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Evaluation of Deep Geothermal Resources Using Rare Earth Elements, Snake River Plain, Idaho, USA

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ABSTRACT

Although more than ten Known Geothermal Resource Areas (KGRAs) were previously identified by the USGS over large portions of eastern Oregon and southern Idaho, very little geothermal development has occurred in this region during the past 30 years. We hypothesize that within some of these KGRAs, large under-characterized geothermal prospects exist with significantly elevated heat flow that are representative of commercial grade resources. The objective of this project is to provide a new assessment of these high heat flow systems associated with the Snake River Plain (SRP) in southern Idaho using modern exploration tools and techniques. The Snake River Plain is an area with significant potential geothermal resources. However, rapid groundwater flow in high permeability surficial basalts effectively masks high heat flows and thermal signatures of deep-seated geothermal systems in the SRP. To identify potential signatures of hidden geothermal systems, we have measured chemical and isotopic compositions of thermal fluids from across the region sampled from hot springs and thermal wells. Here we report the rare earth element (REEs) data collected from more than 150 geothermal springs and wells within and along the margins of the Snake River Plain. As with most natural waters, the concentrations of REE in geothermal water samples in the SRP are low, less than 1 ppb. However, the measured REE values are useful tools that can be used to characterize the geothermal systems. The REE concentrations and their chondrite normalized values in volcanic rocks from the SRP show two distinct rock-type specific REE distribution patterns – one for rhyolitic rocks and other for olivine tholeiite basalts. In general, the chondrite-normalized REE pattern for the composite rhyolitic rocks shows an enrichment in light REE La to Eu (LREE), a depletion of middle REE (MREE) Eu to Tb, and an almost flat heavy REE (HREE) trend from Tb to Lu. The REE pattern for basalts from the Eastern Snake River Plain (ESRP) appears to exhibit a mostly decreasing trend from LREE to HREE with some less-pronounced features superimposed. The SRP geothermal waters show more variable REE patterns, as several samples show very strong Eu enrichment whereas other samples show increasing trends in the middle REE (MREE) or HREE regions. Similarly, some samples show depletions of Ce and/or Eu. Various REE distribution patterns observed in geothermal water samples are mostly associated with the interaction of geothermal waters with overlying cold aquifer water and water-rock interactions within the host rocks. This REE dataset provides a valuable window into the geothermal conditions that exist deep in the SRP. Additionally, the REE data provide important insights into the geochemical changes that occur as geothermal water migrates from deep in the SRP to the springs and wells along the margin of the SRP.

1. INTRODUCTION

More than a decade ago, the U.S. Geological Survey estimated more than of 30 GWe of undiscovered conventional geothermal resource in the Western United States (Williams et al., 2008). Although more than 6% of the potential is located in Idaho, very little geothermal development has occurred in this region during the past 30 years. The Snake River Plain (SRP) in southern Idaho is a volcanic province characterized by a high thermal flux with a great potential for geothermal resources (e.g., McLing et al., 2016, Williams et al., 2008, Blackwell et al., 1992. USGS 2008). During much of the last decade, a team of scientists from the Idaho National Laboratory, Lawrence Berkeley National Laboratory, and the University of Idaho have been re-visiting and evaluating the geothermal resource potential in the SRP and surrounding areas using geological, geochemical, isotopic, and thermal tools (e.g., Neupane et al., 2014; 2016; Dobson et al., 2015; Mattson et al., 2016; McLing et al., 2016; Conrad et al., 2016; Lindsey et al., 2018). For these studies, we collected water samples from more than 150 wells and springs and analyzed them for major cations and anions, trace elements, rare earth elements (REE), noble gasses, and isotopes to refine estimates of deep reservoir temperatures (e.g., Cannon et al., 2014; Mattson et al., 2016; Neupane et al., 2016). In addition to SRP waters, we have also sampled and analyzed samples of regional volcanic rocks as well as compiled literature and unpublished results into a comprehensive data base of water and rock chemistry. In this paper we expanded our geochemical characterization of the SRP geothermal waters by providing some preliminary results on the distribution of REE in geothermal waters and their potential relationships with the major SRP rock types.

2. RARE EARTH ELEMENTS

The REE and their patterns (normalizes concentration vs. atomic number) have long been used as geochemical tracers for evolution of rocks and waters. The REE are a suite of 15 elements that span from atomic numbers from 57 (La) to 71 (Lu) (lanthanide elements). In general, all REE have +3 valance state in the environment and exhibit similar geochemical behavior with systematic trends arising from difference in ionic radii (or atomic number). However, Ce and Eu can occur in other valance states (+4 and +2, respectively) depending on the prevailing redox conditions resulting in deviation from their expected +3 behavior. Variations or anomalous behaviors of a single or a few of the REE are interpreted to reflect a combination of differences in the fractionation/dissolution among the REE with different phases (e.g., magma-minerals, water-minerals, etc.), variations in dominant complexing anions, and varying response to redox conditions.

