

Do Magmatic-Related Geothermal Energy Resources Exist in Southeast Idaho?

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ABSTRACT

This paper assesses the possibility that magmatically related geothermal systems occur as blind geothermal resources in southeast Idaho. A brief summary is provided of the robust late-Pleistocene-Holocene structural, thermal and volcanic evolution of southeast Idaho, and contrasts that with the relative paucity of surficial manifestations of geothermal activity in the area. The paper presents and evaluates three hypotheses for the paucity of surficial expressions of magmatic-geothermal activity: 1. Accessible magma-related heat does not exist in the region. 2. Accessible magmatic heat exists but the hot rock bodies have not generated significant circulation of high-temperature geothermal fluids. 3. Magmatic geothermal systems exist in the region, but their surficial geothermal expression is diverted and/or muted owing to external factors (i.e. they exist as blind resources). Each hypothesis is examined in light of documented features of the regional geology, petrogenesis of late-Pleistocene-Holocene volcanics and hydrogeology. Arguments are presented which suggest that the first two hypotheses are unlikely. The paper concludes that magmatic-related geothermal systems are likely to exist in southeast Idaho, and it proposes that those systems are masked by the combined effects of a distinctive shallow hydrogeologic conditions and deeper crustal anisotropy that controls fluid pathways at depth.

Introduction

SE Idaho is a distinctive region within the northeastern Basin and Range with significant geothermal exploration potential, but little development (e.g., Neely and Galinato, 2007; Fleischman, 2006; Laney and Brizzee, 2003) (Fig. 1). Evidence for geothermal potential is indicated mainly by some of the highest regional heat flow in North America, young basalt-dominated volcanism and

ongoing crustal extension (e.g., Brott et al., 1981; Blackwell et al., 1992, 1993; Kuntz et al., 1992; Hughes et al., 1999; Payne et al., 2008). Additionally, numerous large Pleistocene (<2 Ma to 0.058 Ma) rhyolite lava domes and cryptodomes dot the region (e.g., McCurry et al., 2008). Similar rhyolites support major high-T (>200°C) geothermal systems in other parts of the Basin and Range, mainly near the periphery of the Great Basin (e.g., Koenig and McNitt, 1983). Following usage by Arehart and others we refer to geothermal systems which are spatially and temporally

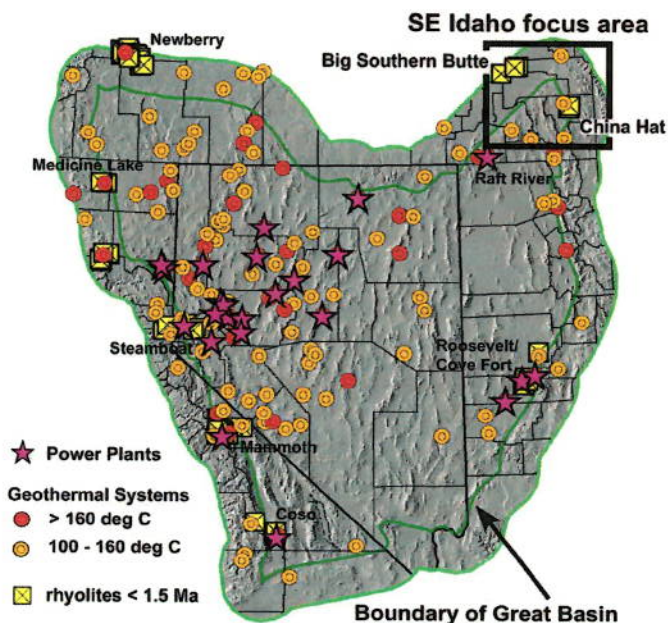


Figure 1. Overview of geothermal systems in the Great Basin, modified from Coolbaugh (personal communication, 2012). Of the seven young (<1.5 Ma) rhyolitic volcanic regions around the periphery of the Great Basin (Roosevelt/Cove Fort, Coso, Mammoth, Steamboat, Medicine Lake, Newberry), all but southeast Idaho are associated with unambiguous surficial evidence for magma-related geothermal potential. Raft River, a non-magmatic geothermal system (e.g., Ayling et al., 2011; Jones et al., 2011), is the only power producing geothermal field currently in operation in Idaho.

associated with these young silicic volcanic fields, and which are believed to derive significant heat from cogenetic shallow magma bodies, as 'magmatic-related' (e.g., Arehart et al., 2002, 2003).

Importantly, in contrast to systems which are generally believed to be magmatic-related and that are located elsewhere in the Basin and Range (e.g., Roosevelt/Cove Fort, Coso, Mammoth, Steamboat Springs, Medicine Lake, Newberry), Quaternary rhyolites in SE Idaho lack many of the obvious signatures of those young silicic volcanic fields such as hot springs, fumaroles, geochemical indicators of derivation from high-T reservoirs, or surficial hydrothermal alteration (Fig. 2).

