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Geochemical Evaluation of the Geothermal Resources of Camas Prairie, Idaho

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ABSTRACT

The Camas Prairie in Blaine, Camas, and Elmore Counties, Idaho has long been identified as an area with geothermal potential, and is one of several promising geothermal prospects that were identified by play fairway analysis of the Snake River Plain region. The geothermal activity in the area is manifested by the presence of several hot springs. Moreover, a number of groundwater wells with elevated temperatures have been identified in the area. However, the location of geothermal resources within the basin is poorly constrained, as they are concealed by Quaternary and Neogene sedimentary deposits and volcanic rocks. The prairie is likely formed by failed rifting or extensional faulting as a response to the down warping of the central Snake River Plain to the south. Young volcanic activity and faulting are evident within the prairie and along its margins. As a part of a more comprehensive effort to assess the geothermal resource potential of the area, we present new water chemical and isotope results from the area in the context of existing water chemistry data. We applied conventional and multicomponent geothermometry tools to estimate the reservoir temperatures for the area. Specifically, our geochemical and geothermometry analysis indicated two interesting areas, one in the central-west northern side and other in the central-west southern side of prairie. Our results show that the Camas Prairie area could potentially host resources with temperatures as high as 200 ºC. Water chemical and isotopic results suggest that the highest temperature resource is a mixture between deeply circulated fluids with a magmatic affinity and local meteoric recharge. The water geochemistry suggests that there are two potential geothermal resource types: one associated with the Idaho Batholith to the north, and a second related to elevated heat flow associated with Quaternary volcanism and intrusions within the Snake River Plain province. Ongoing geophysical, geological, and geochemical investigation of the area could be instrumental in defining the Camas Prairie geothermal resource.

1. INTRODUCTION

Camas Prairie is an east-west elongated (about 50 km by 15 km) valley in Blaine, Camas, and Elmore Counties in south-central Idaho (Figure 1). In general, the prairie is bounded by the Mount Bennett Hills to the south and the Soldier Mountains to the north. The Mount Bennett Hills represents an east-west trending horst that runs parallel to the Camas Prairie. On the south side of Mount Bennett Hills lies the central parts of the Snake River Plain, which is a magmatic region of high heat flow with great potential for significant geothermal resources. Similarly, the Soldier Mountains to the north of Camas Prairie represents a large area of central Idaho with faulted mountains associated with Cretaceous-Miocene magmatic/volcanic activity.

The Snake River Plain is a topographic depression along the Snake River in southern Idaho. The western Snake River Plain is a basalt- and sediment-filled tectonic feature defined by a normal fault-bounded graben whereas the eastern Snake River Plain is formed by crustal down-warping, faulting, and successive caldera formation that is linked to middle Miocene to Recent volcanic activity associated with the relative movement of the Yellowstone Hot Spot (Pierce and Morgan, 1992; Hughes et al., 1999). The genesis of the Mount Bennett Hills along with Camas Prairie have been associated with the evolution of the Snake River Plain over time (Cluer and Cluer, 1986).

The occurrence of several clusters of hot springs within and along the margins of the prairie suggest the presence of geothermal resources in the Camas Prairie (Mitchell, 1976). Specifically, five local areas with hot-spring activity are identified as having geothermal potential. The Magic Hot Springs and the Elk Creek Hot Springs areas are located in eastern and northeastern sides of Camas Prairie, whereas the Sheep and Wolf Hot Springs (~50 ºC) are located in western part of Camas Prairie. Another area with geothermal potential is associated with the Wardrop Hot Springs (60 °C) located in the north-central part of the prairie near the base of the Soldier Mountains. The fifth hot springs area in Camas Prairie is represented by the Barron Hot Springs (73 °C) area located on the southern side of the prairie near the base of the Mount Bennett Hills. Several hot wells are also located in the vicinity of these hot springs. With the exception of residential space heating applications, the geothermal resources of the area are not utilized for any commercial activities.

Since 2014, we have been conducting field studies in this area as a part of geochemical, isotopic, and geothermometric evaluations of the geothermal resources in and around the Snake River Plain in southern Idaho (e.g., Neupane et al., 2014; Cannon et al., 2014; Dobson et al., 2015; Neupane et al., 2016; Conrad et al., 2016). This work represents the continuation of our work in southern Idaho with a fresh impetus for the Camas Prairie area as one of the Snake River Plain Play Fairway Phase II focus areas (Shervais et al., 2016). In this paper, we present geochemical, isotopic, and geothermometric results based on recent as well as previously published geochemical/isotopic data (e.g, Mitchell, 1976).

