INL/CON-15-36826
PREPRINT

Potential Hydrothermal Resource Temperatures in the Eastern Snake River Plain, Idaho

41st Workshop on Geothermal Reservoir Engineering 2016

Ghanashayam Neupane, Earl D. Mattson,
Travis L. McLing
(Idaho National Laboratory)

Cody J. Cannon, Thomas R. Wood, Wade C. Worthing
(University of Idaho)

Trevor A. Atkinson
(Ormat Technologies, Inc.)

Patrick F. Dobson and Mark E. Conrad
(Lawrence Berkeley National Laboratory)

February 2016

PROCEEDINGS, 41st Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 22-24, 2016
SGP-TR-209

Potential Hydrothermal Resource Areas and Their Reservoir Temperatures in the Eastern Snake River Plain, Idaho

[1,2]Ghanashayam Neupane*, [1]Earl D. Mattson, [2,3]Cody J. Cannon, [4]Trevor A. Atkinson, [1,2]Travis L. McLing, [2,3]Thomas R. Wood, [2,3]Wade C. Worthing, [5]Patrick F. Dobson, and [5]Mark E. Conrad

[1]Idaho National Laboratory, Idaho Falls, ID 83415, USA

[2]Center for Advanced Energy Studies, Idaho Falls, ID 83401, USA

[3]University of Idaho-Idaho Falls, Idaho Falls, ID 83402, USA

[4]Ormat Technologies Inc., Reno, NV 89511, USA

[5]Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA

E-mail: Ghanashyam.Neupane@inl.gov

Keywords: Eastern Snake River Plain, ESRP, RTEst, geothermal, geothermometer

ABSTRACT

The Eastern Snake River Plain (ESRP) in southern Idaho is a region of high heat flow. Sustained volcanic activities in the wake of the passage of the Yellowstone Hotspot have turned this region into an area with great potential for geothermal resources as evidenced by numerous hot springs scattered along the margins of the plain and several hot-water producing wells and hot springs within the plain. Despite these thermal expressions, it is hypothesized that the pervasive presence of an overlying groundwater aquifer in the region effectively masks thermal signatures of deep-seated geothermal resources. The dilution of deeper thermal water and re-equilibration at lower temperature are significant challenges for the evaluation of potential resource areas in the ESRP. Over the past several years, we collected approximately 100 water samples from springs/wells for chemical analysis as well as assembled existing water chemistry data from the literature. We applied several geothermometric and geochemical modeling tools to these chemical compositions of ESRP water samples. Geothermometric calculations based on principles of multicomponent equilibrium geothermometry with inverse geochemical modeling capability (e.g., Reservoir Temperature Estimator, RTEst) have been useful for evaluating reservoir temperatures, and have indicated numerous potential moderate to high temperature geothermal prospects in the ESRP. Specifically, areas around southern/southwestern side of the Mount Bennett Hills and within the Camas Prairie in the western-northwestern regions of the ESRP and its margins suggest temperatures in the range of 140-200°C. In the northeastern portions of the ESRP, Lidy Hot Springs, Ashton, Newdale, and areas east of Idaho Falls have expected reservoir temperatures ≥140 °C. In the southern ERSP, areas near Buhl and Twin Falls are found to have temperatures as high as 160 °C. These areas are likely to host potentially economic geothermal resources; however, further detailed study is warranted at each site to evaluate hydrothermal suitability for economic use.

1. INTRODUCTION

The eastern Snake River Plain (ESRP) in southeastern Idaho is a region of high heat flow with great potential for significant geothermal resources (Figure 1). A limited number of deep wells (such as INEL-1) and several hot springs and wells along the margin of ESRP also provide direct evidence of a high-temperature regime at depth in the area. However, most of the shallow wells within the ESRP generally have low field-measured temperature, and it is likely that the Eastern Snake River Plain Aquifer (ESRPA) is obscuring geothermal signature from depth. The ESRPA is a prolific aquifer hosted in a thick sequence of thin-layered, highly transmissive basalt flows. The aquifer rapidly transports cold water from the Yellowstone Plateau and surrounding mountain basins to springs along the Snake River Canyon west of Twin Falls, Idaho. The flush of cold water through the overlying ESRPA masks the geothermal signature of the heat existing at depth (e.g., Smith, 2004). Importantly, the geothermal gradient below the ESRP aquifer system increases rapidly (Blackwell, 1989; McLing et al., 2002; Nielson et al., 2012) providing additional evidence of the presence of a deep geothermal resource in the area.

Previously, we made an initial geothermometric assessment of the ESRP using limited water chemistry dataset (Neupane et al., 2014; Cannon et al., 2014). We followed on that work by collecting several new water samples from numerous geothermal features in the ESRP and surrounding areas. In this paper, we provide geothermometric assessment of some potential geothermal resource areas in the ESRP. Specifically, we present geothermometric temperatures of geothermal areas distributed around southern/southwestern side of the Mount Bennett Hills, Camas Prairie, Lidy Hot Springs, Ashton area, Newdale area, and areas east of Idaho Falls. Similarly, we also present geothermometric results of geothermal areas around Buhl and Twin Falls area in the southern ESRP. The reservoir temperatures of these geothermal sites were estimated with traditional (e.g., Fournier, 1977) as well as a multicomponent geothermometry tool [e.g., Reservoir Temperature Estimator (RTEst) (Palmer et al., 2014; Mattson et al., 2015)] based on the chemical composition of thermal water samples.

2. GEOLOGIC AND GEOTHERMAL SETTING OF EASTERN SNAKE RIVER PLAIN

The Snake River Plain (SRP) is a topographic depression along the Snake River (Figure 1) in southern Idaho. The SRP is divided into two parts, the western Snake River Plain (WSRP) and the ESRP. The WSRP is a basalt- and sediment-filled tectonic feature defined by a normal fault-bounded graben whereas the ESRP is formed by crustal down-warping, faulting, and successive caldera formation that is linked to the middle Miocene to Recent volcanic activities associated with the relative movement of the Yellowstone Hot Spot (Figure 1) (Pierce and Morgan, 1992; Hughes et al., 1999; Rodgers et al., 2002). The 100 km wide ESRP extends over 600 km (Hughes et al., 1999). Four events in the late Tertiary are important for creation and shaping the ESRP (Hughes et al., 1999): (1) successive Miocene-Pliocene rhyolitic volcanic eruptive centers from southwest near the common border of Idaho, Oregon, and Nevada trending northeast to Yellowstone National Park in northwest Wyoming, (2) Miocene to Holocene crustal extension which produced the Basin and Range province, (3) Quaternary basaltic flows, and (4) Quaternary glaciation and associated eolian, fluvial, and lacustrine sedimentation and catastrophic flooding.

