountains (Ferns et al., 2004). Potential field modeling reveals local faulting has complicated the CRBG (Figure 2) and subsequently any hydrological system within (Ritzinger et al., 2018). As a result, springs are located in seemingly random places across the Blue Mountains, most of them cold, though geothermometry data is being collected by the CTUIR. Multiple north-trending faults intersecting the Wilahatya Fault zone are imaged with both MT and aeromagnetics, where some structures are associated with conductive anomalies at depth and zones of lower magnetic susceptibility indicating hydrothermal alteration.

The heat source is unknown as no recent volcanic intrusions, nor a thinning crust exists and heat production of the Blue Mountain basement rock is not well known. Nevertheless, Bingham Hot Springs, to the east of the study area along the Wilahatya Fault, has been measured to at 110° C, indicating geothermal potential is likely along the Wilahatya Fault system. Electrically conductive zones occur near fault intersections at the boundary of the Herren Formation and the Blue Mountain basement rock. The depths range from 1.5 km to the east and deepen towards the west to 3 km, implying a series of down dropping faults westward into a basin west of the Blue Mountains. These conductive zones could indicate clay alteration and/or fluids indicative of a permeable zone. A conceptual model includes meteoric fluids penetrating the various near surface fractures in the CRBG that blanket the Blue Mountains, migrating down deep-seated faults (Ritzinger et al., 2018). At some depth within the Herren Formation or underlying basement rocks, the fluids become thermally buoyant and collect in highly permeable zones at fault intersections. Here the fluids hydrothermally alter the host rock and possibly become more saline increasing electrical conductivity. These areas would be likely targets for further geothermal exploration.

