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Provisional Conceptual Model of the Camas Prairie (ID) Geothermal System from Play Fairway Analysis

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ABSTRACT

Camas Prairie, Idaho, is an EW-trending structural graben that lies north of the Snake River Plain hotspot track. It is bounded on the north by the Idaho Batholith, and on the south by the Mount Bennett Hills. This region was investigated by the SRP Geothermal Play Fairway Analysis team, which included focused geologic, geochemical, and geophysical studies. The Camas Prairie geothermal system resource is indicated by warm springs and wells, geophysical analysis of buried faults and basins, mapped faults, structural analysis of all faults and lineaments, high $^3He/^4He$, cation and multicomponent geothermometry, and the occurrence of young basalt vents and lava flows along the range front.

Our provisional conceptual model includes the following components: (1) High permeability is indicated by the confluence of intersecting faults, including the major range front system and The Pothole fault system, with releasing bends as deduced from detailed field studies, and the presence of springs along mapped structural features; (2) High heat is inferred to result from mid- to shallow crustal sills, as evidenced by the location of vents along the range front; the youngest dated vent is 692 ka, but 2 ka vents lie to NW; (3) an effective seal is indicated by magnetotelluric studies, which suggest a clay seal over the prospective target area that is likely a result of hydrothermal alteration.

This model is similar to that proposed for the western SRP but is less energetic due to the smaller volume of magma inferred. It is also similar to Basin-and-Range geothermal systems, but differs by including a distinct magmatic heat component.

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1. INTRODUCTION

The Snake River Plain Geothermal Fairway Analysis project identified the Camas Prairie in south central Idaho as a region with a potential commercial resource (e.g., capable of ≥10 MW of electric power generation) based on the presence of hot springs and thermal wells, active faults that appear to control the upflow of thermal fluids, and the presence of basin-filling sediments to form a seal (Shervais et al., 2016). It is a relatively under-characterized geothermal system (e.g., Mitchell 1976; Young, 1978), and is located close to a potential market for renewable energy (Sun Valley, Idaho).

The Camas Prairie is an elongate EW-trending valley situated between the Idaho Batholith and the Mount Bennett Hills that formed as a rift basin during passage of the Yellowstone hotspot to the south (Cluer and Cluer, 1986; Cluer, 1987). The Prairie is bounded on the north by late Cretaceous to early Tertiary granitoids of the Idaho Batholith, and by the Eocene Challis volcanics, and on the south by the Mount Bennett Hills, which consist of basalt overlying rhyolite basement related to the Yellowstone Hotspot track (Wood and Gardner, 1984). The Pliocene to Holocene age valley fill consists of poorly sorted sediments derived mainly from the Idaho batholith to the north, interbedded with young volcanic units that flowed northward from eruptive centers in the Mount Bennett Hills. Basin formation occurred between 5 and 1.8 Ma, based on limited age control on rifted silicic and basin-filling basalts (Cluer and Cluer, 1986).

The Camas Prairie rift basin resembles other extensional basin-and-range systems, like those in the Great Basin, which involve moderate temperature, amagmatic resources associated with fault-controlled deep crustal hydrothermal circulation. However, the Camas Prairie system displays little direct evidence for major basin-bounding or intra-basin structures. In addition, the Camas Prairie geothermal system involves contributions from magmatic sources, based on the presence of Quaternary volcanism in the southern part of the basin, and it has elevated heat flow similar to the rest of the Snake River Plain (Blackwell, 1989). The youngest flows are associated with The Pothole – a Pleistocene basaltic vent and associated flows that are cut by a northwest-trending fault – and associated basaltic vents.

A number of hot springs and wells in Camas Prairie are exploited for direct use applications. These include Barron's Hot Springs (now inactive) with measured surface temperatures of 72°C, and a nearby well with a measured temperature of 91ºC at a depth of 91 m (Mink, 2010). Early geophysical surveys of the Camas Prairie region (Stoker and Gertsch, 1980) identified several structural features that were suggested as potential targets for accessing geothermal resources for direct use applications in this area. Calculated reservoir temperatures at Barron's Hot Springs suggest a low- to moderate-temperature system. However, elevated ^{3}He/^{4}He ratios imply significant mantle-volatile inputs (Dobson et al., 2015; Neupane et al., 2017), and this further supports our hypothesis of heat contributions from magmatic sources.