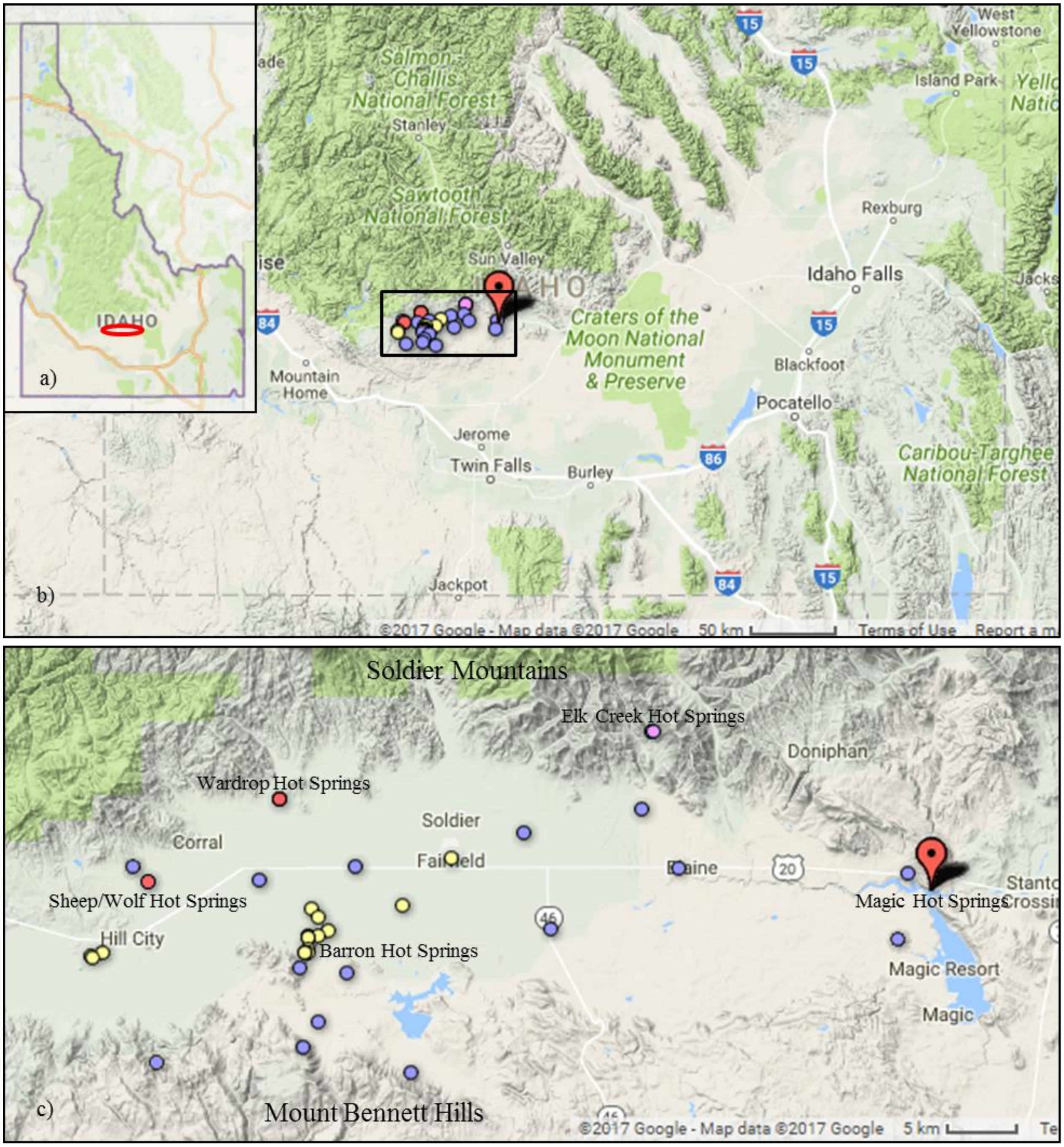
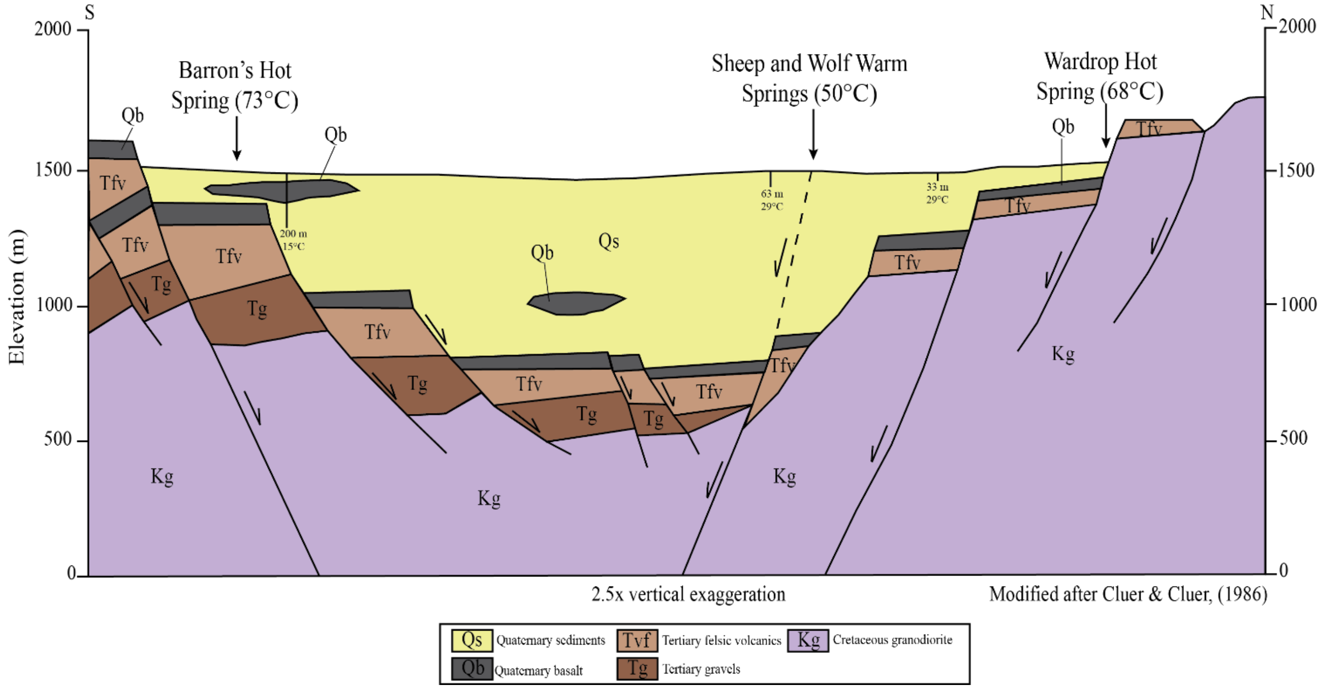


Figure 1. Maps of (a) Idaho with an ellipse indicating the general location of Camas Prairie, (b) southern Idaho showing the general distribution of sampling features in the Camas Prairie area, and (c) Camas Prairie area showing locations of various sampled sites - Magic Hot Springs Reservoir Landing well (RLW): red push-pin; Wardrop/Sheep/Wolf Hot springs: red circles; Elk Creek Hot Springs: purple circles; Barron Hot Springs (and associated samples): yellow circles; cooler groundwater wells and cold springs: blue circles.

2. GEOLOGIC AND GEOTHERMAL SETTINGS

Camas Prairie is an intermontane valley filled with sediments and basalt layers over granites/granodiorites of the Cretaceous Idaho Batholith (Garwood et al., 2014). Mitchell (1976) considered this area as a simple depression in the granitic surface of the Idaho Batholith that has been filled in with valley alluvium and colluvium from the hills/mountains on both sides. This structural setting was thought to be supported by outcrops of granite on the northern and southern borders and granite found at a shallow depth beneath alluvium in the center of the prairie (Mitchell, 1976). However, previously, Smith (1966) referred the basin as a fault-bounded graben. Cluer and Cluer (1986) compiled a suite of geologic and topographic evidence and suggested that the prairie is a result of failed rifting of the area controlled by north-south extensional tectonics. They made an argument for a “Camas Prairie Rift” which was believed to have occurred between 2-5 Ma and lasted for a relatively short time. The loading and down-warping of the Snake River Plain to the south created an extensional regime along the Camas Prairie region that created marginal faulting and development of a rift valley separating the Snake River Plain from the Idaho Batholith region. Subsequently, basalt and sediment layers filled in the rift valley and shaped the present day Camas Prairie (Figure 2). Although the schematic diagram (Figure 2) shows almost a kilometer of valley-fill sediments at the center of Camas Prairie, preliminary results of the ongoing Snake River Play Fairway Phase II project indicate that the valley-fill sediments may be much thinner. Concerted efforts combining seismic, electromagnetic, and gravity surveys (Glen et al., 2017) will help define the structural setting of this area in the near future. In general, faults that parallel the Snake River Plain with opposite senses of displacement are present in the Mount Bennett Hills and along the edge of the Soldier Mountains. One of these faults is inferred to be continuous but concealed through the prairie in close proximity to the Sheep/Wolf Hot Springs area. The spring waters have likely migrated upward from a deeply buried fracture zone in the granodiorite along this fault. The water could also be under slight artesian pressure because most of the Camas Prairie is below the regional potentiometric surface (Mitchell, 1976).