Figure 2 illustrates the lack of obvious spatial correlation between shallow aquifer temperatures and potential magma-related heat sources, shown in black shading. Warmer aquifer waters define fields (yellow lines), but none exhibit obvious coincidence with the young evolved volcanic centers. The westernmost of the fields could be an exception. It overlaps with a cluster of evolved

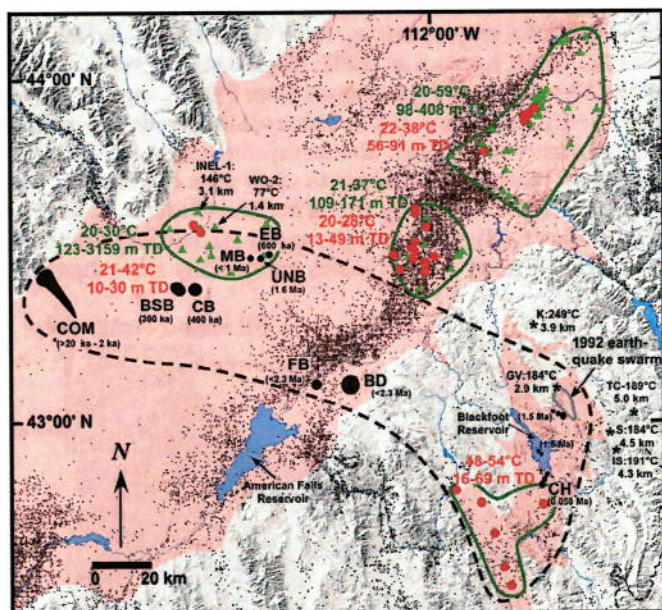


Figure 2. Map illustrating selected geothermal-related features of the northeast trending Eastern Snake River Plain (ESRP) and Blackfoot volcanic fields (BVF). The latter is located in the bottom-right part of the diagram. Pink shading illustrates areas underlain by late Pliocene to Quaternary olivine tholeiite lavas. Water wells with temperatures $<20^{\circ}\text{C}$ are shown as black dots; wells deeper than 90 meters (300 ft) with water temperatures exceeding 20°C are shown as green triangles, and those shallower than 90 m with temperatures greater than 20°C are shown as red circles (TD = total well depth in meters). Well temperature data are from Idaho Dept. of Water Resources (K. Neely, 2012, written communication). A black dashed line encompasses the region of Quaternary evolved volcanic centers in SE Idaho. Evolved mafic to silicic volcanic fields and hypabyssal cryptodome intrusions are shown in black (shown with dates or age estimates): COM - Craters of the Moon; BSB - Big Southern Butte; CB - Cedar Butte; MB - Middle Butte; UNB - Unnamed Butte; EB - East Butte; FB - Ferry Butte cryptodome; BD - Buckskin cryptodome; CH - China Hat. Deep oil and gas boreholes are labeled and include borehole depths (in kilometers) and bottom-hole temperatures: K=King#2-1, GV=Gentile Valley 9-1, TC=Tincup Mtn. Federal 1, S=Stoor A#1, IS=Idaho State A-1 (from Idaho Geological Survey, 2012, Idaho Oil and Gas Wells, 1903-1988), and deep geothermal test holes, INEL-1 and WO-2 (Blackwell, 1990).

centers (MB= Middle Butte, UNB=Unnamed Butte, EB=East Butte). Interestingly, McLing et al. (McLing, personal communication, 2012) have mapped more subtle thermal features (between 10 and 20°C) of the Eastern Snake River Plain Aquifer (ESRPA), the most prominent of which appears to originate near East Butte. This paper investigates possible reasons for differences in surficial thermal expressions of the respective volcanic/magmatic systems and speculates that shallow magmatic-related geothermal systems exist in SE Idaho as blind geothermal resources.

In the following narrative, we briefly summarize key aspects of the volcanic and tectonic setting and evolution of SE Idaho, focusing on features of the young silicic volcanic fields. We consider the following hypotheses for the paucity of recognizable surficial expressions of high-T geothermal systems in southeast Idaho:

1. Accessible magma-related heat/fluids do not exist in this region because:
 - a. magma origin/storage is too deep (no upper crustal storage); or
 - b. all magmas that are stored in the upper crust have brief residence times and are quickly and completely erupted.
2. Accessible heat exists but the hot rock bodies lack extractable geothermal fluids because the original magmatic systems were unusually dry or have not generated significant circulation of high-temperature fluids because of insufficient permeability or a lack of adequate fluid flow pathways; possibility of an EGS resource.
3. Magmatic systems in this region are similar to other magma-related Basin and Range systems but their surficial geothermal expression is diverted and/or muted owing to external factors.

Structural and Volcanic Context for Geothermal Systems of SE Idaho

The large scale crustal framework of southeast Idaho is dominated by thick (~ 42 km) Archean to early Proterozoic crust consisting of pronounced mafic lower and felsic upper parts, that are overlain by 6-10 km of late Proterozoic to Mesozoic platform sediment (Fig. 3). Supracrustal sedimentary rocks are 'shingled' to the east in major thrust sheets produced during Laramie, Sevier and older orogenies (e.g., Dixon, 1982). East-west extension ensued beginning in the mid-Miocene and is regionally and temporally focused by interactions with the Yellowstone-Snake River Plain hot spot track (YSRP) (e.g., Rodgers, 2002; Payne et al., 2008; Pierce and Morgan, 2009).

The late Cenozoic tectonic and magmatic geology of SE Idaho is dominated by the YSRP (Pierce and Morgan 2009). The YSRP is a 17-1 Ma time-transgressive volcanic field developed in cogenetic association with the 17-15 Ma mafic Columbia River Plateau mafic Large Igneous Province (LIP, e.g., Shervais and Hanan, 2009). Both are expressions of interaction of a deep mantle thermal plume with the continental lithosphere (e.g., Smith et al., 2009; Leeman et al., 2007, 2009; McCurry et al., 2008; Pierce and Morgan, 2009).