In this paper, we develop a preliminary conceptual model for the Camas Prairie geothermal system based on structural, geochemical, geophysical, and petrologic evidence. This model will be refined as new data are collected in coming field campaigns.

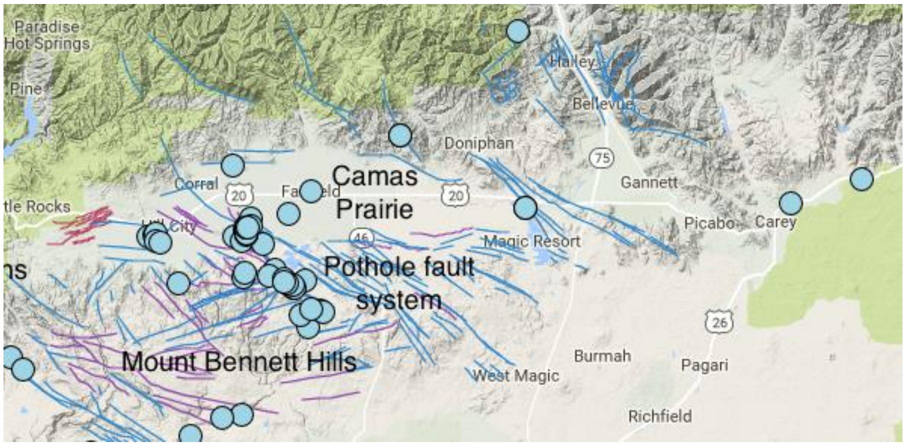

Figure 1. Location map for Camas Prairie geothermal area. Mapped faults in blue and purple, blue dots are water samples from springs and wells. Most springs are concentrated along The Pothole fault system. High terrain to North is Idaho Batholith, low hills south of Camas Prairie are the Mount Bennett Hills.

2. DATA CONSTRAINTS

2.1 Field Mapping and Sampling

Basalt volcano vents are clustered along the southern margin of Camas Prairie, just north of the Mount Bennett Hills. Young volcanic rocks in Camas Prairie are tholeiitic basalts erupted around 1.45 to 0.70 Ma. The youngest vent is The Pothole, a prominent spatter cone vent located at the northern margin of the Mount Bennett Hills, which is cut by a late Pleistocene normal fault that offsets its rim. Similar age volcanic rocks occur in the Magic Reservoir area at the east end of Camas Prairie (Struhsacker et al. 1982).

The Camas Prairie-Mount Bennett Hills region contains two dominant fault sets that strike WNW and ENE. In general, the WNW-trending faults are found in the eastern Mount Bennett Hills, east of The Pothole fault, whereas the ENE-trending faults are found in the western Mount Bennett Hills, west of The Pothole fault (Figure 1). Geologic reconnaissance mapping of The Pothole fault system for this project documents more complex structures. The Pothole fault system is characterized by two dominant fault sets, which strike WNW and NNW. Both are predominantly east/northeast dipping. Fault striations were most commonly dextral-normal and secondarily normal. These orientations are more or less consistent with the attitudes of the major features at depth in the Camas basin, as interpreted from the geophysical studies described below in Sections 2.2 – 2.4. Relative ages of these fault sets could not be determined by cross-cutting relationships, however, the NNW-striking faults cut Cretaceous basement, the Oligocene Challis Volcanic Group, and The Pothole volcanic crater (circa 700 ka), so these fault systems remained active into the late Pleistocene.

2.2 Seismic Reflection Surveys:

Boise State University (BSU) acquired ~56 km of active source seismic data along five north-south and two east-west county roads in Camas Prairie (Figure 3; Glen et al., 2017). Data were acquired using the BSU seismic land streamer and accelerated weight drop system that allowed survey rates of 5-km per day at 4-m 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.