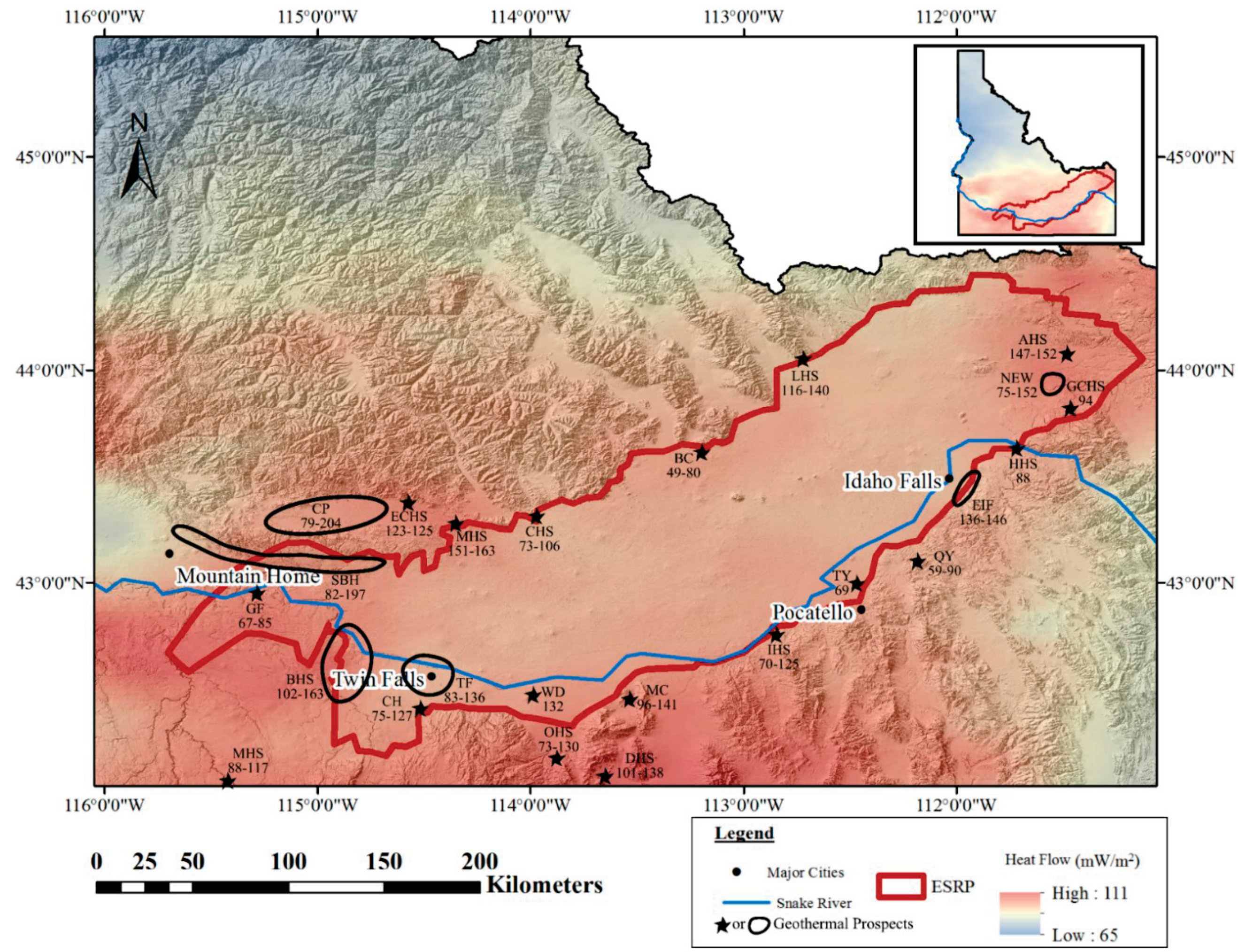

Figure 1. Map of the southern Idaho was prepared by draping heat flow map (Williams and DeAngelo, 2011) over DEM. The thick red line demarcates the margins of the ESRP from the surrounding Basin and Range province. Stars and polygons represent geothermal prospects (codenames are given in Table 1) in and around ESRP. The number or range of numbers associated with each geothermal prospect is the RTEst estimated reservoir temperature (ºC).

The ESRP consists of thick volcanic ash-flow tuffs, which are overlain by >1 km of Quaternary basaltic flows (Figure 2). The felsic volcanic rocks at depth are the product of super volcanic eruptions associated with the Yellowstone Hotspot. These rocks progressively become younger to the northeast towards the Yellowstone Plateau (Pierce and Morgan, 1992; Hughes et al., 1999). The younger basalt layers are the result of several low-volume, monogenetic shield-forming eruptions of short-duration that emanated from northwest trending volcanic rifts in the wake of the Yellowstone Hot Spot (Hughes et al., 1999). The thick sequences of coalescing basalt flows with interlayered fluvial and eolian sediments in the ESRP constitute a very productive cold water aquifer system above the volcanic ash-flow tuffs (Whitehead, 1992).

Recent volcanic activity, a high heat flux [~110 mW/m^2 (Blackwell, 1989; Smith, 2004)], and the occurrence of numerous peripheral hot springs suggest the presence of undiscovered geothermal resources in the ESRP. As a consequence of these geologic indicators, we hypothesize that the ESRP at depth hosts a large geothermal resource with the potential for one or more viable conventional or enhanced geothermal reservoirs. In particular, we consider the lower welded rhyolite ash-flow tuff zone (Figure 2) to have exploitable heat sources that can be tapped by EGS development.

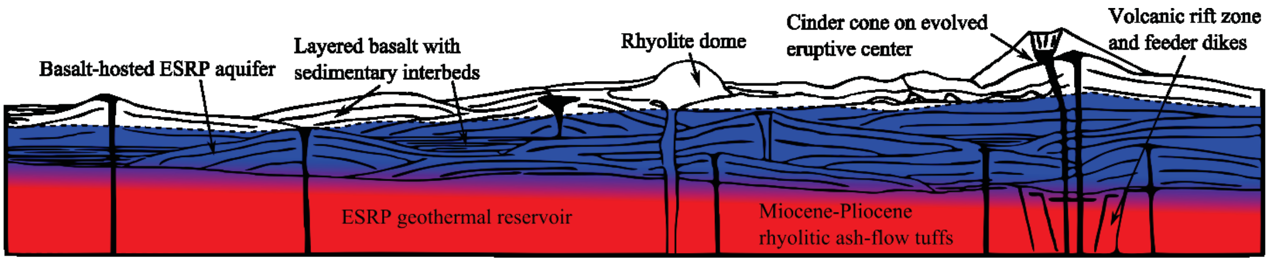

Figure 2. Schematic cross-section across the ESRP (modified from Hughes et al., 1999; Neupane et al., 2014) showing underlying rhyolitic ash-flow tuffs and overlying basalt flows with few sedimentary layers. The underlying rhyolite ash-flow tuffs are assumed to be the ESRP geothermal resource. Small amount of thermal waters are considered to be upwelling from underlying reservoir into the overlying basalt-hosted ESRP aquifer system. The presence of very productive, cold groundwater aquifer system is regarded to mask the underlying geothermal regime in the ESRP.

The ESRP system as a whole (including the deep geothermal reservoir and the overlying cold-water aquifer system) is an open and dynamic hydrogeologic system. Most water from shallow wells and springs in the ESRP are mixed waters of multiple sources, particularly a mix of meteoric water and deep-sourced reservoir water (McLing et al., 2002; Smith, 2004; Welhan, 2015). The upwelling thermal waters interact with the basalt at the base of the regionally extensive cold water aquifer (Morse and McCurry, 2002), with the altered basalt forming a permeability barrier: this helps mask the expression of the deep thermal resource (Figure 2).

3. GEOTHERMOMETRY

One of the tools used to prospect for geothermal resources is geothermometry, which uses the chemical compositions of water from springs and wells to estimate reservoir temperature. 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 that exhibit some level of elevated temperatures are needed. The application of geothermometry requires several assumptions. The most important assumptions are that the reservoir minerals and fluid attain a chemical equilibrium and as the water moves from the reservoir to sampled location, it retains its chemical composition (Fournier et al., 1974). The first assumption is generally valid (provided a long residence time); however, the second assumption is more likely to be violated because of composition altering processes, such as, re-equilibration at lower temperature, dilution (mixing), and loss of fluids (boiling) and volatiles (e.g., CO_2) with the decrease in pressure.

Traditional geothermometers such as silica geothermometers, Na/K geothermometer, etc., are empirical to semi-empirical approaches where a user enters the measured concentration of certain component(s) into the geothermometer equation. The reliability, sensitivity, and responsiveness of traditional geothermometers to various composition altering processes vary. For example, geothermometers based on cation concentration ratios (e.g., Na/K geothermometer) are minimally sensitive to boiling or mixing with dilute water; while geothermometers based directly on the concentration of component(s) (e.g., quartz geothermometer) are highly sensitive to these processes (D'Amore and Arnórsson, 2000)). A drawback of many existing geothermometry approaches is that they do not adequately account for physical processes (e.g., mixing, boiling) and geochemical processes (e.g., mineral dissolution, precipitation, degassing) that may occur after the water leaves the reservoir and thereby alters its composition. If these changes are not taken into account, predictions of in-situ reservoir conditions (e.g., temperature, fCO_2) based on the chemical composition of water samples taken from shallower depths or at the surface may be erroneous, or too imprecise to be useful.

In addition, it is difficult to quantify uncertainties associated with temperatures estimated with these geothermometers. As a result, it is not uncommon to find diverse temperature estimates for the same water using multiple traditional geothermometers. Nevertheless, because these geothermometers are easy to use and sometimes provide good results, they are considered to be an essential part of the geothermal exploration toolkit (D'Amore and Arnórsson, 2000).

A more advanced geothermometric approach is multicomponent equilibrium geothermometry (MEG). The MEG approach of geothermometry utilizes multiple chemical constituents measured in water samples for inverse geochemical modeling considering a suite of selected minerals (selected based on some knowledge of the system) so as to provide more robust temperature estimates with quantifiable uncertainties. Geothermal temperature predictions using MEG provide apparent improvement in reliability and predictability of temperature over traditional geothermometers. The basic concept of this method was developed in 1980s (e.g., Michard and Roekens, 1983; Reed and Spycher, 1984). Some previous investigators (e.g., D'Amore et al., 1987; Hull et al., 1987; Tole et al., 1993) have used this technique for predicting reservoir temperatures in various geothermal sites. Other researchers have used the basic principles of this method for reconstructing the composition of geothermal fluids and formation brines (Pang and Reed, 1998; Palandri and Reed, 2001). More recent efforts by some researchers (e.g., Bethke, 2008; Spycher et al., 2011; Smith et al., 2012; Cooper et al., 2013; Neupane et al., 2013, 2014; Cannon et al., 2014; Spycher et al., 2014; Peiffer et al., 2014; Palmer et al., 2014; Neupane et al., 2015a,b,c; Mattson et al., 2015; Neupane et al., 2016a,b) have been focused on improving temperature predictability of the MEG.