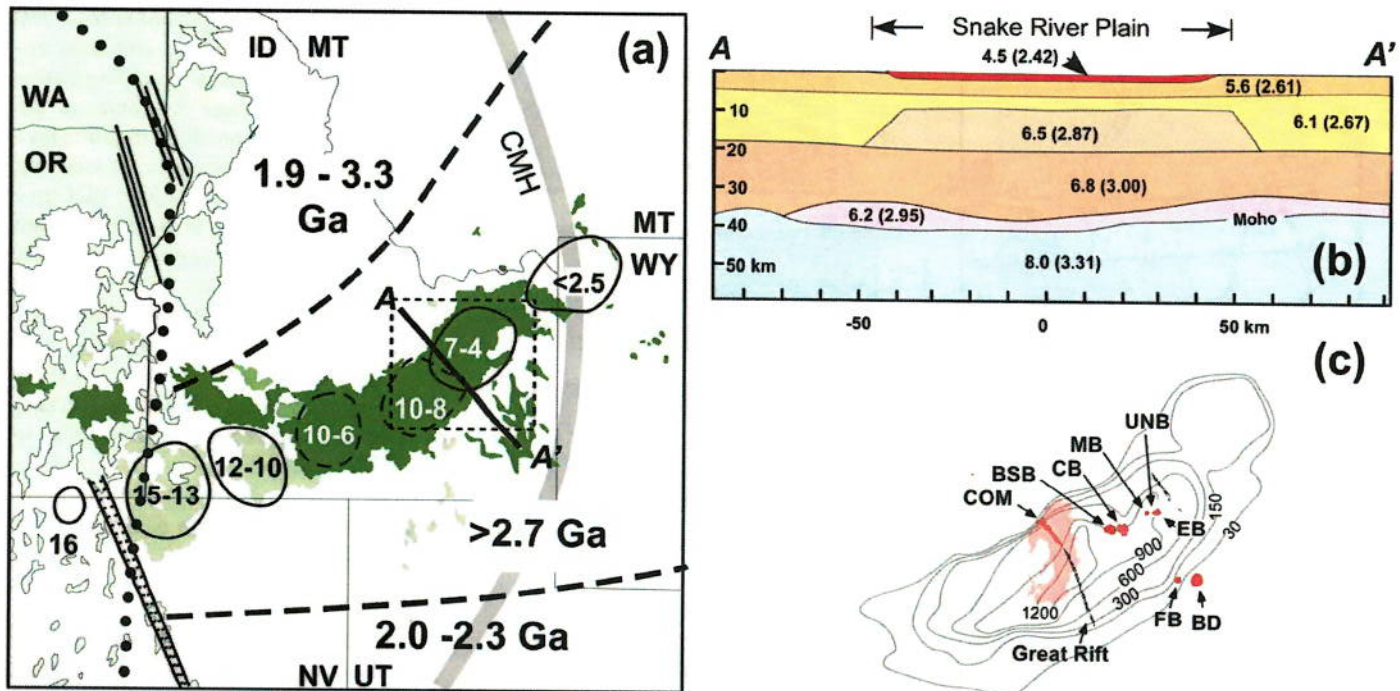


Figure 3. Regional geologic setting and crustal architecture, modified from McCurry et al. (2008). (a) Light green and dark green shading, respectively indicates Miocene (17-15 Ma) basalts of the Columbia River large igneous province, and Quaternary basalts. Bold dotted line indicates boundary between late Proterozoic terrain to the east and Mesozoic and younger terrain to the west. CMH - Cordilleran Miogeoclinal hinge line and approximate eastern limit of fold and thrust belt. Circled regions are silicic volcanic fields of the Yellowstone-Snake River Plain hot spot track (ages shown in Ma). (b) Crustal profile illustrating seismic velocities and densities of major layers, red - silicic volcanic rocks (~2 km average thickness) and overlying mafic lavas (thickness contours shown in (c) in km); orange - late Proterozoic to Mesozoic miogeoclinal; yellow - Archean granitic upper crust; brown - mid-crustal high density zone; dark orange - Archean mafic lower crust; pink - partial melt zone at Moho; blue - upper mantle. (c) Illustrates basin-like geometry of late Pliocene-Holocene Eastern Snake River Plain volcanic field. Evolved mafic to silicic volcanic fields and hypabyssal cryptodome intrusions are shown in red and pink. Abbreviations are the same as in Figure 2.

SE Idaho Magmatic Systems and Thermal Evolution

Large amounts of mantle derived basaltic magma and heat were transferred to the mid- and upper crust on a regional scale during passage of the hot spot beneath the Eastern Snake River Plain (ESRP) (e.g., McCurry and Rodgers 2008; Leeman et al., 2007; Nash et al., 2006), producing a mid-crustal zone of high-density. During the climax of hot spot heat transfer temperatures exceeded the solidus in the mid-crust generating a zone of melting, assimilation, storage and homogenization ("MASH" zone, Hildreth and Moorebath 1988), which in turn led to formation of large volumes of rhyolitic melts. Those melts subsequently segregated from the MASH zone and were transferred into the upper crust to produce A-type (ferroan, Frost and Frost, 2008) granites and cogenetic rhyolites that define the YSRP volcanic track (Christiansen and McCurry, 2008; McCurry and Rodgers, 2009; Leeman et al. 2007, 2008). Isostatic instability of the densified upper crust produced counterflow in the lower crustal into regions marginal to the plain (Rodgers and McCurry, 2008; Yuan et al., 2010). Collectively these processes produced the now waning YSRP thermal anomaly in the ESRP (e.g., Smith et al., 2009). The current conductive heat flow (110 mW/m²) is among the highest in North America (Smith 2004). Blackwell et al. estimate that 75% of the ESRP is above 200°C at a depth of ~4km, although much of this resource is likely EGS-type owing to low reservoir permeability conditions (Blackwell et al., 2007; Roberts, 2009).