Five south-north seismic profiles (each 7-10 km long) and two west-east profiles (5-8 km long) were acquired along section roads within the Camas Prairie. The focus of the seismic profiling effort was to identify permeable faults and to characterize the sedimentary cover that overlies basement. Seismic results suggest crystalline basement (volcanic rocks or granite) depths of <1.0 km beneath the southern margin of Camas Prairie, and define a complex network of active faults that correspond to locations of elevated groundwater temperatures (Figure 2). These faults offset basement (inferred to be older volcanic and granitic rocks), and overlying strata, and show that the depocenter of the basin is located towards its southern margin. Multiple, basin-wide unconformities are identified with late Quaternary sediment fill of less than 0.2 km along the basin margins.

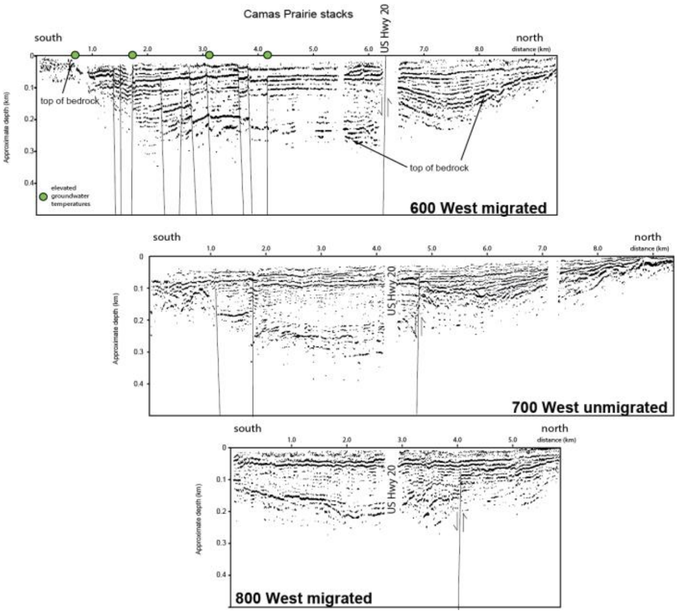

Figure 2. Three NS active source seismic profiles that identify depth to basement, offset sediment reflectors, and fault locations. Numerous faults in basement are evident as offsets in highly reflective markers. A major buried EW-trending faults lies under US HW20. The 600W profile shows location of thermal springs (green dots) relative to seismically identified faults. These faults correlate with offsets in gravity and magnetic potential fields, and are being integrated into the overall structural models.

2.3 Gravity and Magnetic Surveys

New and existing data were gridded to create gravity and magnetic maps of the Camas Prairie and surrounding regions (Figure 3). Several intrabasin structures that have little or no surface manifestation can be inferred from the residual isostatic gravity and magnetic grids. There are two dominant trends: West to WNW-trending structures that reflect the major basin-bounding faults, and NW-trending structures that control the major subbasin geometries.

Potential field modeling along two profiles (600W and 900W) reveal a deep (500-1000 m) structurally-controlled sedimentary basin that displays offsets along numerous structures that also appear in the seismic profile. This basin is floored by crystalline basement partially capped with volcanic flows derived from the south. Interbedded volcanic flows are offset along the same structures identified in the seismic profiles, reinforcing the potential field results.

Regional gravity mapping documents several elongate NW-trending sub-basins characterized by gravity lows (Figure 3). The deepest of these inferred sub-basins is found just north of Barron’s Hot Springs (up to 1 km). This area is characterized by anomalously high groundwater temperatures. The steep gradient bounding the southwest side of the gravity low appears to be most structurally active part of the basin. This gradient is aligned with the inferred NW-trending structures that extend through Barron's Hot Springs. The location of the hot springs may be related to the intersection of this NW-trending structure with more westerly-oriented basin-bounding structures that delineate the northern margin of the Mount Bennett Hills.