For this study, both traditional [e.g., quartz (no steam loss) (Fournier, 1977), chalcedony (Fournier, 1977), and Na-K-Ca (Truesdell and Fournier, 1973; Fournier and Potter, 1979)] and RTEst (Palmer et al., 2014; Mattson et al., 2015) geothermometric approaches were applied to estimate reservoir temperatures. For the silica geothermometers, pH correction on silica concentrations was not applied. While applying RTEst to each water sample, a mineral assemblage consisting of 5-7 representative minerals (Mg bearing minerals – clinochlore, illite, saponite, beidellite, talc; Na bearing minerals – paragonite, saponite; K-bearing minerals – K-feldspar, clinoptilolite-

K, illite; Ca bearing minerals – calcite; fluorite, and chalcedony) was used for the development of the reservoir temperature estimate for each sample. For each site, the same mineral assemblage was used for all samples using the same thermodynamic database (e.g., LNNL database based thermo.dat database of Geochemist's Workbench). In general, the mineral assemblage is selected based on available information such as water chemistry (e.g., pH), likely reservoir rock types and temperature range, etc. For more detailed information on selection of the mineral assemblage, see Palmer et al. (2014).

4. WATER SAMPLES

4.1 New data

As a major part of this work, we initiated a sampling campaign during the spring and summer of 2014 and 2015 (Cannon et al., 2014; Dobson et al., 2015; Neupane et al., 2015c). The sampling campaign was aimed at collecting samples from thermal features that either have incomplete available data or were not sampled/analyzed previously. Our goal was to develop an extensive thermal expression chemistry data set to be used for geothermometry calculations using RTEst as well as for analyzing for other trace elements, isotopes, and noble gases. Over the course of the project period, we collected and analyzed over 90 samples from thermal features in the ESRP and surrounding area. The water chemistry data will be available from the National Geothermal Data System (NGDS) web portal.

4.2 Historical data

Existing southeast Idaho water composition data have been obtained from the Idaho Department of Water Resources, literature searches from the Web of Science, and examining dissertations at the University of Idaho. Existing water composition data were evaluated for their quality (e.g., charge balance, etc.) and completeness (except Al) for MEG. Almost all of the historical data lacked measured concentration of Al, and for these samples, a value determined by assuming equilibrium with K-feldspar (Pang and Reed, 1998) was used in the geochemical modeling. In some instances, the Al values measured in new samples collected from nearby hot springs or hot wells were used.

Existing data and new chemical data were used for the estimation of reservoir temperatures with traditional geothermometers as well as with RTEst. In the past, we used historical data for preliminary evaluation of geothermal resources along the margins of the ESRP (e.g., Neupane et al., 2014). Some of the geothermal features with available good quality and complete geochemical data were also sampled during our sampling campaigns, and for most of these features, the existing data were found to be similar to the new chemical data.

4.3 Hot springs and nearby hot wells

Both compositions of water samples collected from hot springs as well as shallow hot wells were used with equal importance for the temperature estimation of several geothermal prospects in ESRP. It is generally assumed that the geothermal system manifest some kind of surface signals such as hot springs or fumaroles, however, there have been some hidden or blind geothermal systems. For example, the Raft River geothermal system was identified when shallow (120-150 m deep) wells that were drilled for domestic and stock use encountered boiling water (Williams et al., 1976). Similarly, in the ESRP, the Newdale prospect (NEW in Figure 1) was first identified by the presence of numerous hot shallow wells in the area. However, how useful hot shallow waters can be for geothermometric calculations in the southern Idaho was an issue for us when we started this work. Recently, we compared the temperature estimates of hot springs and nearby wells in southern Idaho (Neupane et al., 2015c). That study indicated that that the reservoir temperatures estimated using water compositions measured from surface thermal features and wells produce similar results. However, there are a few systems where the estimated reservoir temperatures based on water compositions measured from hot springs and hot wells are different. Neupane et al. (2015c) emphasized that when such differences exist, it is imperative to consider the consistency of the water types and distance between the sources when estimating reservoir temperatures. With the exception of the Durfee Hot Spring prospect [the same system was also noted by Neupane et al. (2015c) as one of two systems examined in southern Idaho that have divergent temperature estimates with hot spring and hot well compositions] (DHS in Figure 1), all other prospects with measured compositions from samples collected from hot springs and hot wells in the ESRP yielded similar results (see section 5).

4.4 Geothermal prospects

Based on the distribution of samples, 24 geothermal prospects are identified (Figures 1, 3, and Table 1). The number of samples in each prospect (Table 1) vary such that some prospects have multiple samples (e.g., Banbury Hot Springs prospect has 37 samples) from different sources where as some prospects have few number of samples (e.g., Wybenga Diary prospect has only one sample). Much more detailed descriptions of these prospects are forthcoming.

5. RESULTS

5.1 Water chemistry

Compositions of waters from hot/warm springs and wells in southeastern Idaho are presented in Figure 3. All springs/wells (with few exceptions such as Spackman well in Newdale prospect) that we sampled represent the expression of geothermal activities (field T >20 ºC) in the ESRP. The highest field temperature within and along the margins of ESRP was recorded at the Magic Hot Spring Landing well (75 °C) in Magic Hot Spring prospect (MHS in Figure 1). The pH of ESRP thermal waters ranges from 6.3 to 9.6. These thermal waters show a large range in total dissolved solids (TDS) from about 106 mg/L (Sturm well in Ashton prospect, AHS in Figure 1) to more than 7,000 mg/L (Heise Hot Spring, HHS in Figure 1).

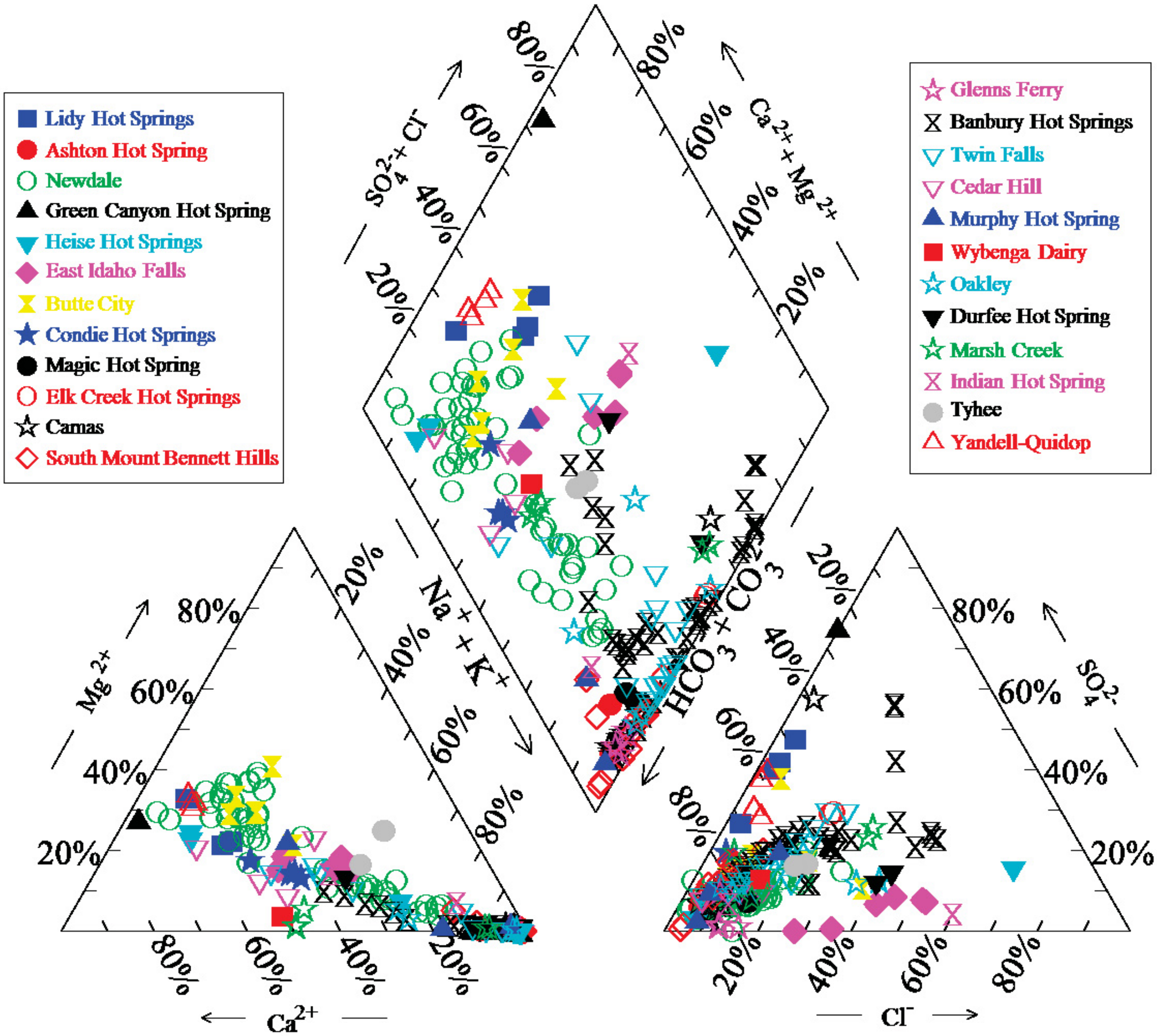

Figure 3. Chemistry of the ESRP thermal water samples shown on Piper diagram

Based on the dominant ions (Figure 3**Error! Reference source not found.**) in water, ESRP waters can be grouped into 10 water types. These are Ca-HCO_3, Mg-HCO_3, Ca-Mg-HCO_3, Na-HCO_3, Ca-SO_4, Na-SO_4, Na-Cl, Na-K-HCO_3, Na-K-Cl-SO_4, and Ca-Na-HCO_3 type waters. In general, ESRP waters have either Ca-Mg or Na as the dominant cations and HCO_3 as the dominant anion. The ESRP waters with dominant HCO_3 may have been the product of carbonated water-rock interaction at low to high temperatures. Specifically, Na-HCO_3 waters are considered deeper ESRP water whereas Ca-Mg-HCO_3 water are shallower ESRPA water. The few water samples (e.g., Heise Hot Spring, Green Canyon Hot Spring, etc.) with Cl and/or SO_4 as dominant anions may have originated with water-rock interaction involving Paleozoic evaporite beds.