For descriptive purposes, the REE can be divided into three groups: light REE (LREE, La to Sm), middle REE (MREE, Eu to Dy), and heavy REE (HREE, Ho to Lu) (Samson and Wood, 2004). To remove concentration variations arising because of the cosmic abundances of these elements, REE concentrations are normalized by some standard materials (e.g., chondrite, North American Shale Composite, etc., Piper and Bau, 2013). Variations in the normalized REE concentrations of geologic sample can more easily be used for comparing, deciphering and understanding the geochemical processes giving rise to observed REE behavior.

3. GEOLOGICAL SETTING

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 Eastern Snake River Plain (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-Snake River hotspot (Figure 1) (Pierce and Morgan, 1992; Rodgers et al., 2002). The 100 km wide, 600 km long (Hughes et al., 1999) ESRP reflects time transgressive volcanic activities that have been preserved by two compositionally distinct rock types; thick sequences of rhyolitic ash-flow tuffs that are associated with the giant caldera-forming super volcanic eruptions overlain by thick sections (> 1 km) of multiple low-volume monogenetic olivine tholeiite basalt layers erupted from shield volcanos and fissures in the wake of the hotspot activities (Leeman, 1982; Ellis et al., 2013). Figure 2 illustrates hundreds of rhyolitic (ignimbrites) as well as basaltic rock samples that were collected and analyzed for their chemistry by several researchers (e.g., Bindeman et al., 2008; Bonnichsen et al., 2008; Wright et al., 2002). Several pairs of oxide abundances presented as binary plots in Figure 2 demonstrate the bimodal nature of the regional volcanism with rocks forming two distinct clusters with very few rocks of intermediate composition (Ellis et al., 2013). In addition to volcanic rocks, the basalt flows of the SRP include interlayered fluvial and eolian sediments that accumulated during periods of volcanic quiescence. Five super volcanic centers/fields have been inferred and mapped in southern Idaho (e.g. Rodgers et al., 1990; Kellogg et al., 1994; Anders et al., 2014) and are shown in Figure 1.

The thick sequences of coalescing basalt flows with interlayered sediments in the ESRP constitute the highly productive Eastern Snake River Plain Aquifer (ESRPA) system above the rhyolitic ash-flow tuffs (Whitehead, 1992). This aquifer system transports cold recharge from the Yellowstone Plateau and surrounding mountain basins to springs along the Snake River Canyon west of the city of Twin Falls, Idaho. The cold water masks a steep geothermal gradient below the ESRPA (Blackwell, 1989; McLing et al., 2002; McLing et al., 2016; Nielson et al., 2012).

4. MATERIALS AND METHODS

4.1 Water Samples

Water samples were collected primarily from hot springs and thermal wells distributed within and along the margins of the ESRP and analyzed for their major, minor, and trace element (including REE) concentrations. Initially, the majority of the samples were collected and analyzed for major cations and anions to estimate potential geothermal reservoir temperatures (Mattson et al., 2016; Neupane et al., 2016). More recently, REE concentrations of water samples from the same locations were measured.

4.2 Sample Processing and REE Analysis

The REE concentrations of near-neutral pH natural waters are extremely low (several ng/L) and challenging to quantify in the presence of high concentration of background (and interfering) cations. The concentration of REE were measured by inductively coupled plasma-mass spectroscopy following pre-concentration. Specifically, our pre-concentration protocols minimize background and interfering cations by selectively capturing REE from the natural waters using ion-selective chelating resins: AG-50W-XR resin (Bio-Rad Laboratories, Inc.) for waters having total dissolved solid (TDS) concentrations of less than 1,500 mg/L and Chelex-100 resin (Bio-Rad Laboratories, Inc.) for waters with higher TDS concentrations. Further details of these protocols can be found in McLing et al. (2014, 2019). Major and minor oxides, trace metals, and REE concentrations for rock samples were measured by Activation Laboratories Ltd. (Actlabs, Ancaster, Ontario, Canada) using inductively coupled plasma-mass spectroscopy and inductively coupled plasma-optical emission spectroscopy following Lithium Metaborate/Tetraborate fusion.

4.3 Regional REE Data Base Development

We prepared a REE database for approximately 150 spring and well sample locations from the Bruneau-Grandview area, ID in the southwest to Yellowstone National Park, WY in the northeast to by combining our results with REE data for acidic Yellowstone (YELL) waters (Lewis et al., 1997) and cooler ESRP groundwater/surface waters (Nelson, 2004). With the exceptions of the YELL springs, the distributions of sample locations are shown in Figure 1. For purpose of comparison we also compiled REE data for regional volcanic rocks from published sources (Kunz, 1992; Reed et al., 1997; Hughes et al., 1997; Shervais et al., 2006), outcrop samples collected and analyzed at Actlabs for this study, and unpublished results from the Department of Geosciences at Idaho State University made available to us by Dr. Michael McCurry. In addition to REE data, the database includes whole-rock compositional data and major cation and anion concentrations (for water samples). Rare earth element results were normalized using chondrite REE values from Schmidt et al. (1963) as reported by Piper and Bau (2013).

