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Evaluation of the geothermal potential of the western Snake River Plain based on a deep corehole on the Mountain Home AFB near Mountain Home, Idaho

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Abstract

A geothermal exploration corehole was drilled to a total depth of 1821.5 m on the Mountain Home Air Force Base near Mountain Home, Idaho. The corehole was used to collect an unusually large amount of data, including uniaxial compressive stress (UCS) experiments on core samples, to evaluate the geothermal potential of the western Snake River Plain. In addition, unlike many exploration holes in this region, a fluid entry was encountered at 1745.3 m and flowed artesian to the surface. A maximum temperature of 149.4 °C was calculated for the entry. A temperature log run on the corehole from 3 to 1675 m is nearly linear with little variation. The average geothermal gradient is 73 °C/km, and the average heat flow between 200 and 1500 m is 102 ± 15 mW/m^2. Chemical analyses of a sample from the fluid entry suggest that a significant proportion of the water is not meteoric. Five geothermometers show equilibrium temperature in the range of 133–157 °C. Furthermore, based on the unconfined UCS experiments on basalt core samples, a brittle unit was found to comprise the fractured reservoir that the geothermal water flows from, while an overlying ductile unit acts as a hydrothermal caprock. This implies that the reservoir/caprock pair may be a target for future exploration wells drilled to delineate the extent of the potential resource and the boundaries of the connected fracture network.

Keywords: Temperature log, Heat flow, Geothermometers, Basalt, UCS experiments

Introduction

The Snake River Plain (SRP) in southern Idaho has high heat flow (Blackwell 1989; Blackwell et al. 2011) due to the emplacement of basaltic magma in the deep to middle crust (Shervais et al. 2011, 2013) and has the potential for commercial geothermal energy development. Heat flow in excess of 100 mW/m^2 has been documented (Blackwell and Richards 2004). This high heat flow is associated with the Yellowstone hotspot, which developed from a mantle plume (Smith et al. 2009). The potential for geothermal resource development in the SRP has long been recognized, but only recently has a well-developed conceptual framework for these systems emerged (e.g., Nielson and Shervais 2014; Nielson et al. 2015, 2017).

The SRP consists of mantle-derived basalts that erupted in the axial portions over the past six to eight million years and rhyolite eruptive complexes that underlie the basalt. The rhyolite eruptive centers, which crop out along the margins of the plain, resulted from the melting of continental crust during intrusion of basalt from the hotspot (McCurry and Rodgers 2009). These sequences provide a complete record of volcanism from about 17 Ma to 200 ka in the west and 2 ka in the east (Shervias et al. 2016).

The eastern SRP is a northeast–southwest downwarp formed from lithospheric thinning and subsidence resulting from passage over the Yellowstone hotspot (Smith and Braile 1994), while the oblique extension, fault-bounded basin of the western SRP is a result of the interaction of the hotspot with western extension of the Basin and Range beginning about 11 Ma (Shervais et al. 2002; Wood and Clemens 2002). The eastern SRP is home to the Snake River Plain aquifer, which is hosted primarily in basalt (Welhan et al. 2002a, b). The majority of these basalts are olivine, tholeiite pahoehoe flows (Greeley 1982; Leeman 1982; Kuntz et al. 1992) and are similar in composition to oceanic island basalts like those forming the Hawaiian Island chain (Bonnichsen and Godchaux 2002; Shervais et al. 2002). The bulk of the volcanic vents is clustered around the axis of the SRP (Smith 2004; Shervais et al. 2016).

The SRP aquifer is one of the most productive aquifers in the United States (US Geological Survey 1985). High-permeability zones in fracture networks and rubble zones at the boundaries of the lava flows act as conduits for rapid transport of groundwater (Smith 2004) and geothermal fluids at greater depths.