5.2 Geothermometric assessments

5.2.1 Giggenbach diagram

The sample compositions are also plotted on a Giggenbach ternary diagram (Giggenbach, 1988) to determine evidence of equilibration and/or mixing (**Error! Reference source not found.**) as well as to illustrate the likely water-rock interaction temperatures in the reservoirs. This plot is useful to classify waters into fully equilibrated waters, partially equilibrated, and immature waters. The diagram uses the full range of equilibrium relationships between Na, K, and Mg to determine the degree of equilibration between the water and the rock at depth. The plot suggests that the waters from several ESRP wells and springs are partially equilibrated that may have interacted with the reservoir rocks at temperatures ranging from 100 °C to 180 °C. However, majority of the ESRP waters are immature waters, as indicated by elevated Mg contents. The immature waters may indicate significant mixing with cool meteoric waters, and traditional geothermometers may not be suitable tools for temperature estimation for these waters.

5.2.2 Temperature estimates with traditional geothermometers

Traditional geothermometers were applied to measured water compositions for general assessment of the geothermal temperature at each sampling site. There have been several established empirical/semi-empirical geothermometers based on the relationship between concentrations (or concentration ratios) of chemical components with temperature. Even though majority of these geothermometers are based on empirically fitted curves, there have been some postulated geochemical basis (assumptions) supporting these relationships. For example, silica geothermometers are based on solubility of solid-phase silica (e.g., quartz, chalcedony, etc.) controlling the aqueous concentration of silica. Similarly, several variations of sodium-potassium geothermometers are based on water-rock interaction involving albite and K-feldspar. Similarly, the sensitivity and responsiveness of geothermometers to various composition-altering processes are not similar. For example, geothermometers based on cation concentration ratios are not sensitive to boiling or mixing with dilute water; however, geothermometers based directly on the concentration of component(s) show large temperature sensitivity to these processes. In practice, it is not uncommon to find diverse temperature estimates for the same water with multiple traditional geothermometers. Therefore, whenever the assumptions on which a geothermometer is based on are not satisfied, temperature estimates with it are likely to be erroneous.

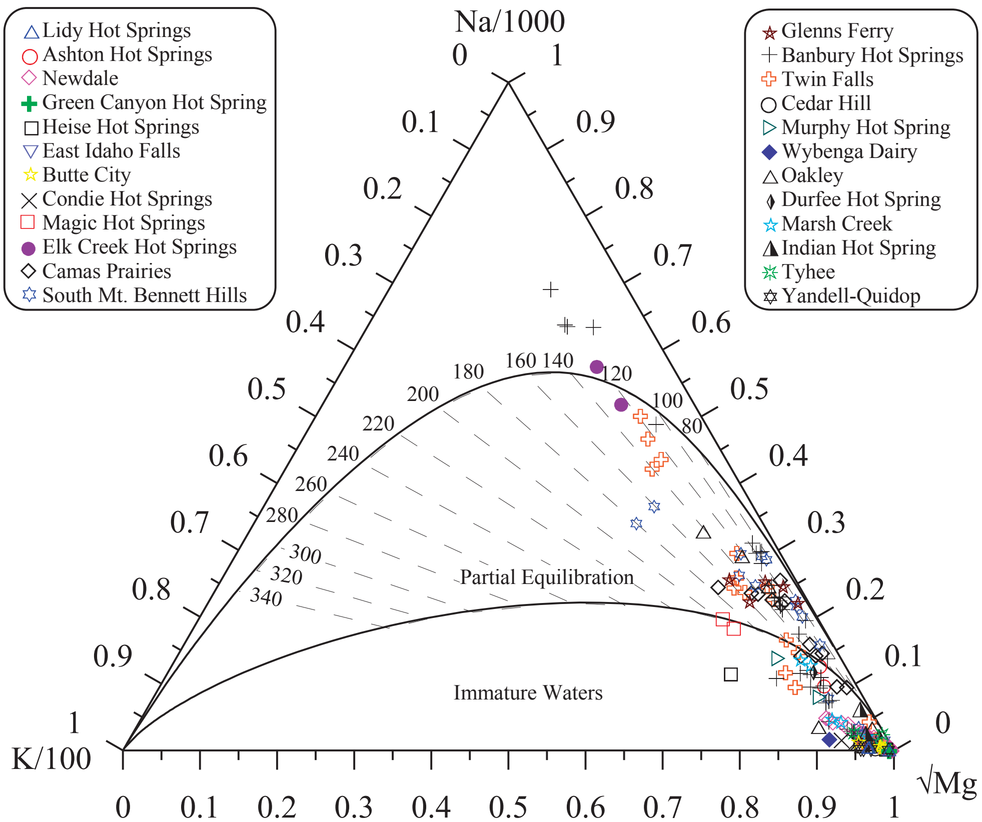

Figure 4. Giggenbach ternary diagram for the ESRP thermal water samples

For the ESRP, the traditional geothermometer-based temperatures can be difficult to use to assess the geothermal potential of prospects. For example, estimated temperature values for the Heise Hot Spring, range from 53 °C using chalcedony to 243 °C using Na/K ratios. Nevertheless, for some samples from other prospects, such as a well at the College of Southern Idaho (CSI Well2) representing the Twin Falls geothermal prospect, the range of estimated temperatures is from 85 °C to 140 °C suggesting relatively good agreement between the traditional geothermometry temperature estimates. In general, we have found that ESRP thermal estimated temperatures using the Na/K rations are higher than estimated temperatures obtained with other geothermometers.

5.2.3 Temperature estimates with RTEst

All water samples collected during the sampling campaigns of 2014 and 2015 as well as useful water compositions assembled from literature for this study were used for the temperature estimation with RTEst. For each sample, 5-7 minerals (consisting mainly of silica-polymorphs, clays, zeolites, carbonates, sulfates, feldspars, etc.) were selected as a mineral assemblage.

An example of the RTEst results for a water sample collected from Miracle Hot Spring well located in Banbury Hot Springs prospect (BHS in Figure 1) is shown in 5a shows log Q/K_T curves of the reservoir mineral assemblage (calcite, chalcedony, beidellite, mordenite, and paragonite) used for the Miracle Hot Spring water composition. The log Q/K_T curves of these minerals intersect the log $Q/K_T = 0$ at a wide range of temperatures, making the log Q/K_T curves derived from the reported water chemistry minimally useful for estimating temperature. The range of equilibration temperature for the assemblage minerals is a reflection of physical and chemical processes that may have modified the Miracle Hot Spring water composition during its ascent to the sampling point.

To account for possible composition altering processes, RTEst was used to simultaneously estimate a reservoir temperature and optimize the amount of dilute near-surface H_2O mixed with the thermal water (a physical process) and the fugacity of CO_2 change (a chemical process) that may have occurred during its accent to the surface. Using these two additional optimization parameters, the results for the corrected fluid composition of Miracle Hot Spring are shown in Figure 5b. Compared to the log Q/KT curves calculated using the reported water compositions (Figure 5a), the optimized curves (Figure 5b) converge to log Q/KT = 0 within a narrow temperature range (i.e., 161±3 ºC).

The optimized temperatures and composition parameters for the other ESRP waters were estimated using RTEst in the same manner. The RTEst estimated temperatures for the ESRP geothermal samples range from about 60 ºC to 204 ºC. The hottest reservoir temperature estimate is obtained for Wardrop Hot Spring located in north-central part of Camas Prairie (CP in Figure 1). Similarly, hot springs located on the southern side of the Mount Bennett Hills (e.g., Prince Albert Hot Spring, Latty Hot Spring) (SBH in Figure 1) also have reservoir temperature estimates as high as 200 ºC.