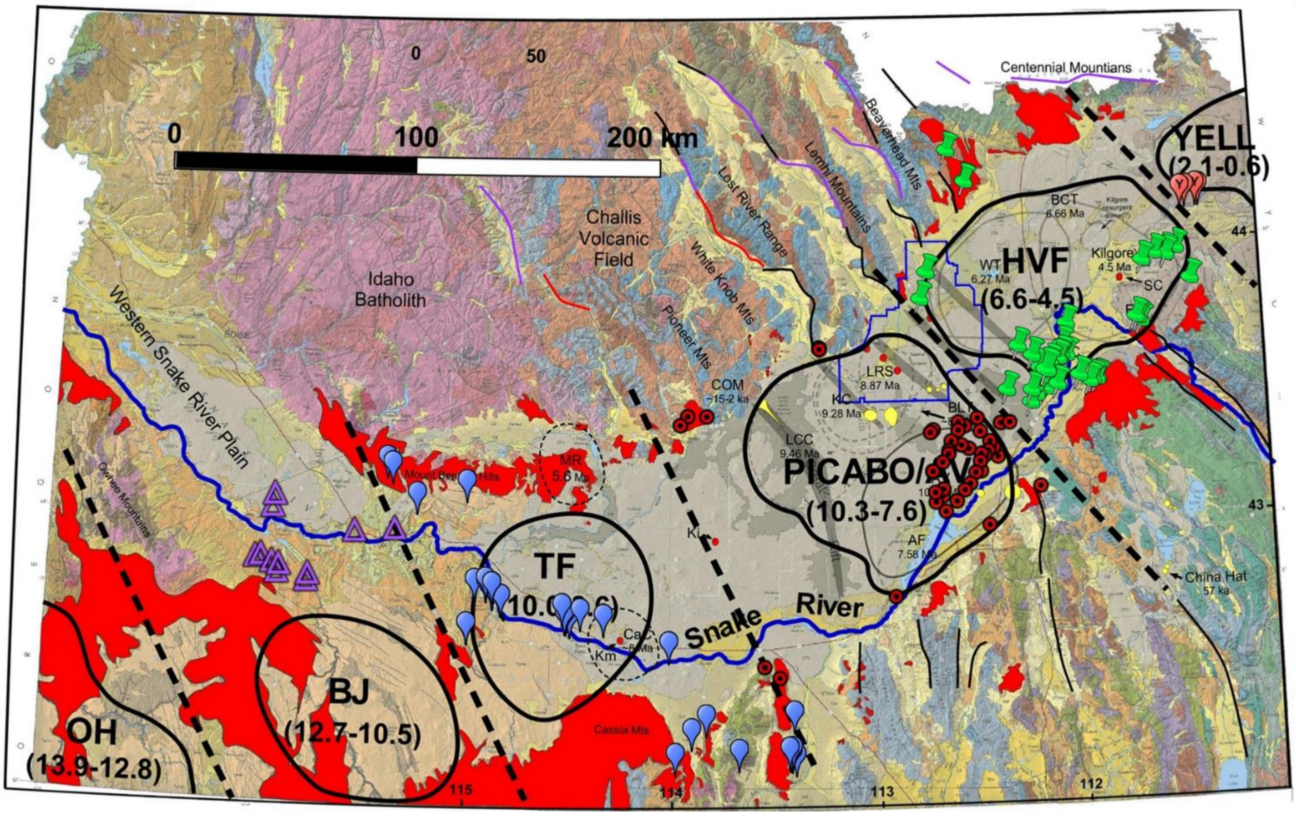

Figure 1. Geologic map of southern Idaho [modified by McCurry et al. (2016) after Lewis et al. (2012)]. Shades of green, blue and purple illustrate late Precambrian to Paleozoic sedimentary rocks exposed in Basin and Range horst blocks north and south of the plain. Pale shades of grey on the Snake River Plain indicate Quaternary basalt lavas (Holocene in darker shade); pale yellow indicates Quaternary sediment. Yellow = Quaternary cryptodomes, lava domes and volcanic fields consisting of geochemically evolved mafic to rhyolitic composition (McCurry and Welhan, 2012; McCurry et al., 2016). Bold red colors indicate rhyolites (mostly ignimbrites) exposed along the margins of the plain. The outline and ages of the eruptive centers are indicated with bold polylines after Anders et al. (2014) and McCurry et al. (2016). The dashed transverse lines are used to separate samples from different volcanic field. Water samples are divided into 5 groups based on their distribution in 5 post-OH (Owyhee) volcanic fields. Other volcanic fields and water sample markers are - YELL (Yellowstone, red drops with Y), HVF (Heise, green push pins), PICABO/AV (Picabo/Arbon Valley, red targets), TF (Twin Falls, blue drops), and BJ (Bruneau-Jarbidge, purple triangles). Some Yellowstone volcanic field samples (Lewis, et al., 1997) are not shown in the map. Location abbreviations (and ages in some instances) are -TF=Twin Falls, after Shervais et al., 2013; MR=Magic Reservoir, after Leeman, 1982; AF=American Falls, LCC=Little Chokecherry Canyon, KC=Kyle Canyon, LRS=Lost River Sinks, are after Anders et al., 2014; AV=Arbon Valley (or Taber), after Kellogg et al., 1994; Kuntz et al., 1992; McCurry, 2009; WT=Walcott, BCT=Blacktail Creek, Kilgore, and CC=Conant Creek, are after Morgan and McIntosh, 2005, modified by Anders et al., 2014; WC=Wolverine Creek, Ek=Elkhorn Spring, are after Anders et al., 2014). Deep boreholes are shown as red dots (Km=Kimberly; Ki=Kimama; SC=Sugar City; after Shervais et al., 2013). Deep holes within the Idaho National Laboratory site (marked with blue polygon) are USGS-142, INEL-1, and WO-2 from NW to SE (after McCurry et al., 2016).