Modified after Cluer & Cluer, (1986)

Figure 2. Schematic geologic cross-section of Camas Prairie (after Cluer and Cluer, 1986).

The Mount Bennett Hills to the south of the prairie are composed predominantly of Miocene rhyolitic ash flows and lava flows of the Idavada Volcanic Group (Tfv) that overlies the Idaho Batholith granodiorite (Kg). Local basalt flows and fluvial/lacustrine sediments are also present. The Soldier Mountains are composed mostly of Cretaceous granodiorite (Kg) with minor amounts of younger intrusives. Camas Prairie is host to an unknown thickness of Quaternary alluvial, fluvial, and lacustrine sediments (Qs) with local lenses of basalt (Qb) encountered in the shallow subsurface (Figure 2).

The Elk Creek Hot Springs area (Figure 1) is located in the southernmost regions of Soldier Mountains near the Elk Creek drainage, a few kilometers north from the Camas Prairie basin. Rocks in the area include - Miocene Tuff of the Cannonball Mountain Formation (Tcm) of the Idavada Group, Eocene dacite and rhyodacite of the Challis Volcanic Group (Tcvd), a diorite and gabbro unit (Tdg), and the Cretaceous Idaho Batholith granodiorite (Kg) (Garwood et al., 2014). Various Tertiary dacite and rhyolite dikes (Td) are mapped throughout the area intruding into batholith granodiorites, and based on local abundance, are inferred in cross-section (Figure 3). Alluvial fan deposits are restricted to slopes and valleys.

Many NW trending normal faults with orientations similar to Basin and Range extensional structures dominate. Locally, the SW dipping, NW trending Elk Creek Fault extends from the Camas Prairie north into the Soldier Mountains. This fault and associated breccia facilitate flow from deeply jointed and fractured granodiorite (Figure 3). Also, the presence of numerous dikes in the area represents planes of weakness within the batholith that could serve as preferential pathways for geothermal fluids.

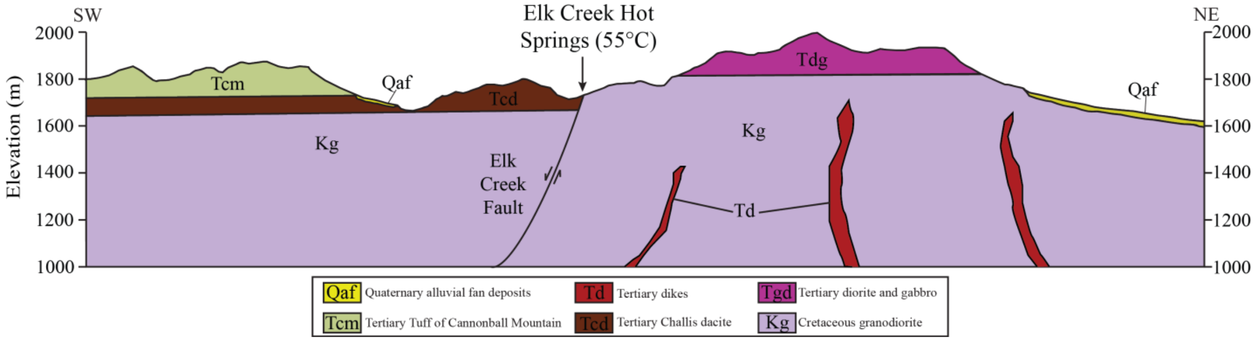


Figure 3. Geologic cross-section through the Elk Creek Hot Springs area (based on Garwood et al., 2014).

The Magic Hot Springs area (Figure 1) lies at the eastern end of the prairie. The Magic Hot Springs area consists predominantly of Miocene-Quaternary silicic volcanic rocks and basalt flows. The Pliocene-Miocene Poison Creek Tuff (Tpct) is the uppermost unit in the immediate vicinity of Magic Hot Springs Reservoir and is underlain by the Miocene Tuff of City of Rocks (Tcort), a rhyolite tuff from the Idavada Group (Figure 4). Other rhyolites and basalt flows are abundant in the surrounding areas but are not shown in the cross-section. The Cretaceous Idaho Batholith rocks (Kg) form the basement throughout the region.

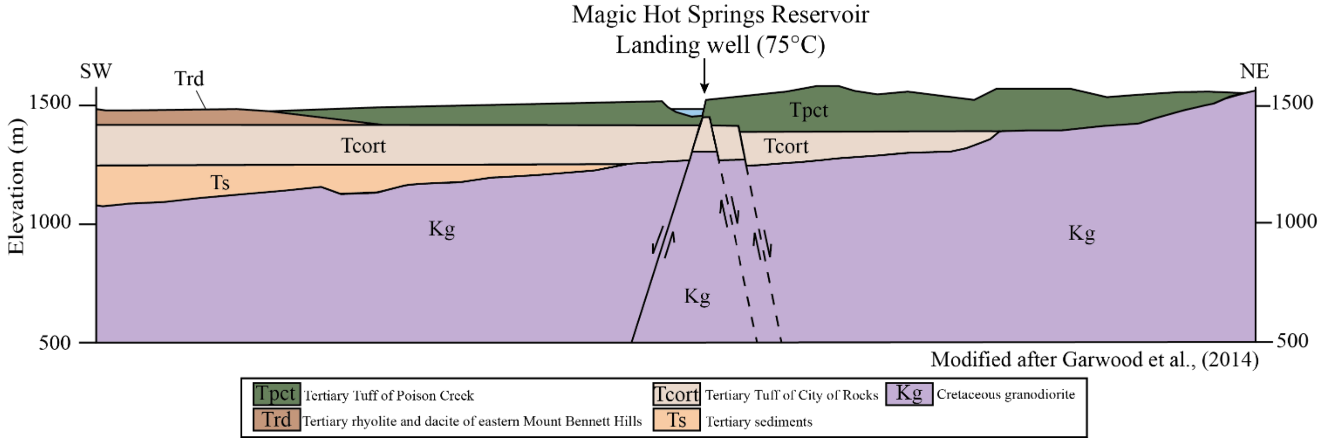


Figure 4. Geologic cross-section of the Magic Reservoir Hot Springs area

Structurally, this area is interesting because of its location at the intersection of several regional to local geographic and geologic features including the Eastern Snake River Plain, Camas Prairie, eastern part of Mt. Bennett Hills, and Idaho Batholith. The Magic Hot Springs area is in a tensional stress regime and includes many high-angle normal faults that create block-faulted configurations (Struhsacker, 1982). Mitchell (1976) recognized two curvilinear features from Landsat false color infrared satellite imagery and discusses their controlling nature in the immediate area. The Magic Hot Springs Reservoir Fault trends northwest and extends the length of the reservoir and into the northern Soldier Mountains. Another fault extends at a slightly less northwest trend along the Clay Bank Hills and intersects the Magic Hot Springs Reservoir fault near the location of the Magic Hot Springs Reservoir Landing well (RLW) (Malde et al., 1963). Struhsacker et al. (1982) refer to the resulting structure as the Hot Springs Landing horst. These structures are interpreted to have occurred prior to Quaternary volcanism due to the lack of deformation in the flat lying young basalts and sediments. They may also be related to a buried caldera inferred from stratigraphic thicknesses and basalt vent locations in the surrounding regions (Leeman, 1982).