Table 1. Estimated temperatures (ºC) for several geothermal prospects in the ESRP

Prospects	Measured[a]	RTEst[b]	Quartz (nsl)[c]	Chalcedony[d]	Na-K-Ca[e]	Map Code[f]
Lidy Hot Springs (4)[g]	56	116-140	57-89	25-58	44-65	LHS
Ashton Hot Spring (2)	63	147-152	113-143	84-116	109-117	AHS
Newdale (50)	87	75-152	66-134	26-112	29-111	NEW
Green Canyon Hot Spring (1)	44	94	75	44	65	GCHS
Heise Hot Spring (1)	48	88	84	53	89	HHS
East Idaho Falls (6)	28	136-146	115-143	86-117	45-74	EIF
Butte City (6)	41	49-80	70-106	38-77	37-43	BC
Condie Hot Spring (4)	51	73-106	71-82	40-51	71-83	CHS
Magic Hot Spring (2)[h]	75	151-163	139-142	113-116	143-149	MHS
Elk Creek Hot Springs (2)	56	123-125	114-115	86	107-110	ECHS
Camas Prairie (13)	73	79-204	103-128	74-100	70-124	CP
South Mount Bennett Hills (13)	68	82-197	110-143	80-117	72-160	SBH
Glenns Ferry (5)	39	67-85	80-109	48-79	74-138	GF
Banbury Hot Springs (37)	72	102-163	98-139	67-127	69-165	BHS
Twin Falls (21)	43	83-136	77-119	45-91	70-132	TF
Cedar Hill (4)	38	75-127	62-116	29-87	50-129	CH
Murphy Hot Spring (3)	55	88-117	119-148	90-122	57-144	MHS
Oakley Hot Spring (5)	47	73-130	77-125	45-97	82-155	OHS
Durfee Hot Spring (2)	45	101-138	96-117	66-88	46-131	DHS
Marsh Creek (5)	60	96-141	96-113	66-83	128-134	MC
Wybenga Dairy (1)	34	132	118	89	189	WD
Indian Hot Spring (2)	39	70-125	64-110	32-80	60-64	IHS
Tyhee (3)	41	69	63-93	31-62	52	TY
Quidop-Yandell (4)	38	59-90	55-63	23-31	43-63	QY

[a]Maximum measured temperature for the prospects; [b] RTEst estimated temperature range; [c]quartz (no steam loss) geothermometer temperature (Fournier, 1977); [d] chalcedony geothermometer temperature (Fournier, 1977); [e] Mg-corrected (where applicable) Na-K-Ca geothermometer temperature (Truesdell and Fournier, 1973; Fournier and Potter, 1979); [f]these map codes are used to represent geothermal prospects in Figure 1; [g]number of samples representing the prospect; [h]both samples represent the same well, one sample was collected directly from the well leak whereas other sample was collected from the runoff channel.

5.3 Geothermal prospects and their reservoir temperatures

Table 1 summarizes likely reservoir temperature range for all geothermal prospects within and along the margins of the ESRP identified in this study. The RTEst estimated temperature range for each prospect is also given in Figure 1. Some of the hottest prospects in the ESRP region are Lidy Hot Springs (LHS), Magic Hot Spring (MHS), Camas Prairie (CP), south of Mount Bennett Hills (SBH), Banbury Hot Springs (BHS), east Idaho Falls (EIF), Newdale (NEW), and Ashton Hot Spring (AHS) (Figure 1). The geothermal potential of some of these prospects are also identified by the first phase of the SRP Play Fairway analysis (Shervais et al., 2015). Below we provide brief summaries for some of the promising geothermal prospects in the ESRP region.

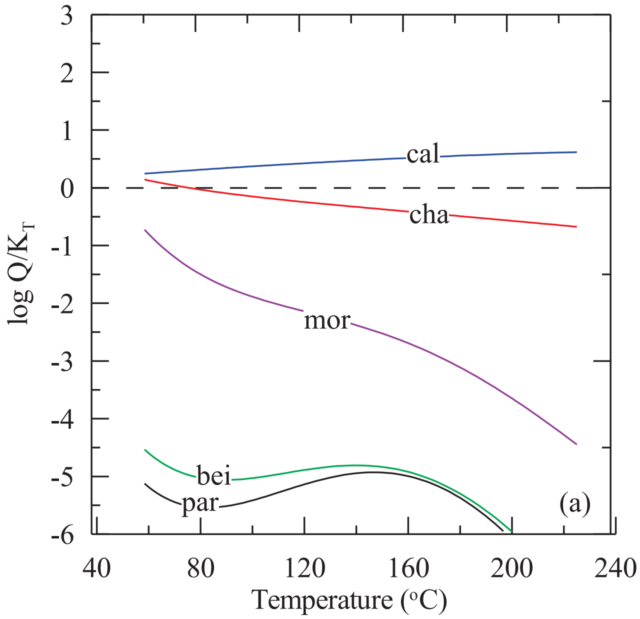

Figure 5. Graphical representation of RTEst analysis of Miracle Hot Spring well located in the Banbury Hot Springs prospect (see Figure 1). a) log Q/KT plot for assemblage minerals using observed fluid composition, b) log Q/KT plot for assemblage minerals using RTEst optimized fluid composition. In this diagram, FT is field temperature, ET is estimated temperature, and the horizontal solid bar underneath ET represents two-standard error in estimated temperature. Mineral assemblage includes: bei: beidellite-Mg, cal: calcite, cha: chalcedony, mor: mordenite-Na, and par: paragonite.

5.3.1 Lidy Hot Springs

The Lidy Hot Springs prospect (LHS in Figure 1) is located at the southeastern end of the Beaverhead Mountains in Clark County in Idaho. Form the early 20th century, the area was gradually developed into a commercial recreation site that provided services such as swimming, soaking, dancing, dining, and lodging to public. However, with the transfer of ownership in the early 1960s, the site ceased to offer those recreational services, and started a travertine mining activity. Two hot springs in the area are still issuing thermal water (52-56 °C). Similarly, in the vicinity of the Lidy Hot Springs, there are other springs (e.g., Warm Spring (29 °C)) issuing warm to cooler waters.

Rocks underlying the Lidy Hot Springs area consist of young volcanics and older meta-sedimentary rocks (Link, 2002). The younger rocks (Upper Miocene and Pliocene) consist of fluvial and lacustrine deposits, felsic volcanic rocks, rhyolite flows, tuffs, ignimbrites. Thick sequences of Paleozoic sedimentary rocks (Pz) underlie the Tertiary rock types, and likely constitute the geothermal reservoir in the area.

The RTEst estimated reservoir temperature for the Lidy Hot Springs prospect is about 140 °C (Table 1). RTEst modeling result shows that the Lidy Hot Springs water may contain up to 60% cooler water and 40% deeper thermal water. Similarly, no-steam loss silica-enthalpy mixing model with the quartz solubility curve (Fournier, 1977; Fournier and Porter, 1982) yields a reservoir temperature of about 130°C. However, silica-enthalpy mixing model with the chalcedony solubility curve (modified from Fournier, 1977; Fournier and Porter, 1982) yields a rather cooler temperature (about 60 °C).

5.3.2 Ashton Hot Spring

The Ashton Hot Spring and associated geothermal area (AHS in Figure 1) is located at northern side of Ashton in Fremont County in Idaho. The existence of Ashton Hot Spring with a surface water temperature of 41 °C was previously reported by Mitchell et al. (1980). A 1220 m deep geothermal exploratory well (Sturm Well-1) was drilled about 2 km NE from the Ashton Hot Spring in 1979 (Occidental Geothermal Inc., 1979). Driller's records indicate a bottom-hole temperature of about 63 °C.

Geologic mapping of the area shows thin layers of Quaternary sediments covering underlying volcanic rocks (Link, 2002). Borehole records from the area reveal presence of thick sequences of flood basalts and felsic volcanics. Specifically, along the Sturm Well-1, the Quaternary sediments near surface are followed by layers of flood basalts (up to a depth of 82 m), felsic volcanics (82-808 m), and again flood basalts (808 -1220+ m) with depth (Occidental Geothermal Inc., 1979).

Quartz and chalcedony geothermometers yielded reservoir temperatures of 143 °C and 116 °C for Ashton Hot Spring and 113 °C and 84 °C for the Sturm Well, respectively. For these two sampled features, Na-K-Ca geothermometer resulted in 117 °C and 109 °C, respectively. Similarly, the RTEst produced reservoir temperatures for the Sturm Well and Ashton Hot Spring are 152±14 °C and 147±5°C, with nearly 70% and 35% admixing of cooler water, respectively. All of these temperatures are significantly higher than the bottom hole temperature measured for the Sturm Well (66 ºC). Given the measured temperature gradient (48 ºC/km, Blackwell, 1989), such temperature conditions might be found at depths of about 3 km.

5.3.3 Newdale area

The Newdale geothermal prospect (NEW in Figure 1) in Madison and Fremont Counties in Idaho represents a blind geothermal system, as it has no hot springs. The geothermal potential of Newdale area was identified in late 1970s by several researchers (e.g., Brott et al., 1976), based on the discovery of relatively high heat flow (167 mW/m^2). The area from Newdale town to NE across the Teton River has been considered as a potential area for geothermal energy (Brott et al., 1976, GeothermEx, 2010; Neupane et al., 2016b)). During 1979-1981, Union Oil of California (Unocal) drilled several geothermal test wells in the area ranging in depth from 183 m (Newdale No. 79-3) to 1204 m (Madison Geothermal No.1 near Rexburg, ID). The highest recorded temperature in the Unocal wells was 87.2 °C (Well # State 2591-07-79-1).