5. RESULTS AND DISCUSSION

To facilitate comparison and reflecting the characteristic bimodal volcanism of the SRP (Ellis et al., 2013) we organized our rock compositional data into rock-type groups. At the highest level, this included two general groups: olivine tholeiite basalts and rhyolitic rocks. The rhyolitic rocks were further divided into 5 sub-groups (from southwest to northeast; Bruneau-Jarbidge, Twin Falls, Picabo, Heise, and Yellowstone) based on their association with individual super volcanic eruptive centers/fields shown in Figure 1. Water chemistry results were also grouped based on their association with super volcanic eruptive centers/fields. The results were further sub-divided based on water types (e.g., dominant cation and anion species) and field temperatures.

4.1 Composition of SRP Waters

Our REE database for SRP waters includes both thermal (T ≥ 20°C) and cooler waters. Field temperatures of the YELL hot springs were as high as 93°C (e.g., Monument Spring; Lewis et al., 1997). Among the non-YELL samples, well samples from the Raft River Geothermal (RRG) area have the highest temperatures (up to 150°C). Some hot springs and wells in the TF Volcanic Field (VF) have temperatures as high as 65°C. Cooler water samples have temperatures as low as 10.6°C. These cooler water samples represent domestic or irrigation wells, canals (n =3), and Snake River (n=3) from the HVF and PVF (Nelson et al., 2004). An additional river sample collected from the Henry's Fork of the Snake River (in the YVF) has a field temperature of ~22°C.

All water samples except the acid (pH 2-4) sulfate-chloride waters of the YELL hot springs are near neutral (pH 6.3-9.6). The SRP thermal waters show a large range in total dissolved solids (TDS) from about 106 mg/L (Sturm Well, in the YVF) to more than 7,000 mg/L (Heise Hot Spring, in the HVF). Major compositions of waters from both hot/warm and cooler sampling features in the SRP are presented in Figure 3. Water samples from each volcanic field are plotted on a separate Piper diagram (Figure 3a-e), and they are also plotted together as on a single diagram (Figure 3f). Based on the dominant ions in water, the majority of the SRP waters are either Na-HCO_3 or Ca-HCO_3. Some samples from the YELL, Heise Hot Springs, and Raft River Geothermal areas are Na-Cl types. A few samples are identified as Ca-SO_4, Na-SO_4, Na-F, and so on (Figure 3). In the SRP, Na-HCO_3 water is generally considered as deeper water whereas Ca-Mg-HCO_3 water represents shallower ESRPA water (McLing et al., 2002). In Figure 3, these water types tend to plot on different regions in the diagram. A few non-YELL water samples (e.g., Heise Hot Spring, Green Canyon Hot Spring, etc.) with Cl and/or SO_4 as major anions may have originated with water-rock interaction involving Paleozoic evaporite beds (Mattson et al., 2016).

4.2 REE in Rocks

As described above, results were grouped based on rock types and sub-grouped based on volcanic fields. For the rhyolitic rocks, the arithmetic mean of each REE was calculated using data for samples collected from the same volcanic field (n ranging from 1 to >100) and using data for all rhyolite samples to calculate concentrations for a SRP composite rhyolite. For basalts, data for all ESRP basalt samples (regardless of volcanic field) was used to calculate average REE concentrations for an ESRP composite basalt. The composite REE concentrations for both types of the SRP rocks show a greater than 14-fold enrichment in REE for their concentrations normalized to chondrite. Arithmetic mean values for REE concentrations are presented in Figure 4.

Figure 4 shows the average chondrite-normalized REE values for each group and sub-group of SRP rocks. In general, REE concentrations and patterns for rhyolitic rocks from the older BJVF to the youngest YVF are similar, showing a general negative slope from LREE to HREE. However, some anomalous features are superimposed on overall negatively sloping spider plots. For example, Nd shows a slightly positive anomaly (in the plot for PVF). Because only one sample from the PVF had the measured Pr value (samples from the other four volcanic fields lack Pr measurements), we included Pr data for an additional 6 samples from the OVF in our calculation of REE concentrations for the SRP composite rhyolite (REE pattern represented by ‘All VF rhyolitic rocks’ in Figure 4) to ascertain if a Nd anomaly is present (a few other elements, such as Er, also had a similar issue). The REE pattern for the normalized SRP composite rhyolite plot also exhibits a positive Nd anomaly in Figure 4. Rhyolitic rocks from all volcanic fields shows a strong negative Eu anomaly. The composite REE plot for the SRP rhyolitic rocks shows an increasing trend from Eu to Tb in the MREE region. In the HREE region, the REE pattern almost become featureless except for a slight positive Yb anomaly and a decreased concentration of Lu. Although Er appears to have a negative anomaly in PVF rhyolitic rocks, it (Er) is represented by only one sample and such a negative pattern does not appear in the plot for the composite SRP rhyolitic rocks that included an additional 16 samples from the OVF.