One focus of geothermal exploration in the SRP has been the western SRP near Mountain Home, Idaho, and Mountain Home Air Force Base (AFB). A geothermal test well was drilled here in 1985–1986 (MH-1: Lewis and Stone 1988) and further exploration was carried out by two projects funded by the US Department of Energy (Breckenridge et al. 2012; Garg et al. 2016, 2017; Glen et al. 2017; Nielson et al. 2018).

An exploration corehole, designated MH-2B, was drilled to a total depth of 1821.5 m on the Mountain Home AFB in the western SRP near Mountain Home, Idaho (Fig. 1). This corehole was one of the three deep (up to two km) holes on the SRP drilled as part of Project Hotspot: the Snake River geothermal drilling project (Potter et al. 2011; Shervais et al. 2011; Delahunty et al. 2012; Lachmar et al. 2017).

The Mountain Home corehole was drilled into Miocene basalt flows typical of the central and eastern SRP (Shervais et al. 2013) after passing through approximately 210 m of Pleistocene to Holocene basalts overlying about 640 m of Pleistocene lacustrine sediments from ancient Lake Idaho (Bonnichsen and Godchaux 2002; Wood and Clemens 2002). The sub-lacustrine basalts include lava flows and hyaloclastites that have been variably altered by hydrothermal fluids (Walker and Wheeler 2016; Atkinson et al. 2017).

Materials and methods

Drilling

The drilling was done by Drilling, Observation, and Sampling of Earth's Continental Crust (DOSECC), which is a non-profit organization that works in concert with the International Continental Drilling Program (ICDP) on scientific drilling projects such as Project Hotspot. DOSECC drilled the corehole with an Atlas-Copco CS4002 diamond drilling rig. Drilling commenced on 10 July and ceased on 8 December 2011 at a depth

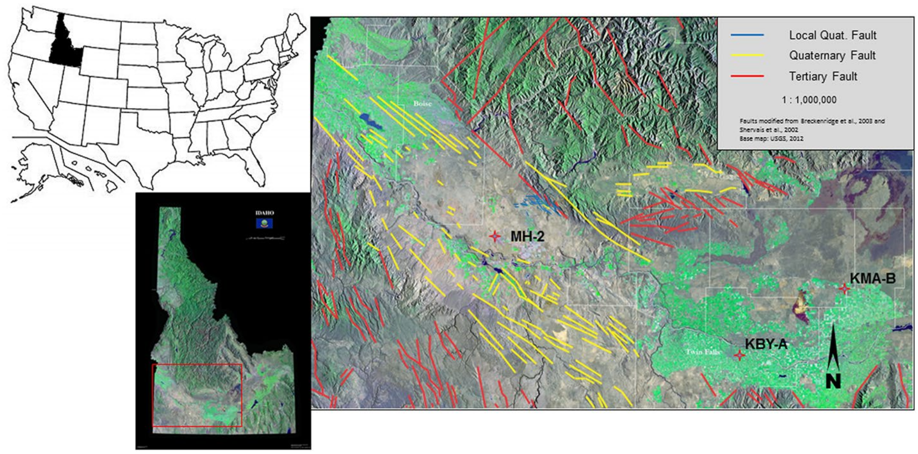

Fig. 1 Locations of Project Hotspot coreholes and regional faults. Green shading represents vegetation, either forests or farmland

of 1675 m. Geophysical logging was carried out from 15 to 22 January 2012, after which sufficient funds were secured to continue drilling. A fluid entry was encountered at 1745.3 m on 26 January 2012, and on 3 February 2012 the hole was completed to a total depth (TD) of 1821.5 m (Delahunty et al. 2012).

Descriptive core logging

The MH-2B hole was cored from 162 m to TD. Field logging took place as soon as the core reached the surface. Field logging consisted of washing, measuring, writing a physical description, photographing, and boxing the core. Once boxed, the core was transported off site for more detailed descriptions using the ICDP Drilling Information System (DIS). These logs are available through the ICDP website (https://www.icdp-online.org/).