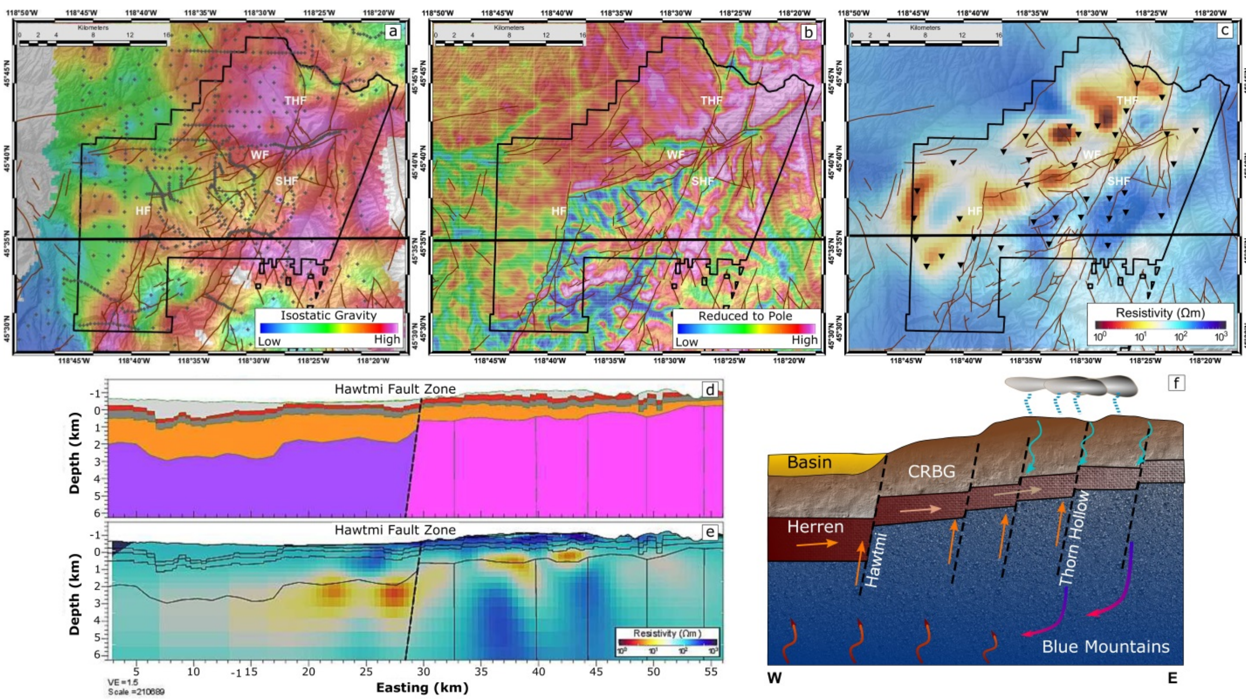

Figure 2: Umatilla Geothermal Prospect, Oregon. Top: map view of geophysical data. Black line represents the profiles shown in d and e. HF, Hawtmi Fault; WF, Wilahatya Fault; THF, Thorn Hollow Fault; SHF, Saddle Hollow Fault. a) Residual isostatic gravity with station locations. b) Reduced-to-pole magnetic susceptibility with flight lines. c) Depth slice of the 3D resistivity model at 3 km with MT station locations as black triangles. d) Potential field 2D model. e) Slice through the 3D resistivity model along the profile line, same color scale as c. f) Conceptual model of the system, arrows indicate potential fluid flow.

2.3 Gabbs Valley, NV

Gabbs Valley in Nevada lies within the Walker Lane and the Basin and Range. The study area is located ~15 km south of the Don A. Campbell geothermal power plant that is a low-temperature geothermal system (measured at around 130° C, Orenstein and Delwiche, 2014). Previously drilled 2 m temperature holes have located an area of enhanced temperatures within the southern part of Gabbs Valley making it a target for play-fairway analysis (Faulds et al., 2017). The goal was to employ geophysical measurements to characterize the structures that possibly control hydrothermal fluid flow.

Potential field data (Earney et al., 2018) and a 3D resistivity model demonstrate that the thermal anomaly lies on a steep gradient, interpreted as a complex fault intersection that bounds metavolcanic rocks to the southeast and volcanic rocks to the northwest (Figure 3). A magnetic low and a conductive anomaly in the near surface indicate a zone of hydrothermal alteration; this delineates the thermal zone according to previously collected 2 m temperature holes. The hydrothermally altered zone is bound to the northwest by a subparallel fault system defined by geologic mapping (Faulds et al., 2017) that is partially imaged by gravity and MT.

A potential conceptual model follows the general Basin and Range model of meteoric fluids and/or formation fluids percolating deep into the upper crust, heating up, and upwelling through deep-seated fault. At Gabbs Valley, fluids upwell near the northwest trending fault and flow along the boundary between impermeable metavolcanic rocks to the southeast and more porous Tertiary volcanics to the northwest. A series of northeast trending faults create a zone of local extension where fluids near the surface create a zone of hydrothermal alteration.