3. GEOCHEMICAL TOOLS

3.1 Solute Geothermometry

One of the tools applied by our group for geothermal prospection is solute geothermometry, which entails estimating deep reservoir temperatures from the chemical compositions of water from springs and wells. As an exploration tool, geothermometry offers a cost effective method to decrease exploration risk by evaluating a potential geothermal reservoir's temperature. To conduct geothermometry, measured chemical compositions of water from wells and springs are needed. The application of geothermometry requires several assumptions. The most important assumptions are that the reservoir minerals and fluids at depth are at or near chemical equilibrium, and that the chemical signature of this equilibrium is preserved as the water moves from the reservoir to the sampled location (Fournier et al., 1974).

Traditional (i.e., quartz, chalcedony, Na-K-Ca, Na-K-Mg trilinear,) and multicomponent (RTEst and GeoT) geothermometers were used to assess the reservoir temperatures of the geothermal systems in Camas Prairie area. Details about these tools can be found elsewhere (e.g., Fournier and Truesdell, 1973; Fournier, 1977; Fournier and Potter, 1979; Giggenbach, 1988; Palmer et al., 2014; Spycher et al., 2014).

3.2 Isotopes and isotopic geothermometry

Another independent geothermometric approach carried out for this study was to compare the isotopic compositions of different components of the fluids to calculate the temperature at which the two components would have been in isotopic equilibrium (e.g., the oxygen isotopic composition of dissolved sulfate and the water or the carbon isotopic composition of dissolved inorganic carbon and methane). For this work, we used sulfate-water oxygen isotope values to estimate reservoir temperatures (Fowler et al., 2013) and compared the isotopic temperature estimates with temperature estimates obtained with geochemical geothermometers.

We also measured hydrogen isotope (deuterium) values in some water samples from this area. It is known that the hydrogen and oxygen isotopic compositions of meteoric water are generally related to each other in a systematic way (Craig, 1961), that waters of distinct isotopic compositions can represent distinct sources (Giggenbach, 1992), and that the water interactions with rocks at high temperatures can shift the oxygen isotopic composition of the water towards equilibrium with the rocks with little effect on the hydrogen isotopic composition of the water (Taylor, 1974). In this study, the distinct isotope exchange behavior of oxygen and deuterium was used to infer high temperature interaction between the water and rocks. As a concerted geochemical/isotopic evaluation of geothermal resources in the Camas Prairie (and broader southern Idaho areas, Dobson et al., 2015), we also measured He isotopes in water/gas samples from various features and used them to identify the source of the He and associated fluids (Ballentine et al., 2002; Graham, 2002; Dobson et al., 2015).

4. WATER CHEMISTRY RESULTS

4.1 Water compositions

Water samples from numerous geothermal features such as hot springs and wells with elevated temperatures were collected, and their chemical constituents were analyzed in 2014-2016. Furthermore, existing water composition data were also assembled from the literature (e.g., Mitchell, 1976; NWIS data base, etc.). The water sampling locations are shown in Figure 1. The highest field temperature was recorded at the Magic Hot Spring RLW (75 °C). The pH of water samples ranged from 6.7 (Monument Gulch Spring, a cold spring) to 9.9 (Sheep Hot Spring). These thermal waters show a large range in total dissolved solids (TDS) from about 120 mg/L (unnamed spring #4, a cold spring) to about 1500 mg/L (Magic Hot Spring RLW).

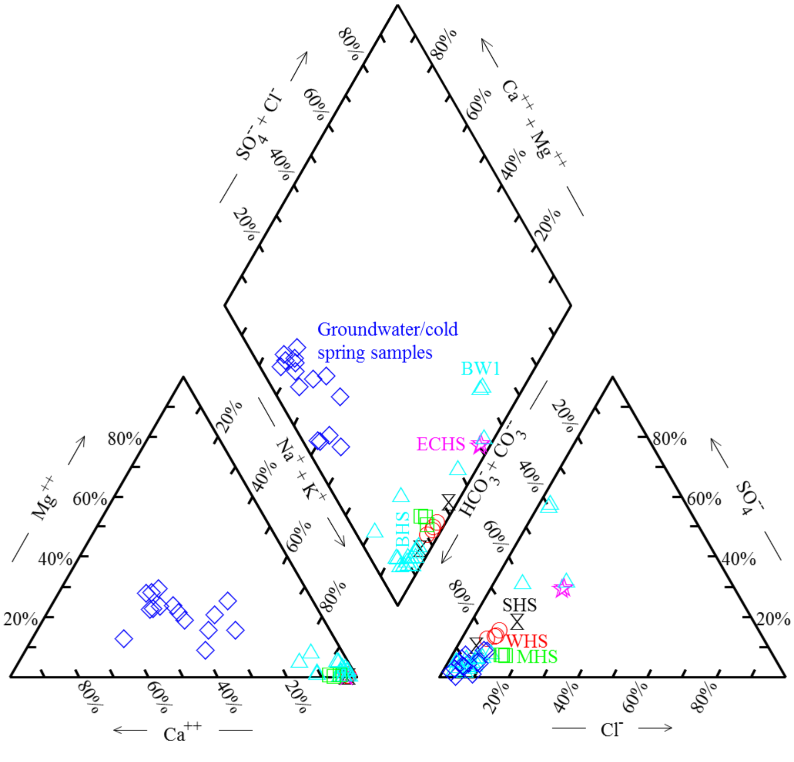


Figure 5. Piper diagram representing chemistry of water samples from Camas Prairie area. Samples are grouped as groundwater/cold springs (blue diamonds), Barron Hot Springs area (BHS, cyan triangles; BW1 indicates recent (2014 and 2016) water chemistry data of high sulfate water samples of the Barron Well 1), 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).

The concentrations of major anions and cations in the groundwater and cold springs samples as well as in the water samples collected from hot springs and thermal (with T>18 ºC) wells are illustrated in Figure 5. In most of the groundwater/cold springs samples, Ca and HCO_3 are the dominant cation and anion species, respectively (Ca-HCO_3 type water). In general, groundwater/cold springs water samples have near-neutral pH, low levels of F, Na (except in four wells and one spring that have relatively higher amounts of Na), typically higher Mg concentrations than thermal waters, and a wide range of Ca concentrations. All thermal water samples have Na as the dominant cation and HCO_3 as the dominant anion species, except in samples from the Barron Well 1 where SO_4 is the dominant anion.