Surficial geologic map of this area shows presence of Quaternary sediments, Quaternary flood basalts, and Quaternary felsic volcanic rocks (Bond, 1978; Link, 2002; Embree et al., 2011). Early Pleistocene flood basalts are mapped around the town of Newdale whereas felsic volcanic rocks of similar ages (Huckleberry Ridge Tuff) are mapped NE from Newdale. In geologic cross-section, Embree et al. (2011) show Huckleberry Ridge Tuff lying underneath the Early Pleistocene basalt at Newdale. Below the Huckleberry Ridge Tuff lie the Tertiary sediments intercalated with Tertiary basalt. Subsurface lithologic records of numerous wells in the area as compiled by Idaho Geological Survey indicate the presence of thick sequences of rhyolites and tuff at greater depths.

Quartz, chalcedony, and Na-K-Ca (Mg corrected) geothermometers resulted reservoir temperatures in the range of 66-134 °C, 28-112 °C, 29-111 °C, respectively. A silica (chalcedony)-enthalpy mixing model using all Newdale area samples results in reservoir temperature of about 174 °C. Similar mixing models using quartz solubility results in even higher temperature estimates (224 °C). The RTEst temperature estimates for the Newdale area samples range 75-152 ºC (Table 1). The lower end RTEst temperature estimates of this area are similar to the bottom hole temperatures (83-87 °C) measured at two relatively deeper (~1000 m) Unocal wells. Moreover, it is likely that the area hosts even higher temperatures at greater depths that would correspond to the higher end RTEst temperatures. Assuming an 80 °C thermal gradient (as indicated by two Unocal wells), the higher end RTEst temperatures would be present at about 2 km below ground surface.

5.3.4 East Idaho Falls area

The foothills (1480-1580 m above sea level) along the margins of the ESRP east of Idaho Falls (EIF in Figure 1) in Bonneville County have been known to have some wells producing warm water. The geothermal potential of the area was initially reported by Ralston et al. (1981). Specifically, they reported the existence of two wells in Rim Rock Estate that produce ≥20 °C water. Recently drilled shallow (depth up to 244 m) wells in the Comore Loma and Blackhawk communities few kilometers south from Rim Rock Estate also produce warm (21-28 °C) water.

The area lies on the edge of the SRP where pronounced volcanism has taken place throughout the past 6.5 Ma. The foothills to the east of Idaho Falls consist predominantly of tuffs, ignimbrites, and ash flows related to the Miocene-Pliocene Heise volcanic field (Morgan and McIntosh, 2005). Although all shallow wells in the area bottomed out within the volcanic rocks, the volcanic rocks in the area are thought to be about 300 m in thickness. Mesozoic sedimentary rocks that include the limestones, sandstones, siltstones, conglomerates, and evaporite beds underneath the young volcanic rocks are assumed to be the geothermal reservoir in this area.

Quartz, chalcedony, and Na-K-Ca temperature estimates for east Idaho Falls area range from 115-143 °C, 86-117 °C, and 45-74 °C, respectively. The Mg-corrected Na-K-Ca temperature estimates for these samples are lower because of the presence of high concentrations of Mg. The RTEst temperature estimates of east Idaho Falls water samples are very similar with a range from 136-143 °C (Table 1).

5.3.5 Magic Hot Spring

The Magic Hot Spring prospect (MHS in Figure 1) is located on the northern margin of the ESRP in Camas and Blaine Counties in Idaho. Until a 79 m deep well (Magic Reservoir landing well) was drilled for direct use purposes in 1965, the hot spring issued 36°C water (Ross, 1970). However, with the operation of the well, the hot spring dried out (Mitchell, 1976). At the beginning, the well was producing water at 66°C, however, the water temperature subsequently increased to 74 °C by 1975 (Mitchell, 1976; Mitchell et al., 1980). The most recent (2014) temperature record for the surface discharge of the well is 75 °C.

The Magic Hot Spring area consists predominantly of Miocene-Quaternary silicic volcanic rocks and basalt flows (Struhsacker et al., 1982). The Pliocene-Miocene Poison Creek Tuff is the uppermost unit in the immediate vicinity of Magic Reservoir and is underlain by the Miocene Tuff of the Idavada Group. Other rhyolites and basalt flows are abundant in the surrounding areas but not shown in cross-section. The Cretaceous Idaho Batholith granitic rocks form the basement throughout the region.

Quartz (no steam loss), chalcedony, and Mg-corrected Na-K-Ca geothermometers resulted in 139 and142 °C, and 113 and 116 °C, and 153 and 152 °C with compositions measured in water samples from the well leak and leak runoff channel, respectively. The chalcedony-enthalpy mixing model resulted in an estimated 145 °C reservoir temperature with about 50% dilution. Similarly, the quartz-enthalpy mixing model resulted in 181 °C reservoir temperature with about 60% dilution. The RTEst results indicate that the Magic Hot Spring geothermal area has a reservoir temperature about 163 °C (Table 1).

5.3.6 Camas Prairie area

Camas Prairie (CP in Figure 1) is an east-west elongated (about 50 km by 15 km) intermontane valley in Camas and Elmore Counties in Idaho. The area has several hot springs [besides the Elk Creek Hot Springs (ECHS in Figure 1) in the northeastern part of the prairie]. The Sheep and Wolf Hot Springs are located in the western part of Camas Prairie, about 4 km north of Hill City in Idaho. These two hot springs, separated approximately 100 m from each other, issue hot water at about 50 °C. Two additional hot springs in the area are Wardrop Hot Springs (60°C), located on the northern side of prairie near the base of the Soldier Mountains, and Barron Hot Spring (73 °C), located on the southern side of the prairie near the base of the Mount Bennett Hills. The area also has several hot shallow wells, specifically scattered around the Wardrop and Barron Hot Spring areas.

Camas Prairie is bounded by the Mount Bennett Hills to the south and the Soldier Mountains to the north. The Mount Bennett Hills are composed predominantly of Miocene rhyolitic ash flows and lava flows of the Idavada Volcanic Group that overlies granodiorite of the Idaho Batholith. Local basalt flows and fluvial/lacustrine sediments are also present. The Soldier Mountains are composed mostly of granodiorite of the Idaho Batholith with minor amounts of younger intrusive rocks. Camas Prairie is host to an unknown thickness of Quaternary alluvial, fluvial, and lacustrine sediments with local lenses of basalt encountered in the shallow subsurface (Cluer and Cluer, 1986).

All Camas Prairie thermal water samples provide similar reservoir temperatures with the same traditional geothermometer. The quartz, chalcedony, and Na-K-Ca geothermometers results in temperature estimates in the range of 103-128, 74-99, and 70-124 °C, respectively. The silica-enthalpy model with chalcedony solubility and quartz solubility curves resulted in temperature estimates of about 133 °C and 173 °C, respectively.

Unlike the traditional geothermometers, RTEst temperature estimates of Camas Prairie area samples show a bimodal distribution- higher temperatures for the samples from northern parts and lower temperatures for the samples from southern parts. Specifically, the hot springs from the areas along the northern part of Camas Prairie that abuts the prairie with the foothills of the Soldier Mountains (e.g., Wardrop Hot Spring, Wolf/Sheep Hot Spring) results in higher (181-204 °C) RTEst reservoir temperatures. On the other hand, RTEst reservoir temperature estimates for hot springs and wells (e.g., Barron Hot Spring) in the southern parts are 79-108 °C.

5.3.7 Southern side of Mount Bennett Hills

Several hot springs are located along the southern side of the Mount Bennett Hills in Elmore, Gooding, and Lincoln Counties in Idaho extending over 70 km represent this prospect (SBH in Figure 1). Some of the known hot springs in the area are the Prince Albert (Coyote) (58 °C), Latty (65 °C), and White Arrow (65 °C). The Bostic 1-A well (2950 m) drilled to the south from this area indicated the presence of hot (ca. 200 ºC) rock at depths of about 3 km (Arney, 1982; Arney and Goff, 1982; Arney et al., 1984). The presence of several hot springs and hot rock at depth suggests that this part the SRP has great potential for geothermal resources.

Rocks in the area consist mainly of mafic and felsic volcanic rock with thick sequences of sediments and gravels. The Mount Bennett Hills to the north consist of predominantly of Miocene rhyolitic ash flows and lava flows of the Idavada Volcanic Group that overlies Idaho Batholith granodiorite. At the base of the Mount Bennett Hills, the basalt flows are intercalated with quaternary lacustrine sediments deposited in the Pleistocene-Pliocene Lake Idaho and the sandstones and shales of the Tertiary Glenn's Ferry Formation. At depth, an older basalt unit (Banbury basalt) and Idavada volcanics are encountered at Bostic 1-A well (Arney et al., 1984). The basement rock in the area is considered to be the Idaho Batholith granodiorite.