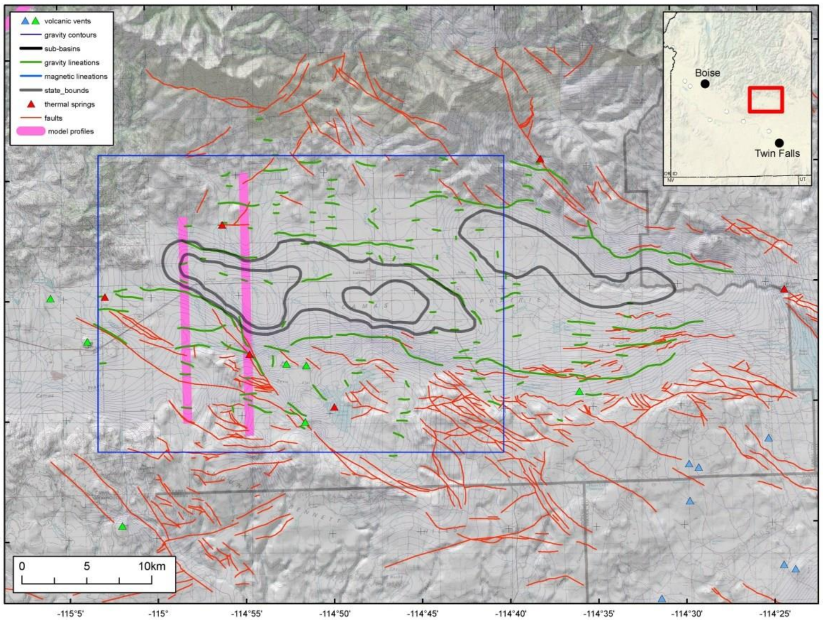

Figure 3. Topographic map of the Camas Prairie study area showing contours of the residual isostatic gravity, volcanic vents, thermal springs, deep drill holes, and profile model locations. Geophysically inferred structural features (gravity lineations) based on maximum horizontal gradients of residual 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. From Glen et al, 2017.

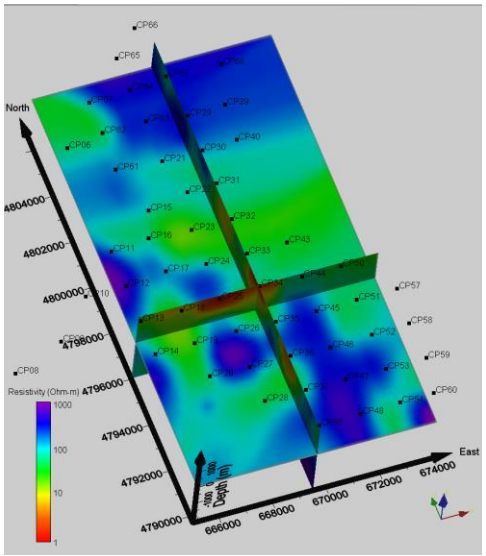

Figure 4. Fence diagram from 3D composite resistivity cube and depth slice of final resistivity structure recovered by MT inversion at Camas Prairie. The outline of the basin east of stations CP15-17 is clearly seen by change in resistivity from low (green color) to high (blue color) to the SW. From Glen et al 2017.

2.4 Magnetotelluric Surveys

Sixty-three magnetotelluric (MT) stations were deployed in Camas Prairie. A 3D inversion of the MT data documents a low-resistivity structure where the EW-trending basin-bounding faults intersect the NW-trending Pothole fault system (Figure 4). This structure, centered around stations CP-25 and CP-34, is interpreted to represent a clay-cap marking a zone of prolonged thermal water upwelling; however, this low resistivity feature could also reflect the presence of clay-rich basin sediments (e.g., Cumming, 2016). The MT data also support the gravity and magnetic data interpretations..