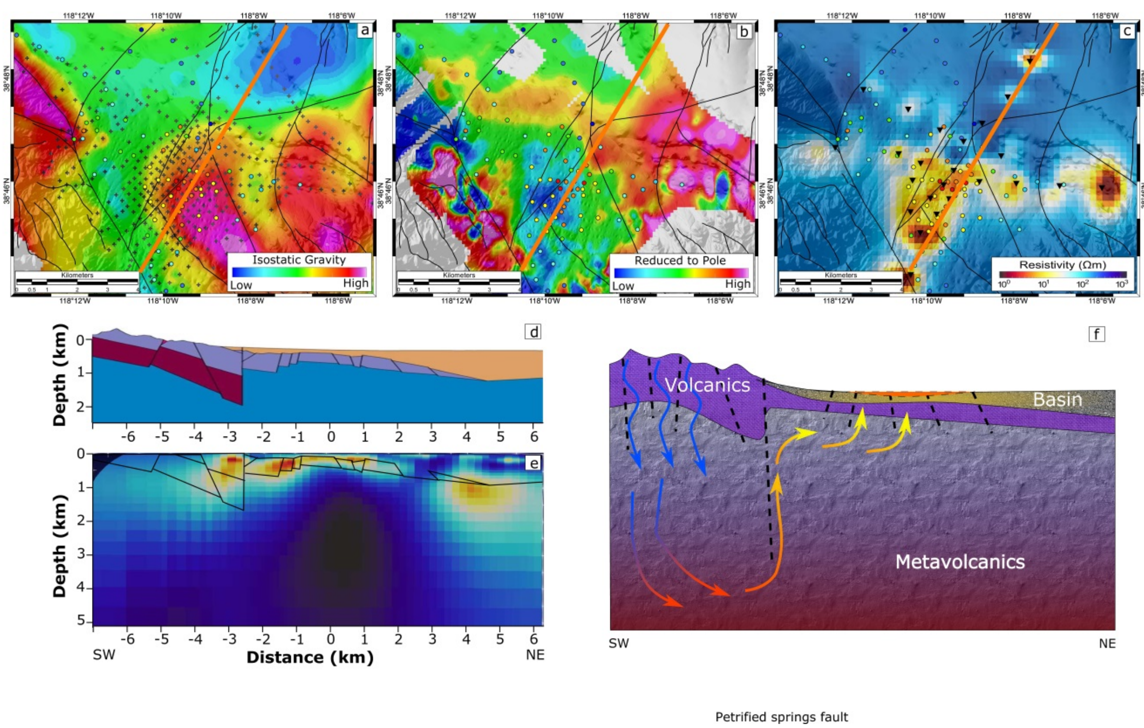

Figure 3: Gabbs Valley Geothermal Prospect, Nevada. Top: map view of geophysical data. Orange line represents the profiles shown in d and e. Data from 2 m temperature holes are represented as circles, where color indicates relative temperature with red colors being the hottest. a) Isostatic gravity with station locations. b) Reduced-to-pole magnetic susceptibility. c) Depth slice of the 3D resistivity model at 200 m with MT station locations as black triangles. d) Potential field 2D model. e) Slice through the 3D resistivity model along the profile line, same color scale as c. f) Conceptual model of the system, arrows indicate potential fluid flow.

2.4 Camas Prairie, ID

The Camas Prairie is a structural graben that trends east-west and is bound by the Idaho Batholith to the north and the Mount Bennet Hills to the south. Recent volcanism is observed in the prairie, as recent as 2 ka, provides a potential heat source. The geothermal focus area is in the south central part of Camas Prairie at the intersection of the Pot Hole fault and the main range front fault system, near the Baron Hot Springs (Shervais et al., 2018).

Potential field data delineate multiple faults in the area, imaging the intersection of the Pot Hole Fault and the range front fault system as a bend (Figure 4; Glen et al., 2017, 2018). This indicates a local zone of extension potentially allowing hydrothermal fluids to up well. Moreover, potential field data discriminates rock types on either side of the fault with basaltic rocks to the southwest and sediments to the northeast. The resistivity model images similar structures as the potential field data, showing the area near the fault intersection as conductive at a depth of 500 m, suggestive of hydrothermal alteration.

A helium RA higher than 2 has been measured in the area (Shervais et al., 2018), indicating the heat source is likely magmatic. One conceptual model suggests meteoric or formation fluids are heated by a sill complex in the mid-crust and upwell along deep-seated faults in basement rocks, namely the Pot Hole Fault and the range front fault system. Fluids accumulate within porous basin sediments and are kept from reaching the surface by near surface clay cap (Figure 4f).

3. DISCUSSION AND CONCLUSIONS

Despite the geologic setting in all examples discussed, the geophysical target is an area of interacting faults, including deep-seated faults. Gravity and magnetic data image these interactions as gradients indicating abrupt changes in physical properties, where deeper faults are imaged as broader gradients. The highest geothermal potential is commonly where an electrically conductive anomaly is associated with potential field gradients. Interestingly, the conductive anomalies typically occur in the less-dense, less-magnetic material, which most often represents sediments or highly fractured basement rock. Therefore, a simple and effective detection method could be locating electrically conductive anomalies collocated with potential field gradients; specifically, conductive anomalies in less-dense, less-magnetic material.