The high heat flow extends beyond the northern and southern margins of the ESRP, consistent with a dominant deep crustal heat source and with the presence of scattered basalt-dominated volcanic fields flanking parts of the SRP (Blackwell et al., 1993). In SE Idaho this form of magmatism and tectonism ceased at ~4-4.5 Ma (Morgan and McIntosh, 2005), shifting to its current location centered in the Yellowstone region (Smith et al., 2009).

In contrast to the older, hot spot track style of magmatism, a second late Pliocene to Quaternary, essentially ongoing phase of magmatism in ESRP consists of a combination of:

1. A time-averaged steady flux of relatively primitive and homogeneous mantle derived olivine tholeiite, reflected at the surface by linear accumulation rates of basalts from episodic monogenetic volcanism (Champion et al., 2002; Whitaker et al., 2007; Kuntz et al., 1992) producing basin-like accumulation of ~12,300 km³ of basalts at the surface, and ~15,000 km³ total magma transfer to the crust over the last 4.5 m.y. amounting to a volume flux of 0.0033 km³/yr (McCurry et al., 2008; McCurry and Rodgers 2009).
2. A coeval, less voluminous flux of mantle derived, but highly evolved cogenetic mafic to silicic magmas. These are distinguished by polygenetic volcanism rooted to mid-to upper-crustal magma reservoirs (e.g., Kuntz et al., 1992). This style of magmatism produce a flux of ~10% that of the olivine tholeiite (McCurry et al. 2008).

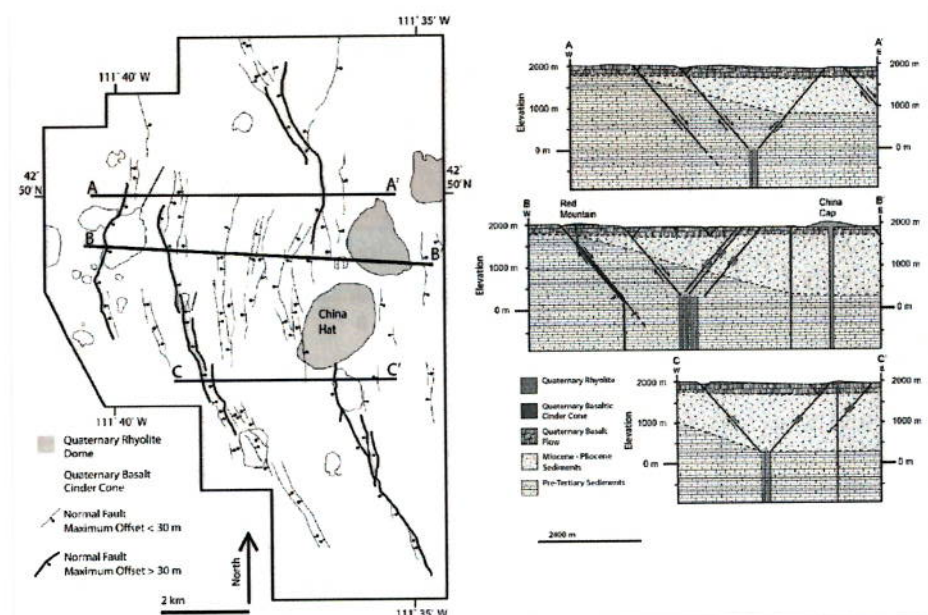


Figure 4. Geologic cross-sections for the Blackfoot Reservoir Volcanic Rift Zone (after Polun, 2011). Dikes (vertical lines in sections A-C) are inferred from surface deformation. On the basis of modeling, dikes are inferred to accommodate 200 – 600 meters of EW directed crustal extension and rise from > 10 km to ~2 km depth in the northern part of the rift, shallowing to ~1 km depth in the southern part of the rift zone. Rift faults and related dike emplacement overlaps the age of the 58 ka China Hat lava dome, and could therefore plausibly range from >100 ka to < 50 ka. Total dike volume between 10 and 1 km depth is likely to be ~10's km³.

Concurrent with development of the ESRP volcanic field, compositionally similar olivine tholeiite volcanism occurred south of the hot spot track within a region of ongoing Basin and Range-type extension which we refer to as the Blackfoot Volcanic Field (BVF) (Fig. 1). This 1500 km² lava field consists of ~100 km³(?) of basalt that have partially infilled a series of north

trending grabens to depths of at least 250 m in some places. Many eruptions appear controlled by range bounding faults. However, located near the center of the volcanic field there are three rhyolitic lava dome fields and a robust north trending volcanic rift zone (Ford, 2005; McCurry and Ford, 2006; Polun et al., 2010; Polun 2011). Polun's work suggests that several ten's of km³ of magma were emplaced into the upper crust via the rift zone alone between ~50 and ~100 ka (Fig. 4).

Figures 5A and 5B illustrate the chronology and volumes of evolved volcanic and inferred cogenetic intrusive rocks in the ESRP and BVF.

Quaternary Magma Storage, Evolution, Degassing and Eruption

Olivine tholeiite volcanoes of ESRP root into deep crustal and mantle reservoirs (e.g., Leeman et al., 2007; Kuntz et al., 1992), and are therefore probably not of interest from a geothermal perspective, except perhaps in helping to maintain high regional heat flow. However, petrologic, geochemical and experimental

work indicates that evolved magmas types could be of significant geothermal potential because they have significant mid- to upper crustal residence times.