2.5 Water Chemistry

Water samples were collected from springs and water wells in the Mount Bennett Hills and Camas Prairie, and several locations were resampled to assess seasonal variations. These samples were analyzed for major and trace elements, and stable isotope ratios of oxygen, hydrogen, and helium. Equilibrium reservoir temperatures were calculated using cation, silica, and multi-component geothermometry, oxygen and hydrogen stable isotopes were used to identify the water sources and water–rock interaction of the geothermal fluids, and helium isotope ratios were used to track mantle volatile inputs (Neupane et al., 2017). Water chemistry for the Camas Prairie and Mount Bennett Hills (Neupane et al., 2017) show that hot spring and thermal well samples are largely Na-HCO_3-type waters, whereas cooler groundwater and spring waters are Ca,Mg-HCO_3-type (Figure 5). A mixing trend is observed between Ca,Mg-HCO_3 and Na-HCO_3 water types. Most of the samples exhibit a small shift in $\delta^{18}O$ to values higher than local meteoric water, whereas a few water samples show significant shift to higher values, which is indicative of oxygen isotope exchange during high-temperature water-rock interaction in hydrothermal systems. In general, water chemistry and isotopic compositions indicate that hydrothermal waters in Camas Prairie area are dominantly meteoric in origin with some modification from water-rock interaction at elevated temperature.

Neupane et al. (2017) estimated reservoir temperatures in Camas Prairie using multicomponent and conventional geothermometry. Their results indicate two areas of interest: one on the northern side associated with the Idaho Batholith, with an estimated reservoir temperature as high as 200ºC, and one on the southern side related to Quaternary volcanism and intrusions with estimated reservoir temperatures of about 110ºC. Neupane et al. (2017) also document elevated helium ^{3}He/^{4}He isotope ratios in geothermal fluids found (~2 R/R_A) along The Pothole fault system adjacent to the Mount Bennett Hills, indicating high flux of mantle volatiles.

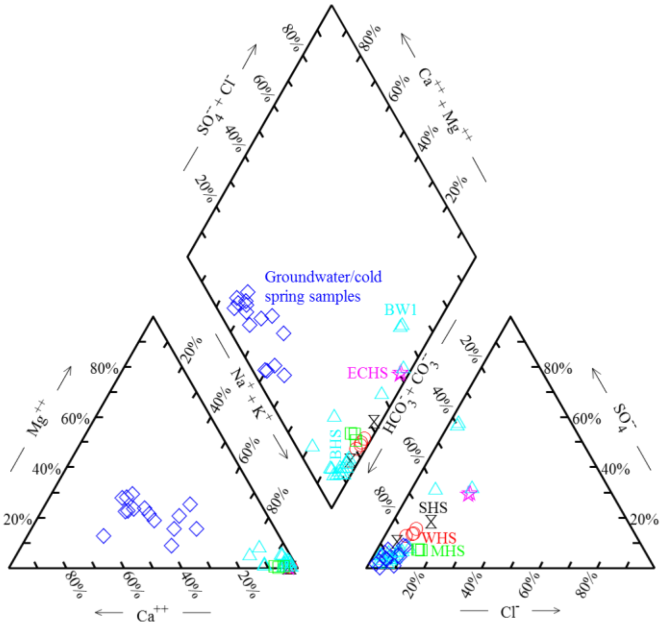

Figure 5. Piper diagram representing chemistry of water samples from Camas Prairie area. Samples are grouped as groundwater/cold springs (blue diamonds), Barron Hot Springs area (BHS, cyan), Sheep/Wolf Hot Springs (SHS, black hourglasses), Wardrop Hot Springs area (WHS, red circles), Elk Creek Hot Springs (ECHS, magenta stars), and Magic Hot Springs area (MHS, green squares). From Neupane et al., 2017.

2.6 Stress-Strain Analysis

Orientation of the local stress field is a critical for inferring reservoir characteristics. We used the nearest stress data point to define the stress regime for each lineation. Our detailed structural mapping of fault systems in Camas Prairie allowed us to evaluate local stress regimes and the strain response to that stress, yielding refined estimates of the local stress fields and their orientation. The stress data are used to weight fault and lineament slip and dilation tendencies, both of which are proxies for permeability on these structures (e.g., Jolie et al, 2015; Siler et al., 2017). These data were integrated with regional stress and strain estimates from previous studies (e.g., Payne et al., 2012; Kessler et al., 2017). Our data suggest that right-stepping geometries between the two WNW- and NNW-striking, right-oblique fault systems (releasing steps) are more conducive to permeability development and geothermal circulation than left-stepping (restraining steps) geometries (Figure 6).