Using the physical descriptions of the core, generalized lithologies can be made. After drilling through approximately 200 m of young, surface basalt flows, the MH-2B hole encountered primarily lacustrine sediments with a few basalt interbeds to a depth of about 800 m, where it transitioned to basalt and basaltic sediments until TD.

Temperature and geophysical logging

DOSECC monitored the temperature of the MH-2B hole to manage the drilling as well as to avoid the possibility of a blowout. The circulation of drilling fluid disturbs subsurface temperatures, making the determination of equilibrium temperatures difficult. The least disturbed area is the core stub that remains at the bottom of the hole while the core is retrieved. A thermistor was placed on the core stub that measured the temperature buildup with time (Nielson et al. 2012), which was then mathematically extrapolated to an equilibrium value using the $F(\alpha,\tau)$ method (Harris and Chapman 2007).

Temperature and geophysical logs also were run by ICDP's Operational Support Group (OSG) from Geo Forschungs Zentrum (GFZ), German Research Centre for Geosciences. OSG used wireline logging tools to record temperature, caliper, dip, resistivity, total gamma, spectral gamma, sonic velocity, and magnetic susceptibility (Schmitt et al. 2012). The temperature tool gave live readings and recorded the temperature while being pulled out of the hole. The OSG logging tool recorded temperature and pressure every 10 cm. These OSG logs end at 1675 m.

In addition to the temperature and geophysical logs, thermal conductivity was measured at the Southern Methodist University (SMU) Geothermal Laboratory using the divided-bar method. A detailed explanation of the procedure and tools used is given in Blackwell and Spafford (1987) and is described briefly here. One-inch (2.54-cm) diameter sample plugs from the intervals chosen were collected from the core and sent to SMU. There, samples were cut to approximately 1.25 in (3.175 cm) in height, and the tops and bottoms were smoothed to insure proper coupling with the divided-bar apparatus (DBA). Samples then were saturated with water under pressure for 8–12 h. Once saturated, samples were put into the DBA at approximately 400 psi (2760 kPa) with a constant temperature of 25 °C on top and 15 °C on the bottom, forcing a heat flux within the sample. Samples stayed within the DBA until they reached thermal equilibrium, at which point relative thermal conductivity was measured and absolute conductivity was calculated by comparison to standard thermal conductivity samples. Samples were not corrected to in situ conditions because the in situ pressure and temperature impact would be minor and likely within measurement error.

Water sampling

A water sample was collected from the MH-2B corehole on 26 January 2012 when the fluid entry was encountered during drilling. This entry produced artesian flow of geothermal fluid through NQ drill rod (60.3 mm ID) at a measured rate of 42 L/min (Nielson et al. 2012). Drilling was halted and the sample was collected directly from the drill rod. After sampling, the hole was mudded up to allow drilling to continue. The mud sealed the fluid entry, making it impossible to collect additional water samples.

The water sample was analyzed in the field for temperature, electrical conductivity (EC), pH and alkalinity. The sample also was analyzed for major ions by the Utah State University analytical laboratory (USUAL) using Inductively Coupled Plasma (ICP) analysis, except for chloride concentrations which were determined using a Lachat flow injector analyzer, which is an automated colorimeter. Separate analyses of the same sample were performed by the Utah Veterinary Diagnostic Laboratory in Logan, Utah, and ThermoChem Laboratory & Consulting Services in Santa Rosa, California. Finally, the sample was analyzed for the stable isotope ratios of deuterium to hydrogen and oxygen-18 to oxygen-16 by the Stable Isotope Ratio Facility for Environmental Research (SIRFER) at the University of Utah, and also for the radioactive isotope tritium at Brigham Young University.