Evolved magmas in SE Idaho have distinctly ferroan geochemical characteristics (e.g., Frost and Frost, 2008) in contrast

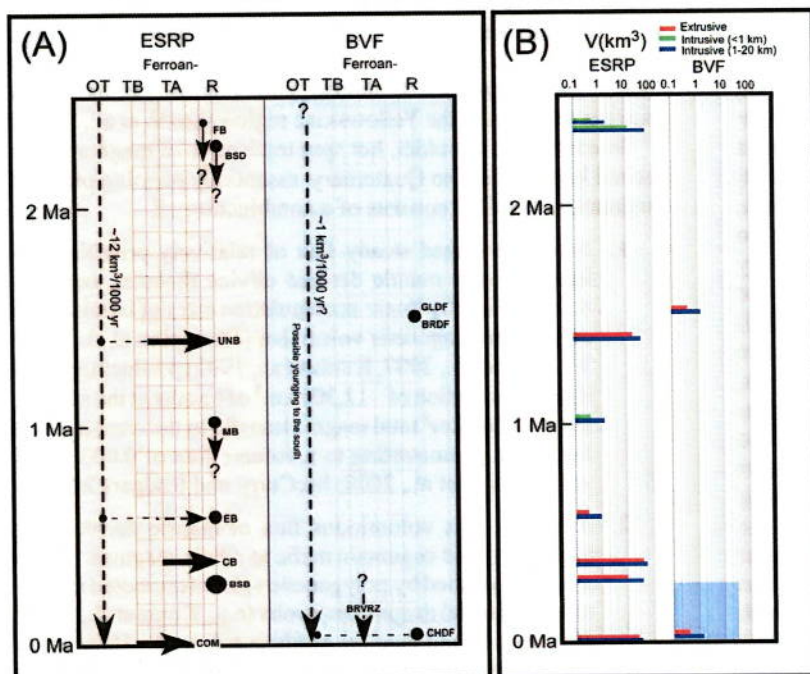


Figure 5A. Quaternary volcanic activity in ESRP and BVF. Horizontal arrows indicate cogenetic compositional spectrum of erupted lavas; horizontal dashed lines indicate magmatic mafic enclaves in more evolved lavas; vertical dashed lines indicate age range for eruptions of olivine tholeiite lavas; vertical arrowed lines with question marks indicate age estimate. Abbreviations: OT = olivine tholeiite; Ferroan series, B = basalt, A = andesite, R = rhyolite. ESRP = Eastern Snake River Plain volcanic field; FB = Ferry Butte; BSD = Buckskin Dome; UNB = Unnamed Butte; MB = Middle Butte; CB = Cedar Butte; BSB = Big Southern Butte; COM = Craters of the Moon. BVF = Blackfoot volcanic field; GLDF = Grey's Lake dome field; BRDF = Blackfoot Reservoir dome field; CHDF = China Hat dome field; BRVRZ = Blackfoot Reservoir volcanic rift zone.

Figure 5B. Estimates of evolved magma volumes extruded and inferred comagmatic magmas intruded into the upper crust. More voluminous olivine tholeiite is excluded with the assumption that most of that magma is erupted directly from the upper mantle or from lower and mid-crustal storage zones. There is no direct indication for the compositions of magmas associated with the BRVRZ; they could include or be dominated by olivine tholeiite and/or have any of the compositions of the evolved ferroan magma suite.

to Tertiary rhyolites of more southern parts of the Great Basin (e.g., Christiansen and McCurry, 2008). The rocks vary from ferroan trachybasalt to ferroan rhyolite, with the more mafic and intermediate volcanic rocks dominating over the most felsic ones (McCurry et al., 2008). The distinctive geochemical characteristics of the rocks result from the dominant role of mantle derived basaltic magmas in the system – in particular the role of equilibrium and fractional crystallization. ESRP rhyolites at Big Southern Butte and Cedar Butte are some of the best examples worldwide of extreme polybaric differentiation of olivine tholeiites. Experimental work on these rocks by Whitaker et al. (2008), ECAFC, MELTS thermodynamic modeling by McCurry et al. (2008), major-, trace- and heavy isotopic analyses and phenocryst thermobarometry by Putirka et al. (2009) at Craters of the Moon and McCurry et al. (2008) at Cedar Butte, indicates that a large fraction of magma differentiation and lesser crustal assimilation (e.g., COM and EB, Putirka et al., 2009; Kuntz et al., 1986; Ganske and McCurry, 2006) occurs in mid- and upper-crustal regions. Compositionally diverse magmatic enclaves are common in the rocks, indicating that magma mixing was a common, albeit minor process of diversification. Mass balance modeling, and simple assumptions regarding melt retention McCurry et al. (2008) indicates that 4–10 times the mass of erupted magmas remains in the mid- to upper crust in the form of unerupted magma and crystal cumulates. These estimates are recorded in Figure 4A.

Rhyolites of the BVF are broadly similar to ferroan ('A-type') rhyolites of the ESRP (McCurry et al., 2008). However, as was the case for ESRP basalts, they also have a variety of unique petrologic and geochemical features (Ford, 2005). Geochemically, the rhyolites are referred to as 'topaz rhyolites' (Christiansen, 1983). Primarily the product of extreme differentiation of basaltic parental magmas, these rhyolites are characterized by very high concentrations of incompatible elements (e.g., Cs, Ta, Yb, Rb, U and Th). In the central dome field concentrations of thorium reached saturation in the magmas, resulting in crystallization of thorite (ThSiO₄).