3.0 PRELIMINARY CONCEPTUAL MODEL FOR THE CAMAS PRAIRIE-MOUNT BENNETT HILLS SYSTEM

3.1 Overview

In the Camas Prairie region, the most prominent geothermal prospect are found along The Pothole fault system, where it forms oblique intersections with numerous small faults to the south and west, as well as with the EW-trending range-front fault system (Figure 6). The resource here is indicated by thermal springs that cluster along the fault systems, thermal and irrigation well geochemistry indicating >110°C reservoir conditions, and elevated ^{3}He/^{4}He ratios (~2 R_A) in groundwater suggesting a recent magmatic volatile source. A failed water well that was drilled to ~168 m (550 ft) near the Pothole Fault encountered a temperature of 91°C at a depth of ~90 m (300 ft) (Mink, 2010); this well confirms the presence of shallow hot outflow associated with this geothermal system. Volcanism is somewhat older (692 ka to 1.45 Ma), but it is also less than 50 km NW from The Pothole crater to the 2.1 ka vent on the Boise River. This high prospectivity is reinforced by field mapping that suggest high dilation in fault intersections, based on dip and slip directions observed on faulted surfaces. MT survey data indicate a region of conductive clay cap within our target zone.

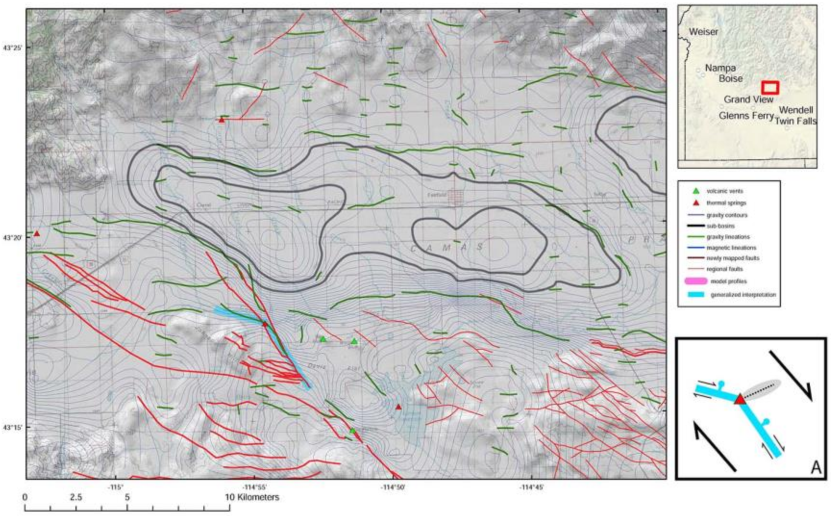

Figure 6. Topographic map of the Camas Prairie study area showing contours of the residual isostatic gravity, volcanic vents, thermal springs, deep drill holes, and profile model locations. Inset shows releasing step in Pothole system. Geophysically inferred structural features (gravity lineations) based 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.

3.2 Structural Model

Our structural model is based on the distribution of mapped surface faults and their orientation within the measured stress field, the distribution and orientation of faults inferred from gravity, and magnetic surveys, which document offsets in crystalline basement topography, and seismic profiles, which document offsets within the sedimentary fill, as well as basement topography. The largest through-going faults systems are the NW-trending Pothole system and the EW-trending range-front system. East of The Pothole fault system, minor faults within the eastern Mount Bennett Hills trend NW, subparallel to the Pothole fault system, whereas to the west most faults trend NE or EW in the western Mount Bennett Hills, and WNW within the Camas Prairie basin (Figure 6).

Fault intersections are abundant along The Pothole fault system. This is especially clear where the NW-trending Pothole fault intersects a series of more WNW-trending faults, creating a series of releasing bends that may allow fluid upflow along the main Pothole fault segment (Figure 6). Regional stress field data indicate that these NW-trending faults have high dilation tendencies (mostly >0.8), whereas NE-trending faults found SW of The Pothole system have high slip tendencies.

Further, the intersection of The Pothole fault system with the ~EW-trending range front fault system creates another high permeability zone marked by the location of Barron Hot Springs.