The typical target for any type of conventional geothermal exploration is regions of increased permeability. Typically, permeability is enhanced near intersections of active faults where local lithology becomes highly fractured, creating conduits for fluids to propagate. If the fault geometry and stress fields are favorable local extension occurs, which dilates the fracture system increasing permeability. Using geophysical methods, namely gravity, magnetics, and MT, these fault intersections can be imaged and characterized. Gravity and magnetic data delineate fault location and lateral boundaries in lithology and forward modeling can characterize fault and lithologic geometry. Paired with geological constraints, these data also provide hypotheses for subsurface lithology. Resistivity models developed from MT data can help locate fluids, hydrothermal alteration, and changes in porosity and temperature. The various examples described in this study demonstrate that geothermal targets can be located by comparing gravity, magnetic, and MT data. However, to fully understand the system, other data needs to be incorporated for interpretation and conceptual modeling. This includes geologic mapping, rock properties, temperature data, geochemistry, and stress analysis. Finally, successfully drilling targets identified from these three geophysical measurements should provide confirmation that this method works.

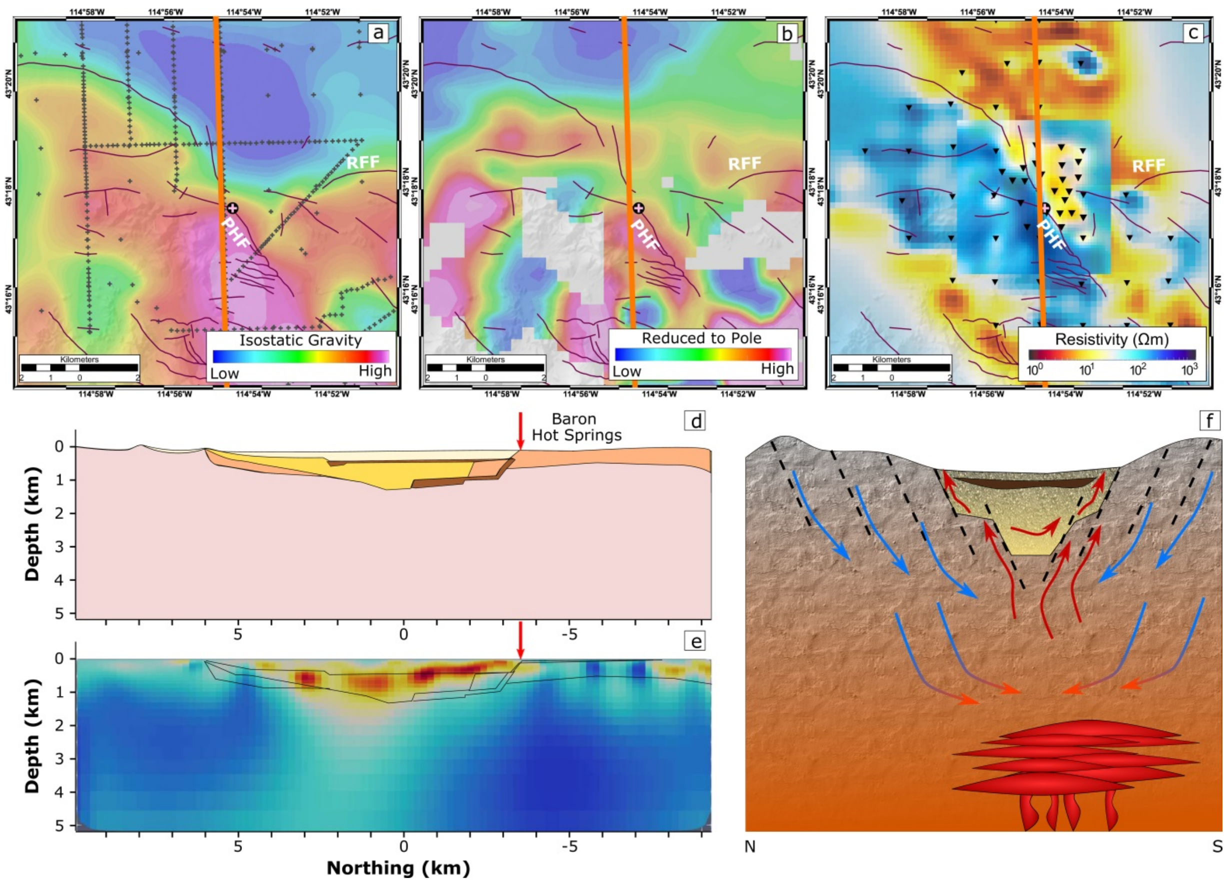

Figure 4: Camas Prairie, Idaho, Geothermal Prospect. Top: map view of geophysical data. Orange line represents the profiles shown in d and e. The black circle with a pink plus is the Baron Hot Springs. PHF, Pot Hole Fault; RFF, Range Front Fault. a) Isostatic gravity with station locations. b) Reduced-to-pole magnetic susceptibility with flight lines. c) Depth slice of the 3D resistivity model at 500 m with MT station locations as black triangles. Note there are 2 resistivity models, one at a regional scale with cell sizes of 200 m and a local model with cell sizes at 100 m. d) Potential field 2D model. e) Slice through the 3D resistivity model along the profile line, same color scale as c. f) Conceptual model of the system, arrows indicate potential fluid flow.