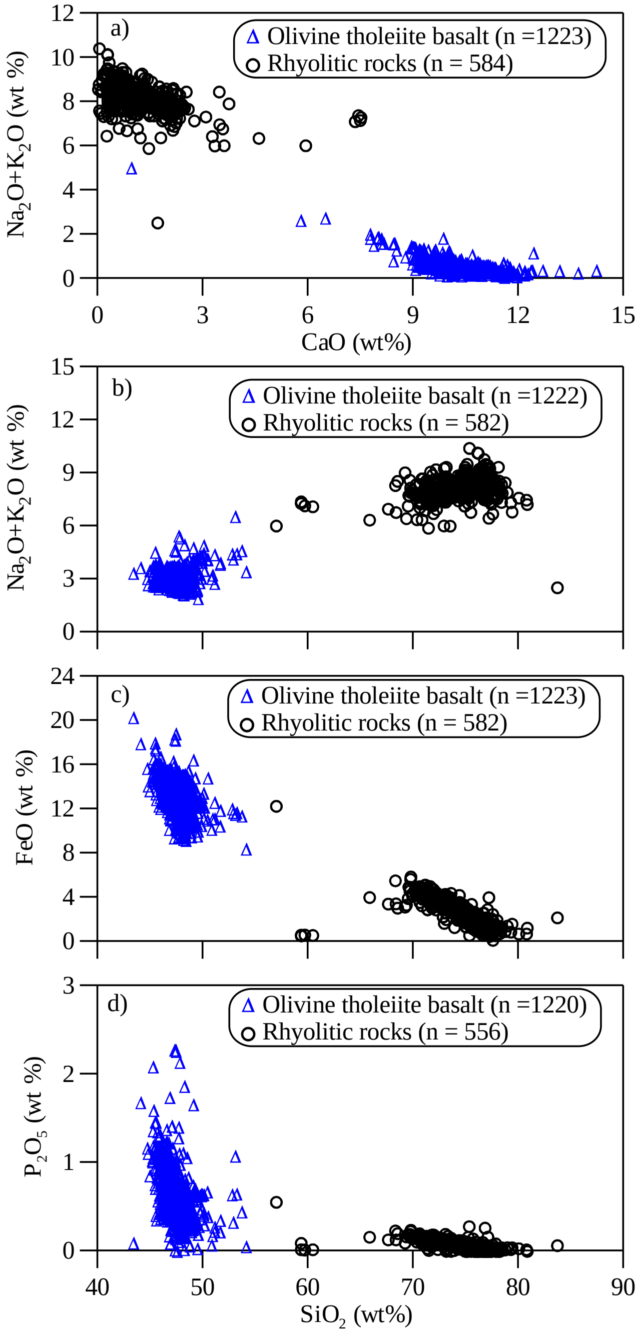

Figure 2. Binary composition plots indicate the bimodal distribution of volcanic rocks in the SRP (data from Kunz, 1992 and Reed et al., 1997).

As with the major metal oxides (Figure 2), the REE data for these rocks clearly differentiate the ESRP basalts from the SRP rhyolitic rocks (Figure 4). Although both rock types share an overall negatively slopped REE pattern, the degree of LREE enrichment in basalts is less than that of the rhyolitic rocks. The strong negative Eu anomaly observed for the SRP rhyolitic rocks is completely absent and replaced by a slight positive Eu anomaly in the ESRP basalts. The basalt composite also shows a convex upward feature region from Ce to Nd as well as a small positive Dy anomaly.