In general, the aqueous chemistry of thermal water samples of Camas Prairie indicates that at least four groups of waters with distinct properties are found in the area. The samples from the easternmost parts of the Prairie, the Magic Hot Springs area (all samples from this area are from the Magic Hot Springs RLW), have relatively higher levels of TDS and silica, near neutral pH, and higher levels of Na and HCO_3 with significant amounts of Cl and SO_4. Two samples from the Elk Creek Hot Springs area are alkaline (pH>9), high-F (15 mg/L), Na-HCO_3 type waters with very low Mg but significant Cl and SO_4. Generally, alkaline pH and high F concentration are used as distinct chemical characteristics of waters that interact with the Idaho batholith. The F-bearing accessory minerals in the granite/granodiorite of the Idaho batholith are thought to be the source of high F content in these waters (Mitchell, 1976). The third distinct group of water samples represents Sheep/Wolf Hot Springs and Wardrop Hot Springs area samples. Water samples from both of these hot springs areas have high pH (9.0-9.9), relatively low level of TDS (220-350 mg/L), low concentrations of both Ca and Mg, and intermediate concentration of F (1.9-3.7 mg/L). Finally, the last group of Camas Prairie water samples is from the southern part of the basin, notably from the Barron Hot Springs area. These samples are near-neutral to slightly alkaline (pH 7.4-8.5) with slightly higher TDS (380-640 mg/L), low concentrations of Mg, and moderately high concentrations of F (7-13 mg/L). Samples from Barron Well 1 from this area have unusually high SO_4 (170-210 mg/L). This well is also noted for its large variations in measured temperature. For example, we recorded a temperature of 38 ºC for this well in March, 2014; however, the same well was measured at 23 ºC in August, 2016. Another unusual aspect of waters from this well is the silica concentrations, which was measured at 52 mg/L in 2014 and 15 mg/L in 2016. This well (and its neighbors) is near the no longer active Barron Hot Spring – perturbation of the local water table due to extensive groundwater withdrawal for irrigation may be in part responsible for this hot spring's demise. These spatial and temporal variations in chemistry and T indicate that this well may be a less reliable feature for resource assessment, and may be affected by seasonal pumping/irrigation activities. Therefore, this well is excluded from the solute geothermometric temperature estimation for this area. Groundwater/cold springs water samples have near-neutral pH, low levels of F, Na, and wide range of Ca.

4.2 Isotopic compositions

The δD and $\delta^{18}O$ of some Camas Prairie area samples are plotted in Figure 6. Most of the samples plot close to the local meteoric water line (Benjamin et al., 2004); however, a few samples have oxygen isotope composition shifted 1-3‰ to the right of the meteoric water line (e.g., Barron Well 1, Elk Creek Hot Spring 2, Magic Hot Springs RLW). These isotopic compositions, in general, indicate that the groundwater/hydrothermal waters in the area are of meteoric origin.

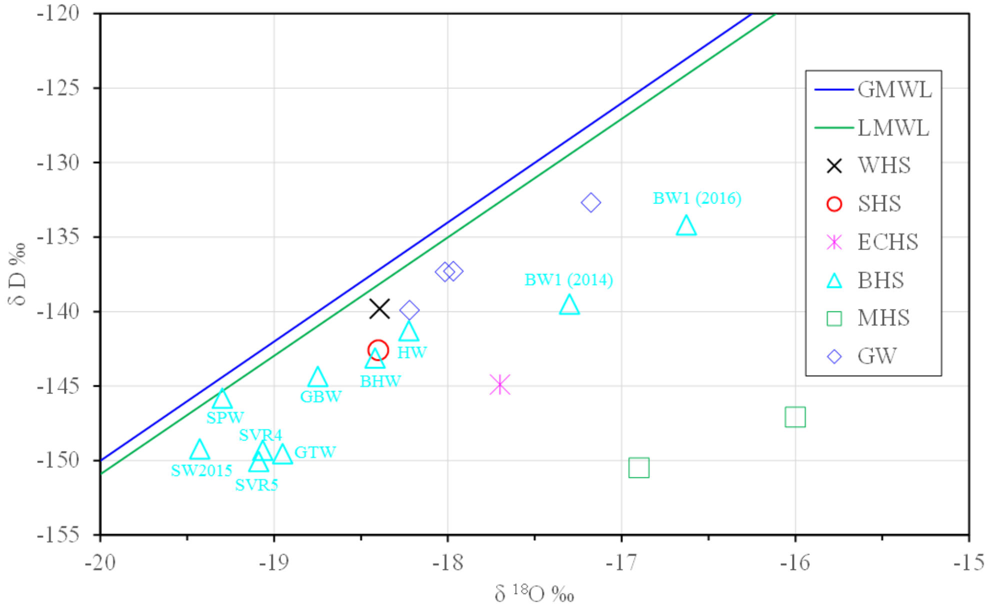


Figure 6. Hydrogen and oxygen stable isotope ratios (‰ vs. SMOW) of Camas Prairie water samples with the global (GMWL; Craig, 1961) and local (LMWL; Benjamin et al., 2004) meteoric water lines. Most of the samples show a small-degree of shift to the right whereas a few water samples [e.g., Magic Hot Springs RLW and its runoff (MHS), Barron Well 1 (BW1), Elk Creek Hot Spring 2 (ECHS)] show a significant shift to the right (towards higher $\delta^{18}O$ values) of the meteoric water lines, which suggests oxygen isotope exchange during high-temperature water-rock interaction in hydrothermal systems, or could also indicate mixing with magmatically derived fluids. Other abbreviations: WHS: Wardrop Hot Spring; SHS: Sheep/Wolf Hot Springs; BHS: Barron Hot Springs area samples, GW: Groundwater/cold spring samples; HW: Higg's well; BHW: Barron House well; GBW: Grandpa Barron well; GTW: Gonzales Thermal well; SPW: Swimming Pool well; SW2015: Strom well 2015; SVR4: Sun Valley Ranch well 4; SVR5: Sun Valley Ranch well 5.

5. GEOTHERMOMETRY RESULTS

5.1 Traditional geothermometry

Figure 7 shows that samples from the Wardrop/Sheep/Wolf Hot Springs, Elk Creek Hot Springs, and Magic Hot Springs are mostly partially equilibrated thermal waters (Giggenbach, 1988). However, the majority of samples from the Barron Hot Springs area are immature samples, with a few (about 6) samples plotting on the partial equilibration field. The Giggenbach plot for the Magic Hot Springs area samples may indicate deep temperatures up to about 200 ºC. Similarly, the Wardrop/Sheep/Wolf Hot Springs samples may indicate water-rock interactions between 120-180 ºC. On the other hand, samples from the Elk Creek Hot Springs and the Barron Hot Springs areas show relatively lower temperatures (120-140 ºC) at depth.