Mineralogical and geochemical features of the rhyolites allow for determination of their depths and temperatures of origin (~13 km and ~760°C, respectively). Interestingly, preliminary melt inclusion analysis indicates that the rhyolites also were strongly hydrous at depth, subsequently degassing during slow ascent towards the surface (Ford, 2005; McCurry, unpublished data; cf. Jaupart, 1998). In addition, as in the case of ESRP evolved rocks, the rhyolites contain common but volumetrically minor amounts of mafic magmatic enclaves. The enclaves are similar in composition to nearby olivine tholeiite lavas, and they indicate that the two magma types intermingled with each other just prior to their eruption.

Magma Volatiles

Pre-eruptive magma volatile content can be estimated from studies of melt inclusions, if suitable phenocrysts occur, and from the presence of volatile bearing mineral phases. The latter are absent in the ESRP. Additionally, few of the rhyolites, or evolved intermediate composition rocks at Craters of the Moon (COM) or Cedar Butte (CB) contain useable melt inclusions. However East Butte (EB) rhyolite lava dome contains a robust assemblage of melt-inclusion bearing phenocrysts. Electron microprobe analyses

of high-silica rhyolite melt inclusions in pyroxene; olivine and quartz phenocrysts consistently yield low-totals (~93–98%), suggesting that the rhyolite magma contained ~2–7% H₂O prior to eruption (F and Cl concentration were near EMP detection limit). A hydrous phase of rhyolite evolution is further supported by the presence of pronounced granophyric textures in one of three texturally distinct populations of sanidine in the EB rhyolite (Ganske and McCurry, 2006; Ganske, 2006; Lowenstern et al., 1997). Ganske and McCurry (2007) speculate that slow ascent of the East Butte rhyolite from mid- to upper-crustal reservoir allowed effective degassing of the H₂O (cf., Woods and Koyaguchi, 1994). Mineral thermobarometry and melt-inclusion data indicates that BVF rhyolites equilibrated at $P = \sim 350$ MPa, $T = 760 - 810$ °C, $DQFM = 0.64$, and $X_{H_2O} \sim 4\%$ (Ford, 2005; McCurry and Ford 2006). The volatile budget for Quaternary rhyolites which lack phenocrysts (e.g. Big Southern Butte), have anhydrous mineral assemblages or lack melt inclusions are more ambiguous. Interestingly, experimental work by Whitaker et al. (2008) requires that parental magmas evolved through a significant water bearing stage in order to match observed fractionation pathways. We infer that most if not all the rhyolites contained $\geq 4\%$ H₂O prior to their eruption.

Magma Residence Time

An important consideration in understanding the potential thermal contribution of magmas to geothermal systems is defining how long they reside as magmas in the upper crust (defined as between 2 and 15 km depth). Recent advances in U-series geochemistry have successfully allowed for estimates of such residence time, where in this case 'residence time' is inferred from time required for precipitation of phenocrysts while they reside in the upper crustal reservoir. Recent application of this type of analysis to rhyolites at the Coso volcanic field yielded unexpectedly short residence times (Simon et al., 2009; cf. Reid, 2003). Interestingly, Heumann (1999) conducted a similar study for a rhyolite sample from China Hat and he obtained similar results to those obtained for the Coso system.

Discussion

The principle objective of this paper is to develop a rational argument for the likelihood of magmatic-related geothermal resources in SE Idaho. We consider three hypotheses:

Hypothesis 1. Accessible magma-related heat/fluid do not exist in SE Idaho because:

- a) Magma origin/storage is too deep (i.e. no upper crustal storage)

This hypothesis is demonstrated to be false, at least as an unqualified assertion. Most, if not all SE Idaho's evolved magmatic systems resided and evolved from extensive fractionation of parental magmas in the mid- to upper crust. However it is not clear what the appropriate time scales are for such systems to wax and wane. Coso is the only system in the Basin and Range, which has been studied, in sufficient detail to define those characteristics.

- b) All magmas that are stored in the upper crust have brief

residence times and are quickly and completely erupted.

U-series work on China Hat suggests that residence time may have been relatively brief in that system (Heumann, 1999). More work is clearly needed on that and other SE Idaho rhyolites. However there appears to be nothing exceptional about China Hat's residence time when compared to the most robust magmatic-related geothermal system in the Great Basin region, i.e. the Coso Volcanic Field.

The second part of this hypothesis is more easily falsified. It seems clear from petrological, thermobarometric and thermodynamic modeling work that SE Idaho rhyolites are dominantly the product of extensive mid- to upper crustal fractionation of mafic parental magmas. Therefore large volumes of unerupted magma and hot crystal cumulates would be expected to reside in the mid- to upper crustal plumbing systems of these volcanic fields.

Hypothesis 2. Accessible heat exists but the hot rock bodies lack extractable geothermal fluids because the original magmatic systems were unusually dry.

Although many of the SE Idaho rhyolites have anhydrous mineral assemblages and were essentially degassed at the time of eruption, it is clear that most if not all had pre-eruptive volatile contents (inferred as dominantly H₂O) that are well within the range of Quaternary rhyolites of the Great Basin (~2-7 wt.%).

Hypothesis 3. SE Idaho's evolved magmatic systems are, from a geothermal perspective, similar to other magmatic-related B&R systems but their surficial geothermal expression is diverted and/or muted owing to external factors.

Given the plausibility that high-T magmatic-related geothermal systems exist in SE Idaho, are there any external factors in that area which would also plausibly account

for systematically masking or diverting their geothermal signatures?