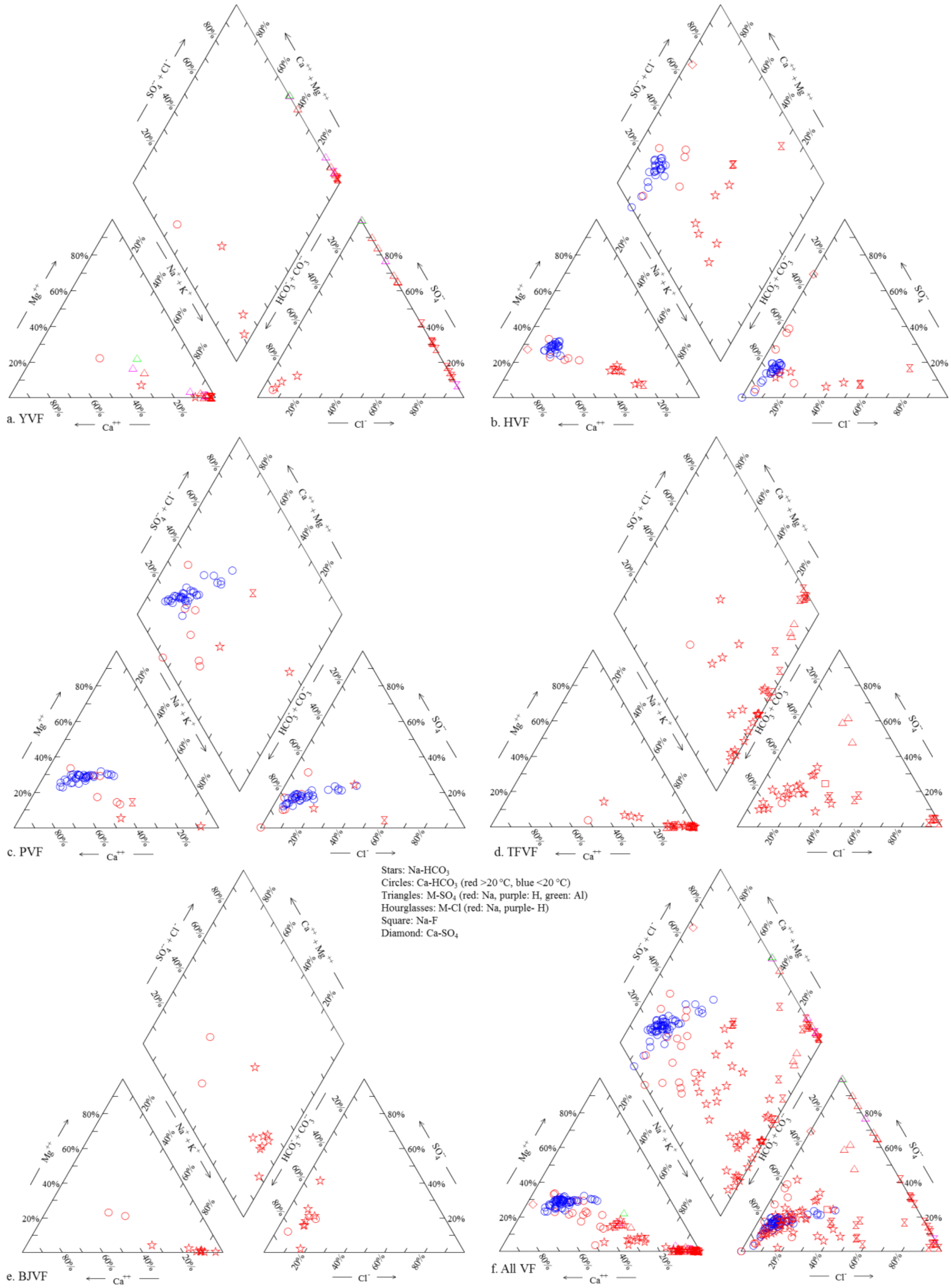

Figure 3. Piper diagrams showing general chemistry of waters from the SRP. Water samples from each of the five volcanic fields are illustrated in a through e. All SRP water samples plotted on f. The volcanic fields are: YVF = Yellowstone; HVF = Heise; PVF = Picabo/Arbon Valley; TFVF = Twin Falls; and BJVF = Bruneau-Jarbidge. Major cation and anion water chemistry data from Lewis et al. (1997), Nelson (2004), and Mattson et al. (2016).

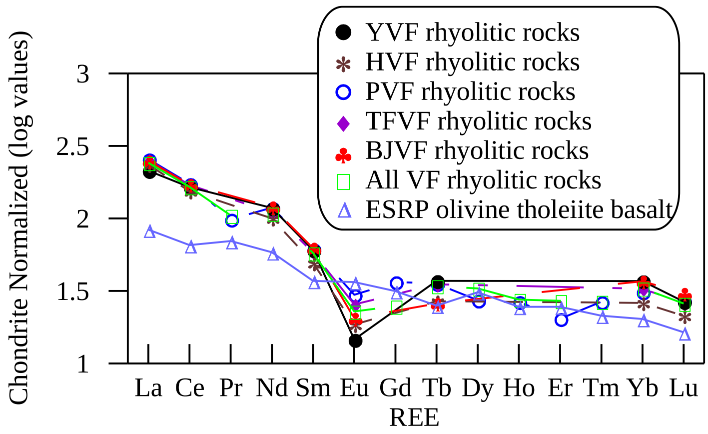

Figure 4. Spider diagrams showing chondrite normalized REE values for rhyolitic rocks from several volcanic fields in the SRP. The volcanic fields are: YVF = Yellowstone; HVF = Heise; PVF = Picabo/Arbon Valley; TFVF = Twin Falls; and BJVF = Bruneau-Jarbidge.

4.3 REE in Waters

The REE concentrations of near-neutral waters were very low and almost all in sub-part-per-billion to parts-per-trillions (or ng/L) level. These concentrations are similar to previously reported REE concentrations in near-neutral geothermal, groundwater, and oil-and-gas produced waters from several basins the United States (Wood, 2001; Nelson, 2004; Nelson et al., 2004; Nye et al., 2017; McLing et al., 2018). In contrast, the acidic waters from YELL (Lewis et al., 1997) had REE concentrations of parts-per-billions (or µg/L) to over 100 parts-per-billion. The range of total REE concentrations for SRP waters are given in Table 1. The lowest total REE concentration was for Green Canyon Hot Springs in HVF. The maximum total REE content for a non-YELL water was for a sample collected from the Laib Well in BJVF. In general, the total REE content < 10 ng/L were not common for the near-neutral ESRP waters.