The next steps are twofold: technological and numerical. One promising technological advance is unmanned aircraft systems (UAS) to collect high-quality potential field data efficiently over large areas (Glen et al., 2013). Numerically, potential field data could be modeled in 3D to complement 3D resistivity models from MT data. To develop a 3D geological model requires other geological and geophysical data, from which thermal and fluid flow models can be tested to fully characterize the system. Using gravity, magnetic, and MT data as a first order detection tool is a viable method to locate geothermal potential; however, much more can be done with the data to fully characterize a geothermal system.

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REFERENCES

Bedrosian, P. A., Peacock, J. R., Schultz, A., Bowles-Martinez, E., Hill, G. J., (2018) Crustal inheritance and top-down control on arc magmatism: Mount St. Helens in focus, Nature Geoscience, In Press.

Blackwell, D. D., J. L. Steele, S. Kelley, and M. A. Korosec (1990), Heat flow in the state of washington and thermal conditions in the Cascade Range, J. Geophys. Res., 95(B12), 19495–19516, doi: 10.1029/JB095iB12p19495.

Bouligand, C., Glen, J. M. G., Blakely, R. J., 2014, Distribution of buried hydrothermal alteration deduced from high resolution magnetic surveys in Yellowstone National Park, J. Geophys. Res., doi: 10.1002/2013JB010802.

Earney, T., Schermerhorn, W., Glen, J. M. G., Peacock, J. R., Craig, J., Hinz, N., Faulds, J., Siler, D., 2018, Geophysical Investigations of a Potential Blind Geothermal System in Southern Gabbs Valley, Nevada, GRC Transactions, This Meeting.

Evarts, R. C., Ashley, R. P., Smith J. G., 1987, Geology of the Mount St. Helens Area: Record of discontinuous volcanic and plutonic activity in the Cascade Arc of Southern Washington, J. Geophys. Res., 92, B10, p. 10,155-10,169.

Faulds, J. E., Hinz, N. H., Coolbaugh, M. F., Sadowski, A. J., Shevenell, L. A., McConville, E., Craig, J., Sladek, C., Siler, D. L., 2017, Progress Report on the Nevada Play Fairway Project: Integrated Geological, Geochemical, and Geophysical Analyses of Possible New Geothermal Systems in the Great Basin Region, Proceedings, 42nd Workshop on Geothermal Reservoir Engineering, Stanford, California, Feb. 13-15, SGP-TR-212.

Faulds, J. E., Hinz, N. H., Coolbaugh, M. F., Cashman, P. H., Kratt, C., Dering, G., Edwards, J., Mayhew, B., McLachlan, H., 2011, Assessment of Favorable Structural Settings of Geothermal Systems in the Great Basin, Western USA, GRC Transactions, 35, 777-783.

Ferns, M.L., V.S. McConnell, and K. Ely, 2004. Field trip guide to the geology of the Umatilla River Basin, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-04-23, 1 cd.