Unconfined uniaxial compressive stress experiments

Unconfined uniaxial compressive stress (UCS) experiments were performed on 17 core samples over a 111-m interval from 1708 to 1819 m. The experiments were part of a larger study carried out at the Experimental Geophysics Group laboratory at the University of Alberta in Edmonton, Canada (Kessler 2014; Kessler et al. 2017a, b). Samples were taken from nine depth locations. Two 5-cm samples were taken from a 15-cm sample collected at each depth location. Two samples were taken from each depth for eight of the nine locations to determine the variability between adjacent samples.

Each sample was loaded into the uniaxial press, and strain gauges were wired to a bus connected to a desktop computer for data collection. The strain gauges measured axial and lateral strain continuously throughout the experiment. Output included the load, the force applied to the sample, the excitation voltage of the power source, and the axial and lateral changes in voltage across the strain gauges that were later converted into strain values.

Results

Geothermal gradient

Geothermal gradients calculated using temperature data from wells can be used to postulate what temperatures might be at greater depths. An average of 25 to 30 °C/km is typical for normal continental crust (Fridleifsson et al. 2008). A higher than average geothermal gradient was expected due to the proximity of the Yellowstone hotspot and recent volcanic activity in the area.

A maximum temperature for the MH-2B corehole of 149.4 °C was estimated using the DOSECC temperature tool. The OSG temperature log was used to determine the average geothermal gradient for the hole, which is 73 °C/km for the entire interval from 3 to 1675 m (Fig. 2). This is identical (73 °C/km) to the gradient obtained in MH-1 drilled 3 km to the southeast (Lewis and Stone 1988). Three linear sections were used for heat flow calculations (Fig. 2).

The temperature data were combined with thermal conductivity measurements of core samples to calculate heat flow. Conductivity was measured on four basalt samples (Table 1). Thermal conductivity is highest in the 169-m sample. This sample is just above the lacustrine section and may contain some lacustrine sediments filling pore space that

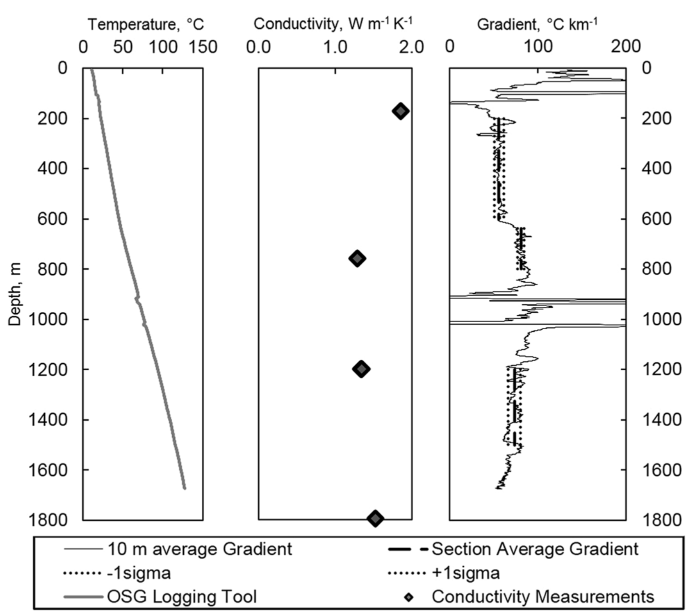

Fig. 2 Temperature log (OSG), conductivity measurements, and average gradient for the MH-2B corehole

Table 1 Thermal conductivity measurements from core

Depth (m)	Thermal gradient (°C/km)	Depth (m)	Conductivity [W/(m K)]	Calculated heat flow (mW/m^2)
200–600	56 ± 5	169	1.86 ± 0.1	104 ± 16
640–800	81 ± 4	758	1.29 ± 0.1	104 ± 13
1200–1500	73 ± 7	1200	1.35 ± 0.1	99 ± 16
		1794	1.53 ± 0.1	

Table 2 Results of chemical analysis of MH-2B water sample by USUAL (all units in mg/L unless otherwise noted)

T (°C)	EC (μS)	pH	Alkalinity	Ca	Mg	Na	K	Cl	SO_4	SiO_2
31.3	870	9.59	100	8.71	0.16	288	9.02	74.8	477	196

increase the conductivity. The 758-m sample was taken from a basalt interbed near the bottom of the lacustrine section. Both the 758- and 1200-m samples have consistent, lower thermal conductivity values than the 169-m sample. The conductivity value at 1794 m was not used in the heat flow calculations because it is below the last temperature measurement and would introduce unnecessary error.