3.4 Heat Model

The likely heat source for Camas Prairie is a sill or dike complex related to young volcanic activity. Volcanic vents are not common but they cluster along the southern margin of the Prairie. The youngest documented vent is The Pothole (~690 ka) and the oldest is the Macon Flat basalt (1.45 Ma; Garwood et al., 2014). Heat flow is uniformly high throughout Camas Prairie at >100 mW/m^2 (Blackwell and Richards, 2004), and helium isotope ratios in groundwater are anomalously high at 1.9-2.2 R_A along the southern margin of the prairie near the Pothole fault system, and 1.1-1.2 R_A along the northern margin of the prairie (Neupane et al., 2017). The elevated $^3He/^4He$ ratios for the southern Camas Prairie indicate a significant mantle-derived volatile flux that may be associated with young magmatism, as well as relatively high crustal permeability that must extend to depth (e.g., Kennedy and van Soest, 2007).

We postulate a heat model similar to that of adjacent Snake River Plain: a basaltic sill complex in the middle to upper crust that represents an accumulation of heat caused by multiple sill injections over time (Nielson and Shervais, 2014). In this model intrusion of the basaltic sill complex is driven by a magma supply rate that exceeds the extension rate of crustal deformation, leading to a build-up of heat that drives geothermal circulation (Nielson and Shervais, 2014; Nielson et al., 2017). This sill complex may underlie the entire Camas Prairie region as well as the Mount Bennett Hills to the south, but it manifests itself primarily along zones of high permeability, for example, the Pothole fault system. The lower level of volcanic activity, and its marginal location, suggest that the heat available in Camas Prairie will be less than the main Snake River Plain.

3.5 Seal

An overlying seal is critical to retain heat and fluids, in order to preserve a viable hydrothermal power source. There are two types of seal in Camas Prairie. First, water well logs document a layer of clay about 30 m (100 ft) thick that underlies much of the southern part of the prairie. This clay layer represents lacustrine deposits formed while the prairie was isolated from other drainages. It is ubiquitous throughout the southern prairie and is thick enough to provide an effective seal in most cases. Second, MT data (Glen et al., 2017) document a clay cap seal that centers around The Pothole fault system near its intersection with the range front fault system and the cluster of WNW-trending faults that splay off from it. We postulate that this clay cap is associated with hydrothermal alteration.

4. Summary and Conclusions

Geothermal systems in the southern part of Camas Prairie have their ultimate source in heat provided by a mid- to upper-crustal basaltic sill complex similar to that thought to underlie the adjacent Snake River Plain (e.g., Shervais et al., 2006). As shown by Nielson et al. (2017) basaltic systems in which the rate of magma supply exceeds the rate of crustal extension may accumulate magma in crustal sills (rather than dikes, which lose heat rapidly to their wall rock). As a result, heat accumulates over time and may become sufficient to support a geothermal system (“thermal ground preparation”). Intersecting fault systems provide pathways for the deep circulation of meteoric water, allowing to exchange heat with the deeper crustal rocks, and also provide pathways for the heated fluids to return to the surface. In Camas Prairie, the most effective fault systems are the Pothole fault system (which trends NW), and its intersections with the EW-trending range front system along the northern edge of the Mount Bennett Hills, and WNW-trending faults that splay off of the Pothole system north of the range front. The NW-trending faults have high dilation tendencies, and the abundant intersections provide enhanced permeability for fluid flow. Finally, the Camas geothermal system has an effective seal composed of both lacustrine muds (regional in extent) and a clay cap that is confined to the Pothole fault and its intersections with other faults.

Ongoing exploration of the Camas region will provide more precise constraints on this system and lead to a more refined and quantitative conceptual model. Our plan is to drill a 700 m (2000 foot) test well in a permeable structure, collecting core in the lower part of the well. If successful we will perform a suite of reservoir tests and down-hole geophysical logs to characterize the system and document reservoir characteristics. The specific location of this well will be determined by data collected in early 2018, but its general location will be along the Pothole fault system near the range front of the Mount Bennett Hills. Our goal is to confirm a low-temperature resource similar to other low-temperature systems that have proved to be economically viable (e.g., Orenstein et al, 2015).

Acknowledgments

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