Forson, C., Steely, A., Cladouhos, T., Swyer, M., Davatzes, N., Anderson, M., Ritzinger, B., Glen, J. M., Peacock, J., Schermerhorn, W., Burns, E., Stelling, P., (2017), Geothermal Play-

Fairway Analysis of Washington State Prospects: Phase 2 Technical Report, Washington Department of Natural Resources, 232 p.

Glen, J. M. G., Egger, A. E., Ippolito, C., Athens, N. (2013) Correlation of geothermal springs with sub-surface fault terminations revealed by high-resolution, UAV-acquired magnetic data, Proceedings, 38th Workshop on Geothermal Reservoir Engineering, Stanford, California, SGP-TR-198.

Glen, J. M. G., Liberty, L., Gasperikova, E., Siler, D., Shervais, J. W., Ritzinger, B., Athens, N. and Earney, T. (2017) Geophysical investigations and structural framework of the Camas Prairie geothermal system, southcentral Idaho. Proceedings, 42nd Workshop on Geothermal Reservoir Engineering, Stanford, California, SGP-TR-212.

Glen, J. M. G., Liberty, L., Peacock, J. R., Gasperikova, E., Siler, D., Earney, T., Schermerhorn, W., Shervais, J., 2018, A Geophysical Characterization of the Structural Framework of the Camas Prairie Geothermal System, southcentral Idaho, GRC Transactions, This Meeting.

Iveson, A. A., Webster, J. D., Rowe, M. C., Neill, O. K., (2016), Magmatic–hydrothermal fluids and volatile metals in the Spirit Lake pluton and Margaret Cu–Mo porphyry system, SW Washington, USA, Contrib. Mineral Petrol, 171, 20-52, DOI: 10.1007/s00410-015-1224-6.

Johnson, S. Y. and Stanley, W. D., 1995, Eocene paleogeopraphy of the Morton Anticline area, southwestern Washington, In Fritsche, A. E., ed., Cenozoic paleogeography of the western United States-II: Pacific Section, SEPM, Society for Sedimentary Geology, book 75, p. 291-309.

McCaffrey, R., Qamar, A. I., King, R. W., Wells, R., Khazaradze, G., Williams, C. A., Stevens, C. W., Vollick, J. J., Zwick, P. C. (2007). Fault locking, block rotation and crustal deformation in the Pacific Northwest. Geophysical Journal International, 169(3), 1315-1340, doi: j.1365-246X.2007.03371.x.

Munoz, G., (2014), Exploring for Geothermal Resources with Electromagnetic Methods, Surveys in Geophysics, 35, 101-122, doi: 10.1007/s10712-013-9236-0.

Orenstein, R. and Delwiche, B., 2014, The Don A. Campbell Geothermal Project, GRC Transactions, 38, 91-98.

Ritzinger, B., Glen, J. M. G., Peacock, J., R., Blakely, Mills, P., Staisch, L., Bennett, S., Sherrod, B., 2018, Geothermal Potential of the Umatilla Indian Reservation, Oregon: Evidence from Detailed Geophysical Investigations, GRC Transactions, This Meeting.

Shervais, J. W., Glen, J. M. G., Siler, D., DeAngelo, J., Liberty, L. M., Nielson, D., Garg, S., Neupane, G., Dobson, P., Gasperikova, E., Sonnenthal, E., Newell, D. L., Evans, J. P., Snyder, N., Mink, L. L., 2018, Provisional Conceptual Model of the Camas Prairie (ID) Geothermal System from Play Fairway Analysis, Proceedings 43rd Workshop on Geothermal Reservoir Engineering, Stanford, California, Feb. 12-14, SGP-TR-213.

Shervais, J., Glen, J., Siler, D., Liberty, L., Gasperikova, E., Neupane, G., Dobson, P., Newell, D., Garg, S., Nielson, D., Peacock, J., 2018, Geothermal Play Fairway Analysis, Phase 3: A Provisional Conceptual Model of the Camas Prairie, Snake River Plain, Idaho, GRC Transactions, This Meeting.