We point to two plausible scenarios:

1. Highly active, basalt-hosted shallow aquifers dilute magma-related heat and solutes via mixing and advection. Detailed studies of the ESRPA in the 1970's led to the discovery of dramatic discordances between heat flow from the ESRP above the aquifer (~27 mW/m²) as opposed to below the aquifer (~100 mW/m²) (e.g., Blackwell, 1992). It was also observed that waters within the shallow aquifer are heated well above their infiltration temperatures (by ~10°C; Brott et al., 1981; Smith, 2004). This mechanism appears to be highly effective in masking deeper heat flow, and likely geochemical signals as well. Shallow basalt aquifers occur in many parts of the Basin and Range, including the Blackfoot volcanic field (e.g., McCurry et al., 2011), and we therefore believe this scenario to be a common problem for blind resources.
2. A second plausible scenario was proposed in a conceptual model for the Blackfoot volcanic field by Autenrieth et al. (2011) (Fig. 6). This scenario recognized two key features of that system. First, that density traps and crustal structural traps may act to focus magma storage. Autenrieth et al. recognized that robust magma thermobarometry for the China Hat rhyolite indicates a storage depth corresponding to a level at which local crustal density drops by 2-3% (near the contact between granitic upper crust and miogeoclinal sediments). In the case of China Hat, storage also appears to coincide with the intersection of major Mesozoic thrust faults at that same location. Secondly, Autenrieth et al. speculated that the crustal structures could provide 'fast paths' for fluid advection that might direct the fluids with a strong lateral component of motion (cf. Thompson and Connolly, 1992). Dormant thrust faults have been shown

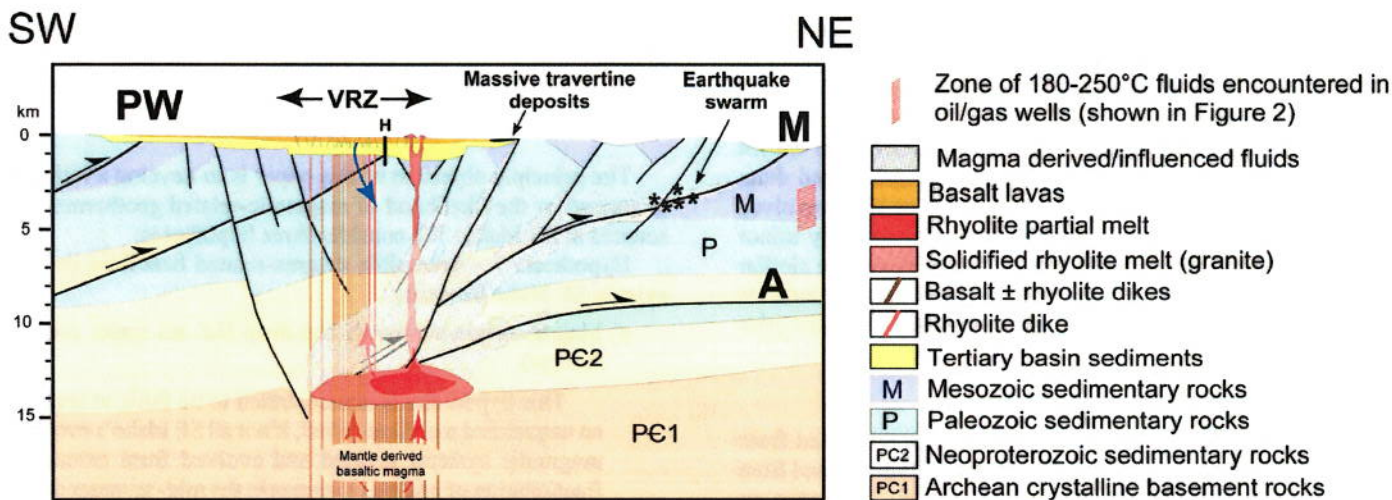


Figure 6. Conceptual model modified after Autenrieth et al. (2011) for the China Hat dome field and Blackfoot Reservoir volcanic rift zone. Upper crustal structures, depths and geometries are from Dixon (1982). Figure emphasizes crustal anisotropies, mainly major thrust faults (PW = Paris-Willard thrust; M = Mead thrust; A = Absaroka thrust), which we suggest may tend to channel geothermal fluids laterally to the northeast, away from the magmatic heat source. The figure also diagrammatically illustrates massive travertine deposits, which formed along the east side of the graben, and the 1992 earthquake swarm foci. Downward pointing blue arrow illustrates possible preferred pathways for deep infiltration of meteoric water (via dikes and dike-related rift faults; J. Moore, personal communication, 2011), resulting in dilution and cooling of deeper magmatic-influenced fluids.

elsewhere to act as conduits for fluid migration (e.g., Blumstein et al., 2005) and enhanced permeability appears to exist in at least some lithologies adjacent to the Meade Thrust (Ralston et al., 1983). Interestingly, Autenrieth et al. note features of the regional geology that could be consistent with northeast transport of deep geothermal fluids, most importantly including massive travertine deposits produced along range front faults on that side of the graben and the existence of 180–250°C waters encountered 10–20 km to the northeast in wildcat exploration wells at depths of 3–5 km (IGS, 2012). Dating of the travertines would be a key test of this hypothesis (e.g., do they record a formation age that coincides with the 58 ka age of China Hat?). Autenrieth et al. also noted the occurrence of higher deep well temperatures, and the occurrence of an earthquake swarm in 1992 in that region that may record some form of fluid motion or shallow tectonic activity (Payne, personal communication, 2005). Welhan (coauthor) will be conducting a thermal gradient drilling program in this area to better define lateral variations in heat flow.