Reservoir temperature estimates for this area calculated with several water samples are given in Table 1. Quartz (no steam loss), chalcedony, and Na-K-Ca geothermometers resulted in 110-143, and 80-117, and 72-160 °C, respectively. The Prince Albert and Latty Hot Springs resulted in highest temperatures for the area with these traditional geothermometers. Silica-enthalpy mixing models with chalcedony and quartz solubility curves resulted in 150 and 182 °C temperature estimates for the area. As with the traditional geothermometers, the RTEst modeling of waters from hot springs yielded higher temperature. The three hot springs in the area, Prince Albert, Latty, and White Arrow Hot Springs resulted in reservoir temperatures at 193±8, 197±5, and 177±6 °C, respectively. Similarly, RTEst temperature estimate for a well (Shannon well) in the area is 137±10 °C. All other wells resulted in lower reservoir temperature estimates (82-122 °C). The reservoir temperature estimates using the hot spring waters are similar to the bottom hole temperature (~200 °C, Arney et al., 1984) measured in the Bostic 1-A well. It is likely that these hot springs are sourced by deep thermal waters that ascend along the range-forming faults.

5.3.8 Twin Falls area and Banbury Hot Springs

The southwestern periphery of the ESRP near Twin Falls and Buhl is one of the Known Geothermal Resource Areas in southern Idaho. The area is comprised of two dense clusters of geothermal surface manifestations, Banbury Hot Springs (BHS in Figure 1) and Twin Falls (TF in Figure 1). Discharging thermal waters range in temperature from 25 ºC to 70 ºC. Locally, thermal waters are being used for space heating, agriculture, and recreation.

The Twin Falls and Banbury hydrothermal areas show characteristics of both the ESRP and Basin and Range regional extension. Tertiary rhyolitic volcanic rocks underlie younger Quaternary and Tertiary basaltic units throughout the study area. Paleozoic metasedimentary rocks are thought to underlie the entire area (Lewis and Young, 1989). The thermal aquifer system in the area is located beneath basalt units within the Idavada volcanics and is under artesian conditions with temperatures of the waters increasing to the northwest. Thermal waters are thought to originate from deep circulation paths from the Cassia Mountain recharge zone to the south and through fractures in the overlying basalts of the thermal area. The waters are subsequently heated by either a regionally high gradient (Lewis and Young, 1989) or the young basaltic sill complexes associated with ESRP volcanism (McLing et al., 2014, Dobson et al., 2015).

Reservoir temperature estimate ranges obtained with traditional geothermometers and RTEst are given in Table 1 for both the Banbury Hot Springs and Twin Falls prospects. The highest reservoir temperatures (ca. 160 ºC) for the Banbury Hot Springs prospect are obtained for Banbury Hot Spring, Miracle Hot Spring well, and Salmon Falls Hot Spring with RTEst as well as other geothermometers. Similarly, for the Twin Falls prospect, the highest reservoir temperatures (ca. 135 ºC) are obtained for samples from two hot shallow wells (used for direct heating – Neely, 1996) within the premises of the College of Southern Idaho.

6. SUMMARY

Geothermometric calculations of ESRP thermal water samples indicate numerous potential geothermal areas with elevated reservoir temperatures. Specifically, RTEst results of thermal water samples from areas around the southern/southwestern side of the Mount Bennett Hills and within the Camas Prairie in the southwestern portion of the ESRP suggest temperatures of 140-200°C. In the northern portion of the ESRP, Lidy Hot Springs, Ashton, Newdale, and areas east of Idaho Falls have expected reservoir temperatures ≥140 °C. Resource temperatures in the southwestern ERSP, specifically, areas near Buhl and Twin Falls are estimated to as high as 160 °C. These areas are likely to host potentially economic geothermal resources; however, further detailed study is warranted for each site to evaluate their suitability for economic use.

ACKNOWLEDGMENTS

This work was supported by funding by the Assistant Secretary for Energy Efficiency and Renewable Energy, Geothermal Technologies Office of the U.S. Department of Energy under the U.S. Department of Energy Contract Nos. DE-AC07-05ID14517 with Idaho National Laboratory and DE-AC02-05CH11231 with Lawrence Berkeley National Laboratory. We thank landowners who provided access to sampling locations. We also thank Dr. Ross Spackman (Brigham Young University-Idaho) for his assistance in coordinating with landowners and filed work. Chemical analyses of the samples were conducted by Ms. Debbie Lacroix (University of Idaho) at Center for Advanced Energy Studies (CAES). We appreciate the discussion with Drs. Bill Phillips (Idaho Geological Survey), Glenn Embree (BYU-Idaho), and Dan Moore (BYU-Idaho).

REFERENCES

Arney, B.: Evidence of former higher temperatures from alteration minerals, Bostic 1-A well, Mountain Home, Idaho. *GRC Transactions*, **6**, (1982), 3-6.

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

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

Bethke, C.M.: *Geochemical and Biogeochemical Reaction Model*ling. Cambridge University Press, pp. 547, (2008).

Blackwell, D.D.: Regional implications of heat flow of the Snake River Plain, northwestern United States. *Tectonophysics*, **164**, (1989), 323-343.

Blackwell, D., Steele, J.L., and Carter, L.S.: Heat flow patterns of the North American continent: A discussion of the DNAG geothermal map of North America. In *Neotectonics of North America*, eds. D.B. Slemmons, E. R. Engdahl, and D. D. Blackwell, Geological Society of America, DNAG, Map, 1:423437, (1991).

Bond, J. G.: Geologic map of the state of Idaho, scale 1:500,000. Idaho Bur. of Mines and Geology, (1978).

Brott, C.A., Blackwell, D.D, and Mitchell J.C.: Geothermal investigations in Idaho, Part 8: Heat flow study of the Snake River Plain, Idaho, Idaho Department of Water Resources. *Water Information Bulletin,* **30**, (1976), 195 pp.

Cannon, C., Wood, T., Neupane, G., McLing, T., Mattson, E., Dobson, P., and Conrad, M.: Geochemistry sampling for traditional and multicomponent equilibrium geothermometry in southeast Idaho. *GRC Transactions*, **38**, (2014), 524-431.

Cluer, J.K., Cluer, B.L.: The late Cenozoic Camas Prairie Rift south-central Idaho, Contributions to Geology, University of Wyoming, **24(1)**, (1986), 91-101.

Cooper, D.C., Palmer, C.D., Smith, R.W., and McLing, T.L.: Multicomponent equilibrium models for testing geothermometry approaches. *Proceedings*, 38th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, CA (2013).

D'Amore, F. and Arnórsson, S.: Geothermometry, in *Isotopic and Chemical Techniques in Geothermal Expl*oration*, Development and Use* (S. Arnórsson, ed.): IAEA (Editorial), Vienna, pp. 152-199, (2000).

D'Amore, F., Fancelli, R., and Caboi, R.: Observations on the application of chemical geothermometers to some hydrothermal systems in Sardinia. *Geothermics*, **16**, (1987), 271-282.

Dobson, P.F., Kennedy, B.M., Conrad, M.E., McLing, T., Mattson, E., Wood, T., Cannon, C., Spackman, R., van Soest, M., and Robertson, M.: He isotopic evidence for undiscovered geothermal systems in the Snake River Plain. *Proceedings*, 40th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2015).

Embree, G.F., Phillips, W.M., and Welhan, J.A.: Geologic map of the Newdale quadrangle, Fremont and Madison Counties, Idaho. Idaho Geological Survey, University of Idaho, Moscow, Idaho 83844-3014, (2011).

Fournier, R.O. and Truesdell, A.H.: An empirical Na-K-Ca geothermometer for natural waters. *Geochim. Cosmochim. Acta*, **37**, (1973), 1255-1275.

Fournier, R.O.: Chemical geothermometers and mixing models for geothermal systems. *Geothermics*, **5**, (1977) 41-50.

Fournier, R.O.: A revised equation for the Na/K geothermometer. *GRC Transactions*, **3**, (1979), 221-224.

Fournier, R.O. and Potter, R.W. II: Magnesium correction to the Na-K-Ca chemical geothermometer. *Geochim. Cosmochim. Acta*, **43**, (1979), 1543-1550.

GeothermEx, Inc.: Independent technical report: Resource evaluation of the Newdale geothermal prospect, Madison and Fremont Counties, Idaho, USA. Geothermix, Inc., Richmond, California, USA, February 10, 2010, p. 101, (2010).

Giggenbach, W.F.: Geothermal solute equilibria. Derivation of Na-K-Mg-Ca geoindicators. *Geochim. Cosmochim. Acta*, **52**, (1988), 2749-2765.

Hughes, S.S., Smith, R.P., Hackett, W.R., and Anderson, S. R.: Mafic volcanism and environmental geology of the eastern Snake River Plain. *Idaho Guidebook to the Geology of Eastern Idaho*. Idaho Museum of Natural History, (1999), 143-168.

Hull, C.D., Reed, M.H., and Fisher, K.: Chemical geothermometry and numerical unmixing of the diluted geothermal waters of the San Bernardino Valley Region of Southern California. *GRC Transactions*, **11**, (1987), 165-184.

Lewis, R.E. and Young, H.W.: The hydrothermal system in central Twin Falls County, Idaho: U.S. Geological Survey Water Resources Investigations Report 88-4152, p. 44, (1989).