Table 1. Total REE content in the ESRP waters (ng/L)

Volcanic Field	Yellowstone	Heise	Picabo/Arbon Valley	Twin Falls	Bruneau-Jarbidge
Range of ΣREE	7.3-161,500	2.9-580	4.4-298	3.3-365	3.8-1,370

Because of the larger variability of REE concentrations in the water samples, average values were not calculated. Instead chondrite-normalized concentrations of some representative waters from each volcanic field are shown in Figure 5. In addition, average normalized concentrations for both rhyolitic rocks from the individual volcanic fields and ESRP composite olivine tholeiite basalt are included in Figure 5. Unlike the similar chondrite-normalized REE patterns for the SRP rock types (e.g., rhyolitic or basaltic), a diversity of chondrite-normalized REE patterns emerges for the SRP waters. In general, the acidic water samples representing the YVF are similar to the REE pattern of the associated rhyolitic rocks (Figure 5a) with the only variation being that the waters have a more pronounced negative Eu anomaly than the rhyolitic rocks. Similarly, some of the non-acidic water samples (e.g., Ashton Hot Springs, and to an extent even water from the Henry's Fork of the Snake River) of this volcanic field show similar REE patterns to that the YVF rhyolitic rock (Figure 5b). However, two other waters (Sturm Well and Warm River Springs 1) have LREE patterns more similar to the composite ESRP basalt. However, these two waters show greater enrichment trends from the MREE to HREE.

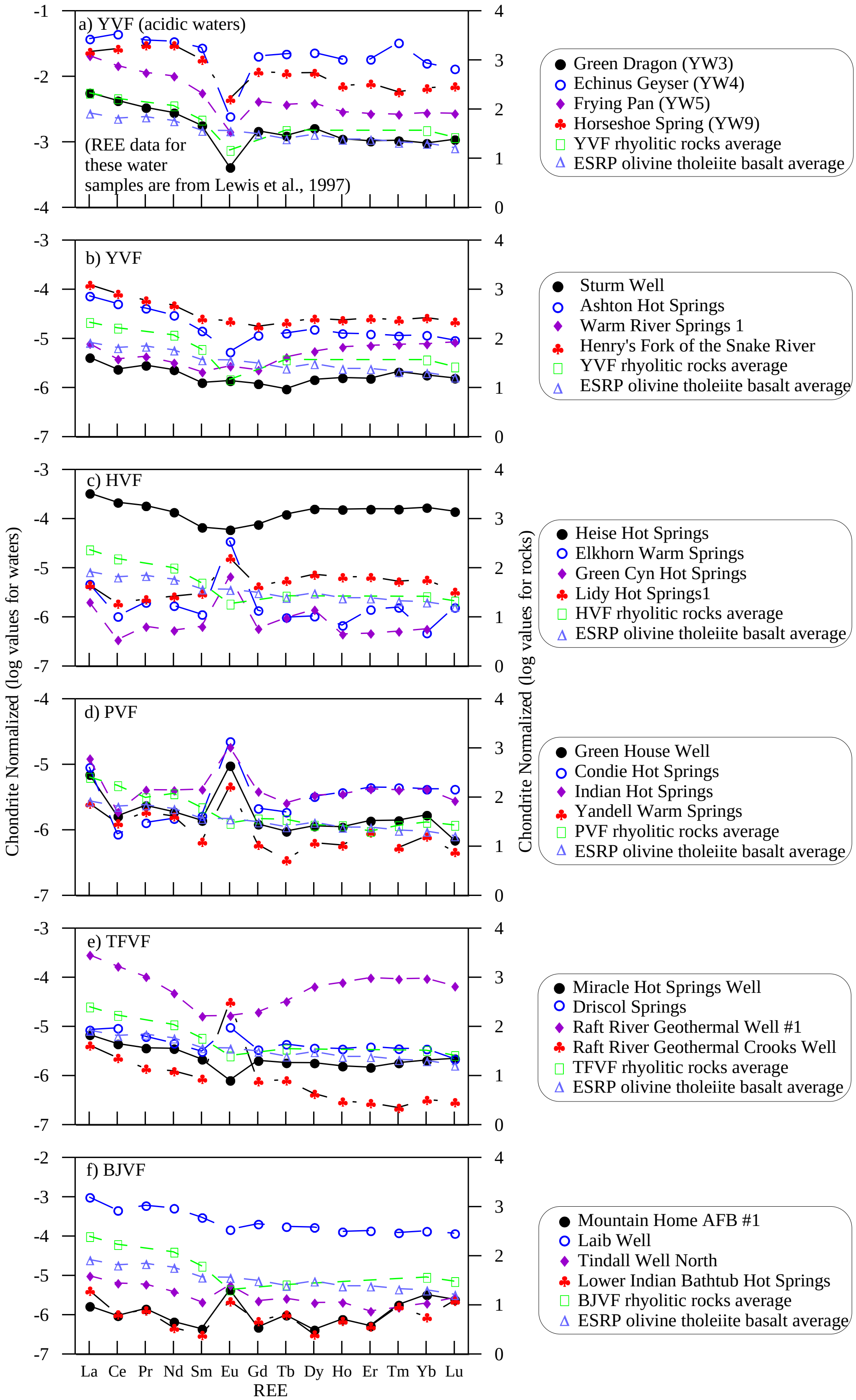

Figure 5. Spider diagrams displaying chondrite-normalized REE abundances for representative water samples and average rhyolitic rocks of each VF and average ESRP olivine tholeiite basalt.