Conclusions

Characteristics of Quaternary volcanic fields in SE Idaho indicate that significant storage of evolved magma and magmatic-related heat energy, comparable to other magmatic-related systems of the Great Basin, occurs in parts of the upper crust (between 2–15 km deep) and may define important targets for future hydrothermal and/or EGS exploration (Fig. 7). The role of crustal anisotropy in trapping and diverting magmatic and hydrothermal fluids (e.g., Faults, 2006) appears to be fertile ground for future research (Fig. 6). However the difficulties posed by mixing and dilution within shallow basalt-dominated aquifers remains a serious obstacle for researching this type of blind resource.

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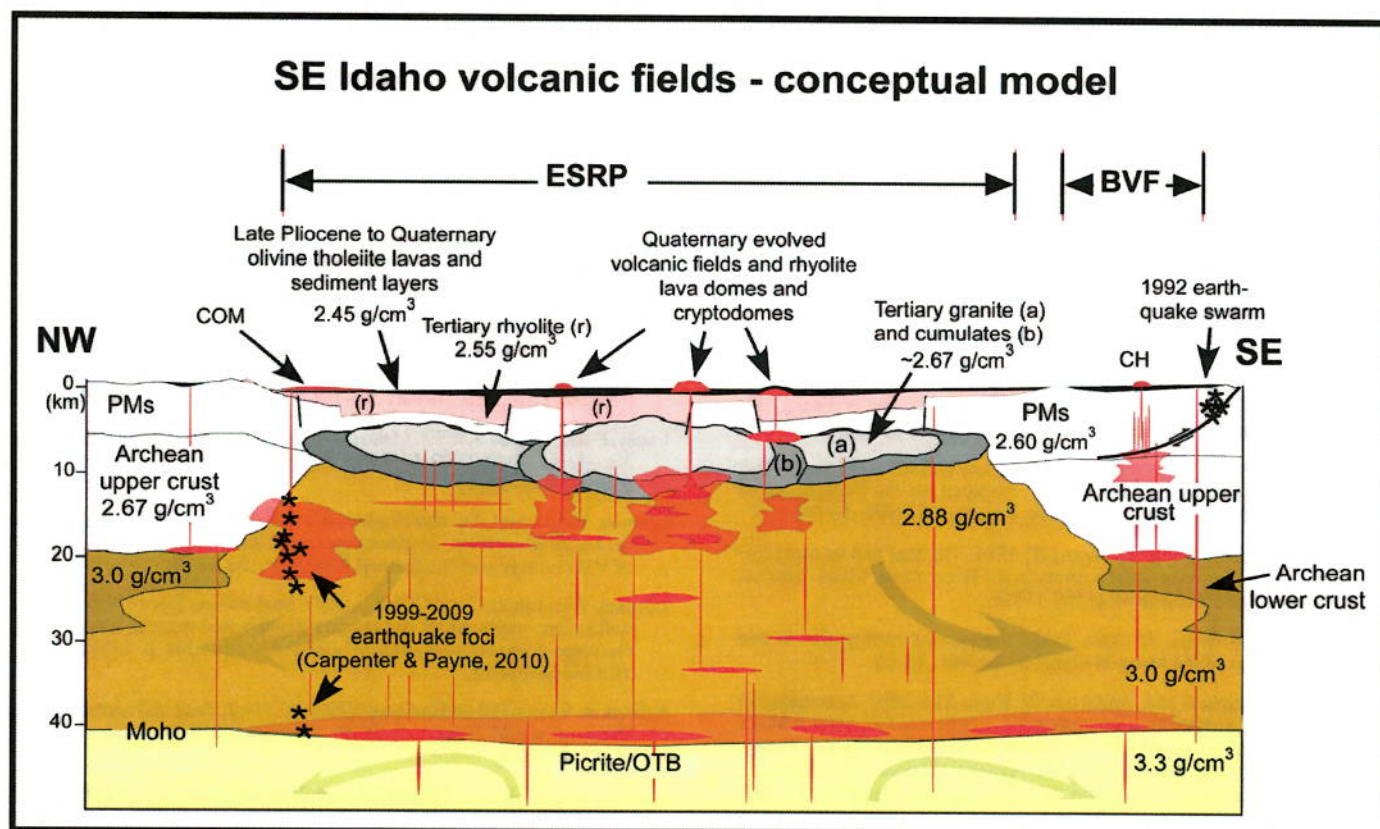


Figure 7. Conceptual model, modified from McCurry and Rodgers (2009) and Christiansen and McCurry (2008), illustrating a plausible crustal architecture and Quaternary magmatic framework for southeast Idaho. Major hotspot related volcanism and intracrustal processes, including development of an A-type batholith, mid-crustal density anomaly, and lower crustal counterflow had ceased by this time. This phase of development is dominated by a reduced but steady flux of mantle derived magmas into the crust. Many of these are extruded to the surface with only brief crustal residence. Others are captured within the crust whereupon they undergo extreme polybaric fractional crystallization (shown as irregular red shapes in the region between 10 and 20 km depth), in some cases accompanied by minor concomitant assimilation of Archean upper crust. Evolved magmas tapped from these zones may be extruded at the surface or become density trapped between Tertiary rhyolites and less dense fractured basalts, inflating to form cryptodomes. Distinctive seismicity, which may record magma transfer or related crustal responses to it, is associated with COM (Carpenter and Payne, 2010), and possibly also near China Hat (CH; Jackson et al., 1993).

ing the seismicity of SE Idaho. A constructive review by Mark Coolbaugh led to improvements in the manuscript and is gratefully appreciated. Temperature data for wildcat and water wells was compiled by the Idaho Geological Survey for the National Geothermal Data Program in part by the Department of Energy's Geothermal Technologies Program under contract IDEE0002850.

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