Link, P.K.: Clark County, Idaho. Digital Atlas of Idaho, Idaho State University, Geosciences Department, p. 3, (2002).

Mattson, E.D., Smith, R.W., Neupane, G., Palmer, C.D., Fujita, Y., McLing, T.L., Reed, D.W., Cooper, D.C., and Thompson, V.S.: Improved geothermometry through multivariate reaction-path modeling and evaluation of geomicrobiological influences on geochemical temperature indicators: Final Report No. INL/EXT-14-33959, Idaho National Laboratory (INL), Idaho Falls, Idaho, (2015).

McLing, T.L., Smith, R.W., and Johnson, T.M.: Chemical characteristics of thermal water beneath the eastern Snake River Plain. In: Geology, Hydrogeology, and Environmental Remediation: Idaho National Engineering and Environmental Laboratory, Eastern Snake River Plain, Idaho, P.K. Link and L.L. Mink, eds. *Geological Society of America Special Paper* **353**, (2002), 205-211.

McLing, T., McCurry, M., Cannon, C., Neupane, G., Wood, T., Podgorney, R., Welhan, J., Mines, G., Mattson, E., Wood, R., Palmer, C. and Smith, R.: David Blackwell's Forty Years in the Idaho Desert, The Foundation for 21st Century Geothermal Research; Geothermal Resources Council Transactions,38, (2014), 143-153.

Michard, G. and Roekens, E.: Modelling of the chemical components of alkaline hot waters. *Geothermics*, **12**, (1983), 161-169.

Mitchell, J.C.: Geothermal Investigations in Idaho – Part 7: Geochemistry and geologic setting of the thermal waters of the Camas Prairie Area, Blaine and Camas Counties, Idaho. Idaho Department of Water Resources, *Water Information Bulletin* **30**, (1976).

Mitchell, J.C., Johnson, L.L, and Anderson, J.E.: Geothermal Investigations in Idaho – Part 9: Potential for direct heat applications of geothermal resources. Idaho Department of Water Resources, *Water Information Bulletin* **30**, (1980).

Morgan, L.A., and McIntosh, W.C.: Timing and development of the Heise volcanic field, Snake River Plain, Idaho, western USA. *Geological Society of America Bulletin*, **117**, (2005), 288-306.

Morse, L.H. and McCurry, M.: Genesis of alteration of Quaternary basalts within a portion of the eastern Snake River Plain aquifer. *Special Papers Geological Society of America*, (2002) 213-224.

Neely, K.W.: Geothermal heat keeps students warm at the College of Southern Idaho. *GRC Transactions*, **20**, (1996), 129-136.

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

Neupane, G., Mattson, E.D., McLing, T.L., Palmer, C.D., Smith, R.W., and Wood, T.R.: Deep geothermal reservoir temperatures in the Eastern Snake River Plain, Idaho using multicomponent geothermometry. *Proceedings*, Thirty-Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 24-26, 2014 SGP-TR-202, (2014).

Neupane, G., Mattson, E.D., McLing, T.L., Palmer, C.D., Smith, R.W., Wood, T.R., and Podgorney, R.K.: Geothermal reservoir temperatures in southeastern Idaho using multicomponent geothermometry. *Proceedings*, World Geothermal Congress 2015, Melbourne, Australia, 19-25 April 2015, (2015a).

Neupane, G., Baum, J.S., Mattson, E.D., Mines, G.L., Palmer, C.D., and Smith, R.W.: Validation of multicomponent equilibrium geothermometry at four geothermal power plants. *Proceedings*, Fortieth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 26-28, 2015, (2015b).

Neupane, G., Mattson, E.D., Mines, G.L., McLing, T.L., Dobson, P.F., Conrad, M.E., Wood, T.R., Cannon, C., Worthing, W.: Geothermometric temperature comparison of hot springs and wells in southern Idaho. *GRC Transactions,* **39**, 495-502 (2015c).

Neupane, G., Mattson, E.D., McLing, T.L., Palmer, C.D., Smith, R.W., Wood, T.R., and Podgorney, R.K.: Geothermometric evaluation of geothermal resources in southeastern Idaho. *Geoth. Energ. Sci*, **4(1)**, (2016a), 11-22.

Neupane, G., Mattson, E.D., Cannon, J.C., Atkinson, T.A., McLing, T.L., Wood, T.R., Worthing, W.C., and Conrad, M.E.: Mixing effects on geothermometric calculations of the Newdale Geothermal area in the Eastern Snake River Plain, Idaho. *Proceedings*, 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 22-24, 2016 SGP-TR-209 (2016b).

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

Occidental Geothermal, Inc.: Sturm 1, Computer Processed Log. Department of Water Resources, Idaho, p. 18, (1979)

Palandri, J.L. and Reed, M.H.: Reconstruction of in situ composition of sedimentary formation waters. *Geochim. Cosmochim. Acta*, **65**, (2001), 1741-1767.

Palmer, C.D., Ohly, S.R., Smith, R.W., Neupane, G., McLing, T., Mattson, E.: Mineral selection for multicomponent equilibrium geothermometry. *GRC Transactions,* **38**, (2014), 453-459.

Pang, Z.H. and Reed, M.: Theoretical chemical thermometry on geothermal waters: Problems and methods. *Geochim. Cosmochim. Acta*, **62**, (1998), 1083-1091.

Peiffer, L., Wanner, C., Spycher, N., Sonnenthal, E., Kennedy, B.M., Iovenitti, J.: Optimized multicomponent vs. classical geothermometry: insights from mod-eling studies at the Dixie Valley geothermal area. *Geothermics*, **51**, (2014), 154–169.

Pierce, K. L., and Morgan, L. A.: The track of the Yellowstone hot spot: Volcanism, faulting, and uplift. *Geological Society of America Memoirs*, **179**, (192), 1-54.

Ralston, D.R., Arrigo, J.L., Baglio, J.V. Jr., Coleman, L.M., Souder, K., and Mayo, A.L.: Geothermal evaluation of the thrust area zone in southeastern Idaho, Idaho Water and Energy Research Institute, University of Idaho, (1981).

Reed, M. and Spycher, N.: Calculation of pH and mineral equilibria in hydrothermal waters with application to geothermometry and studies of boiling and dilution. *Geochim. Cosmochim. Acta*, **48**, (1984), 1479-1492.

Rodgers, D.W., Ore, H.T., Bobo, R.T., McQuarrie, N., and Zentner, N.: Extension and subsidence of the eastern Snake River Plain, Idaho. Tectonic and Magmatic Evolution of the Snake River Plain Volcanic Province. *Idaho Geological Survey Bulletin*, **30**, (2002), 121-155.

Ross, S.H.: Geothermal potential of Idaho. *Geothermics Special Issue* **2**, (1970), 975-1008.

Shervais, J.W., Glen, J.M., Liberty, L.M., Dobson, P., Gasperikova, E., Sonnenthal, E., Visser, C., Garg, S., Evans, J.P., Siler, D., DeAngelo, J., Athens, N., and Burns, E.: Snake River Plain play fairway analysis – Phase 1 Report. *GRC Transactions,* **39**, (2015), 761-769.

Smith, R.P.: Geologic setting of the Snake River Plain aquifer and vadose zone. *Vadose Zone Journal*, **3**, (2004), 47-58.

Smith, R.W., Palmer, C.D., and Cooper, D.: Approaches for multicomponent equilibrium geothermometry as a tool for geothermal resource exploration. *Abstracts*, AGU Fall Meeting, San Francisco, 3-7 December 2012, (2012).

Spycher, N.F., Sonnenthal, E., and Kennedy, B.M.: Integrating multicomponent chemical geothermometry with parameter estimation computations for geothermal exploration. *GRC Transactions,* **35**, (2011), 663-666.

Spycher, N., Peiffer, L., Sonnenthal, E. L., Saldi, G., Reed, M. H., and Kennedy, B. M.: Integrated multicomponent solute geothermometry. *Geothermics*, **51**, (2014), 113-123.

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

Tole, M.P., Ármannsson, H., Pang, Z.H., & Arnórsson, S.: Fluid/mineral equilibrium calculations for geothermal fluids and chemical geothermometry. *Geothermics,* **22**, (1993), 17-37.

Welhan, J.A.: Thermal and Trace-Element Anomalies in the Eastern Snake River Plain aquifer: toward a conceptual model of the EGS resource. *GRC Transactions*, **39**, (2015), 363-375.

Whitehead, R.L.: Geohydrologic framework of the Snake River Plain regional aquifer system, Idaho and eastern Oregon. Regional aquifer system analysis-Snake River Plain, Idaho. *US Geological Survey Professional Paper 1408-B*, (1992).

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

Williams, P.L., Mabey, D.R., Zohdy, A.A.R., Ackermann, H., Hoover, D.B., Pierce, K.L., and Oriel, S.S.: Geology and geophysics of the southern Raft River Valley geothermal area, Idaho, USA. *Proceedings*, Second UN Symposium on the Development and Use of Geothermal Resources, San Francisco, Lawrence Berkeley National Laboratory, (1976), 1273-1282.