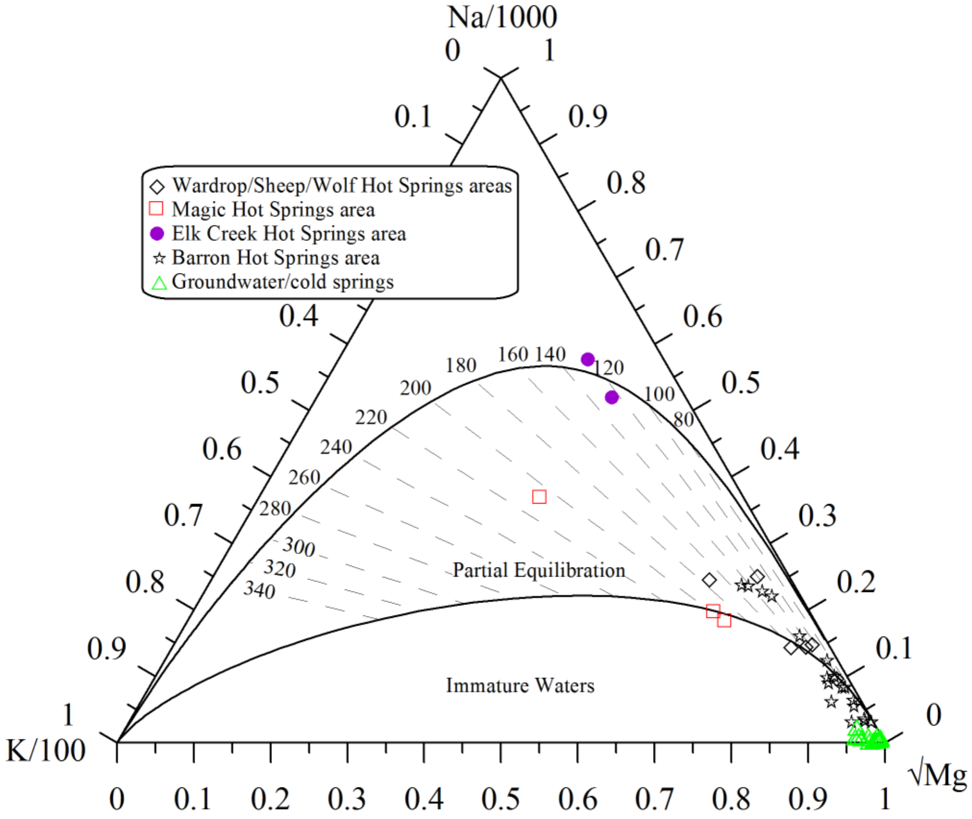


Figure 7. Camas Prairie water samples plotted on a Giggenbach diagram.

Results of other conventional geothermometers for these areas are given in Table 1. Quartz (no steam loss), chalcedony, and Mg-corrected Na-K-Ca geothermometers resulted in temperatures between 113 and 152 °C for the Magic Hot Springs area. Silica-enthalpy mixing models were applied with compositions measured in water samples from the well and a well producing cooler groundwater. The runoff channel sample was not considered because of the apparent heat loss. The chalcedony-enthalpy mixing model resulted in a reservoir temperature of 145 °C with about 50% dilution. Similarly, the quartz-enthalpy mixing model resulted in a reservoir temperature of 181 °C with about 60% dilution.

Samples from Elk Creek (HS1 and HS2) yield quartz (no steam loss), chalcedony, and Na-K-Mg reservoir temperatures between 86 ºC and 115 °C, with values consistent between samples (Table 1). For samples from the Wardrop, Sheep, and Wolf Hot Springs areas these geothermometers yield temperatures between 85 ºC and 124 ºC, while the chalcedony-enthalpy and quartz-enthalpy models yield higher temperatures (133 °C and 173 °C, respectively). Similar results are obtained for the Barron Hot Springs area (Table 1).

5.2 Isotope geothermometry

For a few samples, we measured the oxygen isotope values in SO_4 and water for $\delta^{18}O$ (SMOW) sulfate-water isotope geothermometry. The isotope geothermometric temperature estimate for the Magic Hot Springs RLW is found to be about 237 ºC. This temperature is significantly hotter than the temperature estimates with conventional geothermometers. Moreover, other isotopic compositions for water samples from this area also indicate a high-temperature water-rock interaction. The water isotope composition of the well water (δD = -151‰, $\delta^{18}O$ = -16.9‰, SMOW) is significantly shifted off the meteoric water line (the runoff sample was also shifted, but was also clearly evaporated during cooling). In addition, the isotopic composition of dissolved methane in the water (δD = -203‰, SMOW and $\delta^{13}C$ = -22.0‰, Vienna-PDB) suggests typical of methane produced in a magmatic system (Conrad et al., 2016). The helium isotope value for this system, Rc/Ra = 1.62, is high, and potentially indicates the presence of a magmatic component in these fluids (Dobson et al., 2015).

Table 1. Temperature estimates for Camas Prairie area water samples

Springs/wells[a]	RTEst ±σ[b]	GeoT[c]	$\delta^{18}O_{SO_4-H_2O}$[d]	Quartz (nsl)[e]	Chalcedony[f]	Na-K-Ca[g]	Silica-enthalpy[h]
Magic HS RLW	163±2	194±3	237	139	113	149	145 (181)
Magic HS RLWR	151±3		233	142	116	143	
Elk Creek HS1	125±4	125±3		114	86	110	
Elk Creek HS2	123±4	127±3	136	115	86	107	
Wardrop HS	181±3	186±5	133	123	95	85	133 (173)
Hot Spring Ranch HS 1	188±3	187±5		126	98	89	
Hot Spring Ranch HS 2	194±2	186±3		124	96	124	
Hot Spring Ranch HS 3	188±1	188±4		124	96	101	
Sheep HS	198±11			117	88	70	
Wolf HS	203±2	183±3		114	85	124	
Barron HS1	103±2	141±3		128	100	111	126 (162)
Barron HS2	104±6	143±3		128	100	115	
Barron W2			419				
Barron W2	104±4	129±7		127	99	94	
Barron W3	103±5	129±6		114	85	106	
Punkin Corner area W	105±6			124	96	86	
Sun Valley Ranch W	108±4			124	96	88	

[a] HS: Hot spring, WS: Warm spring, S: Spring, W: Well, RLW: Reservoir Landing well, RLWR: Reservoir Landing well runoff; [b] RTEst estimated temperature with associated standard error (Palmer et al., 2014; Mattson et al., 2015); [c] GeoT multicomponent geothermometer (Spycher et al., 2014); [d] sulfate-water oxygen isotope geothermometer temperature (Fowler et al., 2013); [e] quartz (no steam loss) geothermometer temperature (Fournier, 1977); [f] chalcedony geothermometer temperature (Fournier, 1977); [g] Mg-corrected (where applicable) Na-K-Ca geothermometer temperature (Fournier and Truesdell, 1973; Fournier and Potter II, 1979); [h] Temperature with silica-enthalpy mixing model (where applicable) using chalcedony solubility, temperature with quartz solubility given in parenthesis

The Barron Well 1 from the Barron Hot Springs area resulted in an unusually high (419 ºC) with $\delta^{18}O$ sulfate-water isotope geothermometry. This temperature estimate exceeds the effective range of this geothermometer, but potentially could indicate a high temperature source for the sulfate. This could be supported by the $\delta^{34}S$ of the sulfate, which at -8.3‰ (Vienna-Canyon Diablo) was by far the lowest of any of the measured samples in these areas (Mattson et al., 2016). This is very low value for the sulfate usually indicates that it is formed from oxidation of pyrite, suggesting it might be a reliable indicator of formation in a hydrothermal system. However, it should be noted that SO_4 concentrations measured in this well are 20 to 40 times greater (173-211 mg/L) than in nearby wells (5-9 mg/L) Barron W2 and W3, which yield otherwise similar water compositions and geothermometry results. This suggests that the high SO_4 concentration in Well 1 may be related to the oxidation of shallow pyritic layers/zones that are unrelated to the present hydrothermal activity in this area. However, it is notable that the Barron Well 1 provides the highest He Rc/Ra value (2.36) in the Camas Prairie area. Earlier, Dobson et al. (2016) suggested that such a high He isotope signature in the Barron Hot Springs area might be associated with deeper magmatic activity. Moreover, the Camas Prairie area, especially, the southern parts, has young volcanic activity (the Pothole basalt) as reported by Garwood et al. (2014).