Two distinct REE patterns are observed for waters from the HVF (Figure 5c). The REE pattern for Heise Hot Springs is not only distinct from the REE pattern of other water samples from the HVF; it also has REE concentrations that are 1 to 2 orders of magnitude higher than the other waters. The Heise Hot Springs LREE pattern closely resembles the LREE pattern of the rhyolitic rocks and both exhibit negative Eu anomalies. However, they differ in the MREE region as the Heise Hot Springs water shows greater increasing trend than do the rhyolites. In contrast, several HVF waters exhibit a strong positive Eu anomaly (represented by the Elkhorn Warm Spring, Green Canyon Hot Springs, and Lidy Hot Springs 1). These three waters also have a negative Ce anomaly and a relatively increasing trend from Gd to Dy. However, they differ in HREE patterns. The Lidy Hot Springs shows a rather featureless pattern (with slightly decreasing trend for Lu) and appears similar in trend with the Heise Hot Springs. On the other hand, the Elkhorn Warm Spring and Green Canyon Hot Springs show negative Ho and Yb anomalies in the HREE region.

The waters from PVF (Figure 5d) have REE patterns similar to those of HVF waters (Elkhorn Warm Spring, Green Canyon Hot Springs, and Lidy Hot Springs 1) with all PVF waters showing negative Ce and strong positive Eu anomalies. Additionally, they also share the same general trends in the LREE region. The normalized HREE concentrations of HREE trends of both Indian and Condie Hot Springs appear similar despite being located on the southern and northern edges of the PVF, respectively.

The waters from TFVF (Figure 5e) show greater variability in their REE patterns than waters from the other volcanic fields. Some sampled features, specifically samples from the Raft River Geothermal (RRG) area and a few others, such as the Durfee Hot Springs (not shown), that are included in the TFVF may actually be Basin and Range features located just outside the southern margins of the SRP. The REE pattern of the two RRG wells differ (MREE and HREE) from each other. The RRG Well 1 shows a trough-like pattern from Sm to Gd whereas the RRG Crooks Well (and several other RRG Wells not shown) has a strong positive Eu anomaly. For the Crooks Well, the decreasing REE trend continues to MREE and HREE. In the case of the RRG Well 1, the normalized REE values increases from Gd to Er, and remains flat with a slight decrease in Lu. The REE pattern of the Miracle Hot Springs Well mimics the general REE pattern of the rhyolitic rocks with a negative Eu anomaly. Several other waters (not shown) also exhibit REE patterns similar to the TFVF rhyolitic rocks. In contrast, a few waters had strong positive Eu anomalies as illustrated by the Driscoll Spring (Figure 5e).

The REE patterns for representative BJVF waters are shown in Figure 5f. The REE concentration of the more acidic Laib Well is several orders of magnitude higher than other BJVF water (and all other sampled waters except the acid YELL waters). The normalized REE pattern for this well largely resembles that of the rhyolitic rocks. The other three waters (Mt Home AFB #1, Tindall Well North, and Lower Indian Bathtub Hot Springs) show a positive Eu anomaly, and generally, an increasing trend in the HREE region with atomic number greater than Er. As is the case with the Laib Well, all BJVF waters shown in Figure 5f exhibit a negative Ce anomaly.

5. SUMMARY

The SRP region in southern Idaho has long been known to have a regionally high crustal heat flow. Ongoing volcanic activities and presence of several hot spring systems in the area also indicate a great potential for geothermal resources. Previously, we have chemically characterized geothermal waters from this region. Recently, we measured REE concentrations in these same waters. Supplemented with literature data, we have compiled an aqueous REE database for about 150 geothermal and groundwater features scattered within and along the margins of the SRP. We have also compiled an additional database of REE concentrations for volcanic (rhyolites and basalt) rocks in the SRP.

The REE concentrations and chondrite normalized values of SRP rocks show two distinct rock-type specific REE distribution patterns – one for the rhyolitic rocks and another for the olivine tholeiite basalts. In general, the chondrite-normalized REE pattern for the composite rhyolitic rocks shows a steep decreasing trend from La to Eu and an increasing trend from Eu to Tb followed by almost featureless heavy REE region. In contrast, the REE pattern for the ESRP basalts exhibit a decreasing trend from light to heavy REE with some less-pronounced features superimposed on the trend.

The total REE concentrations of SRP geothermal waters were very low, generally significantly less than 1 ppb (ng/L). The chondrite-normalized REE values for SRP geothermal waters exhibit greater diversity than do the SRP volcanic rocks. Several waters had large positive Eu anomalies whereas others showed an increasing trend in the MREE and/or HREE regions of their REE patterns. Further, some waters showed negative Ce and/or Eu anomalies. The variety of REE distribution patterns reflect differences in the interaction of geothermal waters and reservoir rocks, dominant complexing anions, preferred dissolution/leaching of REE accumulating minerals, and prevailing redox conditions. In our ongoing geothermal assessment, we plan to integrate REE and major element chemistry for SRP waters with the geology and petrochemistry of their associated volcanic rocks to refine our understanding of the SRP geothermal systems.

DATA AVAILABILITY

Data discussed here are publicly available at http://search.geothermaldata.org/dataset

ACKNOWLEDGMENTS

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