The samples from the Elk Creek Hot Springs and the Wardrop/Sheep/Wolf Hot Springs areas resulted in isotope geothermometric temperatures in the range of 133 to 136 ºC. Unlike the Magic Hot Springs and Barron Hot Springs area, these northern Camas Prairie areas exhibit lower He Rc/Ra values. For example, Elk Creek Hot Springs sample resulted in an Rc/Ra value of 0.85, which would suggest an Idaho Batholith-type geothermal system for this area (Rc/Ra values ranging from 0.22-0.95, Dobson et al., 2015). In reality, the Elk Creek Hot Springs are located further north from the proper Camas Prairie area in the Idaho Batholith region (Figure 4). Rc/Ra values for the Wardrop Hot Springs and Wolf Hot Springs, which are located within the Camas Prairie area proper, are slightly higher (1.13-1.33) which may either reflect the Idaho Batholith signature or could represent a mixed signature of the Idaho Batholith and the Barron Hot Springs area type settings.

5.3 Multicomponent geothermometry

The multicomponent geothermometry software tools RTEst and GeoT were applied to several samples from the Camas Prairie area. These tools make use of full chemical analyses to imply deep reservoir temperatures on the basis of computed saturation indices of selected minerals expected (or known) to be part of a deep reservoir mineral assemblage. In addition, both tools make use of numerical optimization to reconstruct the composition of deep thermal fluids to compensate for mixing/dilution and degassing effects that can impact geothermal fluids as they ascend to ground surface. For more information on these tools, we refer readers to Palmer et al. (2014) and Spycher et al. (2014). Although both RTEst and GeoT are based on essentially the same concepts for temperature determinations, it is important to note that they rely on different thermodynamic databases, computational routines, and optimization schemes. Here both tools were applied independently, by different users and purposely without knowledge of each other's mineral selections for temperature determinations. Such "blind" comparison was preferred to a true benchmarking exercise to assess result variability when applying this type of geothermometry approach.

For the Wardrop/Sheep/Wolf Hot Springs area samples, RTEst was applied with a mineral assemblage consisting of analcime, calcite, chalcedony, fluorite, K-clinoptilolite, and K-feldspar. All RTEst runs were performed with three optimization parameters (mass of water, fugacity of CO_2 and temperature), and Al and Mg concentrations were taken as measured values. The RTEst reservoir temperature estimates for these hot springs range from 181-203 °C with a large (up to 4) dilution factor (Figure 8a). The GeoT temperature determinations for the Wardrop Hot Springs samples were based on a mineral assemblage consisting of low albite, Ca-beidellite, calcite, clinoclore, laumontite, Mg-montmorillonite, and quartz. In this case, the concentrations of Mg and Al were optimized (to compensate for re-equilibration effects upon cooling) together with the dilution factor (3.1) and fraction of degassing (assuming 100% CO_2 in the non-condensable gas phase); in addition, best results (in terms of mineral clustering) were obtained assuming reaction of calcite along the fluid cooling path. This approach resulted in a temperature estimation of 185 ºC. A similar GeoT temperature of about 183 ºC was obtained for Wolf Hot Springs using the same approach and similar mineral assemblage (Table 1, Figure 8b).

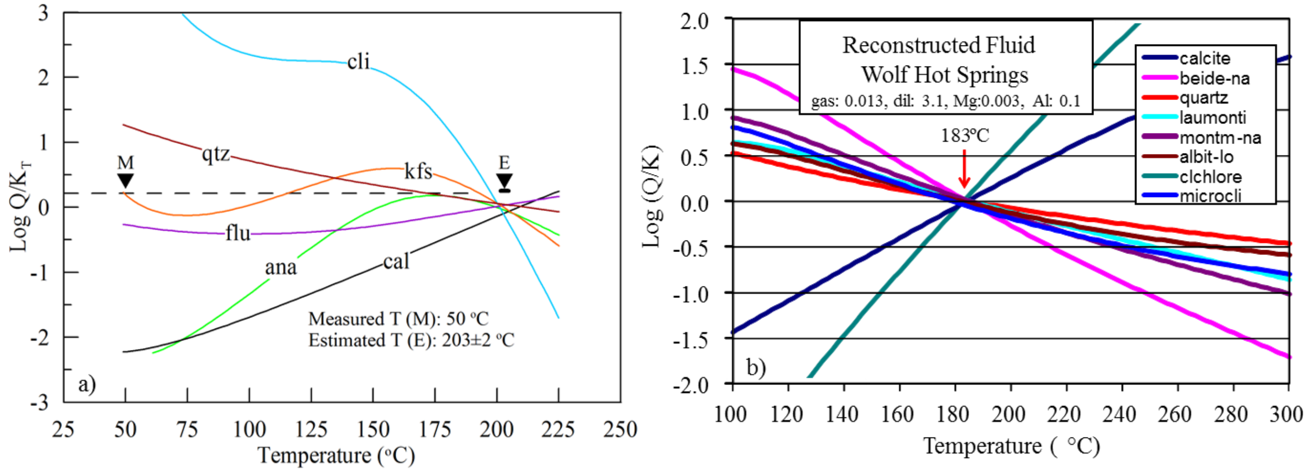


Figure 8. Computed plots of mineral saturation indices (Log (Q/K)) for reconstructed Wolf Hot Spring fluids with: a) RTEst (ana: analcime, cal: calcite, cli: K-clinoptilolite, flu: fluorite, kfs: K-feldspar, and qtz: quartz), indicating a likely reservoir temperature of about 203±2 ºC; b) GeoT, showing a likely reservoir temperature of about 183±3 ºC (including optimization Al and Mg concentrations).

RTEst was applied to the Elk Creek Hot Springs (1 and 2) water samples using a mineral assemblage consisting of calcite, chalcedony, K-clinoptilolite, K-feldspar, Na-beidellite, and paragonite with three optimization parameters (mass of water, fugacity of CO_2 and temperature). GeoT was applied to these samples as described above and with a mineral assemblage consisting of albite-low, calcite, chalcedony, clinochlore, laumontite, microcline, Na-beidellite, and Na-montmorillonite. Both the RTEst and GeoT yielded the same value of 125 ºC as reservoir temperature.

RTEst was used with the Magic Hot Springs area samples using a local groundwater composition to optimize the mass of dilution water and solute concentrations along with two other optimization parameters - fugacity of CO_2 and temperature. A mineral assemblage consisting of chalcedony, dolomite, K-clinoptilolite, K-feldspar, and Mg-beidellite was used to make temperature determinations, yielding a calculated reservoir temperature of about 163 °C for this area (Table 1). Similar to the estimated degree of dilution derived from the chalcedony-enthalpy mixing model, the RTEst modeling indicates that the Magic Hot Springs geothermal water is diluted by 2 times with local groundwater. Using two different mineral assemblages, GeoT yields higher calculated temperatures: 194 ºC and a dilution factor of 3.2, when considering calcite, enstatite, microcline, Mg-montmorillonite, heulandite, low albite, and chalcedony; and 197 ºC and a dilution factor of 2.4 with calcite, clinochlore, microcline, quartz, kaolinite, low albite, and heulandite.

RTEst was applied to the Barron Hot Springs area samples using a mineral assemblage consisting of calcite, chalcedony, fluorite, K-clinoptilolite, K-feldspar, Na-beidellite. The reservoir temperature estimates with three optimization parameters (mass of water, fugacity of CO_2 and temperature) RTEst runs for hot springs and wells of this area resulted in lower reservoir temperatures, ranging from 79 ºC to 108 °C (Table 1). The RTEst results also indicated that the thermal water samples from this area have a negligible dilution, which could imply that the features in this area are taping water from a low-temperature re-equilibrated reservoir. In contrast, GeoT runs for the same samples, using a mineral assemblage of low albite, calcite, clinoclore, laumontite, microcline, Na-beidellite, Na-montmorillonite, and quartz resulted in higher reservoir temperatures (129-143 ºC) (Table 1) and a dilution factor ranging 1.2 - 1.9 (dilution factor = 1 for no dilution).

The chemical compositions of thermal waters from the northern (the Wardrop/Sheep/Wolf Hot Springs areas) and central-southern parts (Barron Hot Springs area) of the Camas Prairie (excluding Magic Hot Springs and the Elk Creek Hot Springs area, both of these areas also have different water compositions) have different water compositions which may indicate different hydrogeological and geochemical settings at depth. Geologically, the northern Camas Prairie basin reportedly has less basalt at depth, whereas the southern Camas Prairie basin is known to have more basalt layers (Glen et al., 2017). In general, both surface and subsurface waters of the Camas Prairie area flow from west to east towards the Big Wood River, and ultimately, to the Magic Hot Springs Reservoir (Wallace, 1972). Precipitation falling in the Soldier Mountains to the north provides the majority of recharge water to the Camas Prairie groundwater/geothermal systems. The thermal water that moves up along the range-forming faults near/along the northern boundary of the Prairie is significantly diluted with pristine water that several south flowing creeks from the mountains bring into the Prairie. On the other hand, the Mount Bennett Hills to the south offers only a minor recharge to the Camas Prairie. Unlike the northern part of the Prairie, the groundwater/geothermal aquifers in the southern parts of the Prairie are likely to have longer residence times (Wallace, 1972). Although a long residence time results in higher field temperatures [the highest temperature of 73 ºC in the area was recorded for Barron Hot Spring II (Mitchell, 1976), however, this feature is no longer active], it also helps re-equilibrate the thermal water at lower temperatures. Because of the structural and hydrogeological controls, the hot springs in the northern parts of the Camas Prairie are issuing diluted thermal waters whereas the sampling features in the southern part are likely issuing re-equilibrated water.

6. CONCLUSIONS

In this study, we combined geochemical and isotopic compositions of water samples from several hot springs and wells (with elevated temperatures) to identify and evaluate the potential geothermal areas in the Camas Prairie in Idaho. All known and accessible sampling features in the area were sampled over the three year period (2014-2016). Specifically, we identified four geothermally active areas in Camas Prairie area. These areas from east to west (and south) are the Magic Hot Springs area, the Elk Creek Hot Springs area, the Wardrop/Sheep/Wolf Hot Springs areas, and Barron Hot Springs area. Although the majority of all thermal features in Camas Prairie area produce Na-HCO_3 type water with likely meteoric origin, the water samples from the four potential geothermal areas can be characterized by their unique geochemical signatures. The Magic Hot Springs area (Magic Hot Springs RLW) water samples have relatively higher level of TDS and silica, near neutral pH, higher levels of Na, and HCO_3 with significant amount of Cl and SO_4. The Elk Creek Hot Springs issue alkaline (pH>9), high F (15 mg/L), Na-HCO_3 type waters with very low Mg but significant Cl and SO_4. The water samples of the Wardrop/Sheep/Wolf Hot Springs have high pH (9.0-9.9), relatively low level of TDS (220-350 mg/L), low concentrations of Ca and Mg, and intermediate concentration of F (1.9-3.7 mg/L). Finally, the Barron Hot Springs area water samples are near-neutral to slightly alkaline (pH 7.4-8.5) with slightly higher level of TDS (380-640 mg/L), low concentration of Mg, and moderately high concentrations of F (7-13 mg/L). The groundwater/cold springs water samples from this area are of mostly Ca-HCO_3 type water with near-neutral pH, low levels of F, Na, and wide range of Ca.

The δD and $\delta^{18}O$ values of the Camas Prairie area samples plot close to the local meteoric water line; however, a few samples have oxygen isotope composition shifted 1-3‰ to the right of the meteoric water line (such as, the Barron Well 1, Elk Creek Hot Spring 2, Magic Hot Springs RLW). These isotopic compositions, in general, indicate that the groundwater/hydrothermal waters in the area are of meteoric in origin. The He Rc/Ra values of some samples from this area are found to be elevated. For example, the Magic Hot Springs RLW and the Barron Well 1 have Rc/Ra values of 1.62 and 2.36, respectively, and these values may potentially indicate a magmatic component in these fluids that may contribute to elevated heat flow in the area. However, the Elk Creek Hot Springs and the Wardrop/Wolf Hot Springs samples show relatively lower (0.85 and 1.13-1.33, respectively) Rc/Ra values and potentially, an Idaho Batholith-type geothermal setting.

Solute geothermometry results indicate promising temperature estimates for the Magic Hot Springs area and Wardrop/Sheep/Wolf Hot Springs area where the temperature estimates could be as high (or higher than) as 160 ºC and 200 ºC, respectively. For the Elk Creek Hot Springs and Barron Hot Springs area, the upper temperature estimates are close to 140 ºC.

In general, our geochemical/isotopic study shows that the Camas Prairie area could potentially host resources with temperatures as high as 200 ºC. Our results suggest that the area might have two potential geothermal resource types: one associated with the Idaho Batholith to the north, and a second related to elevated heat flow associated with Quaternary volcanism and intrusions.

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