Heat flow has been calculated for the three linear geothermal gradient sections (Table 1). The average heat flow is 102 ± 15 mW/m^2. The calculated heat flow for the three sections varied by only 5 mW/m^2 (Table 1), indicating that the temperature and thermal conductivity measurements have high precision and accuracy despite the low number and location of conductivity samples. The ± 15 mW/m^2 error shows that while variability within the section does exist, it is relatively low. This heat flow value is similar to nearby wells and is considered representative of background regional heat flow.

Hydrochemical properties

The results of the field and USUAL chemical analyses of the water sample from the MH-2B corehole are given in Table 2. The temperature is not representative of the temperature at 1745.3 m due to the amount of time it took for the water to reach the surface. For this reason, the temperature logs will be used to analyze the temperature of the water in the hole.

The pH value of the water sample indicates that it is alkaline. However, both the alkalinity and EC are low. Furthermore, the sample is sodium-sulfate water, unlike any of the samples reported in McLing et al. (2002). Those samples included several deep wells, hot springs, and rivers located in the eastern SRP near the Idaho National Laboratory.

The stable isotope results are displayed in Fig. 3. The sample plots far from the global meteoric water line (GMWL) (Craig 1961). While it would be more relevant to compare the sample to the local meteoric water line (LMWL) for southeastern Idaho (Benjamin et al. 2004), the slope and intercept of the LMWL are similar to the GMWL. This suggests that it is not entirely meteoric water, but a mixture of meteoric and a more evolved fluid equilibrated with volcanic rocks and/or magmatic fluids. This is supported by the

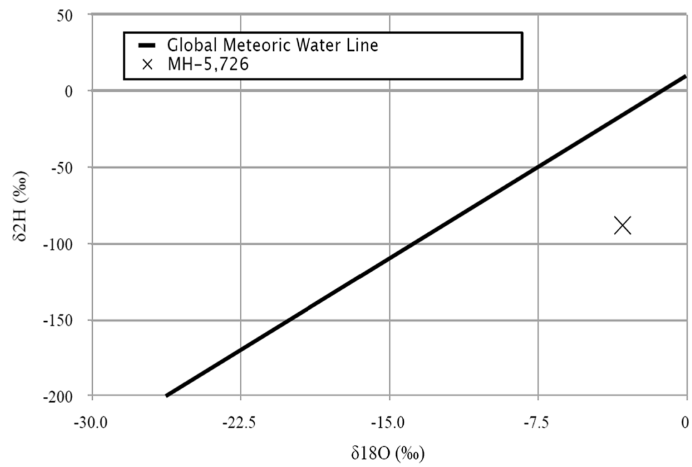

Fig. 3 Plot of deuterium and oxygen-18 for MH-2B sample in comparison to the GMWL

tritium analysis (0.4 ± 0.1 TU), which indicates that a significant proportion of the water may have been isolated from the atmosphere more than 65 years ago.

The chemical analysis of the MH-2B water sample was also used in two other geothermic techniques developed by Giggenbach (1988). The first discriminates between: (1) fully equilibrated, (2) partially equilibrated, and (3) immature waters. The MH-2B sample using the results of the UVDL analysis plots in the middle of the partially equilibrated region, while the sample results using the ThermoChem analysis plots on the bottom line of being fully equilibrated (Fig. 4a).

The second technique developed by Giggenbach (1988) is to plot the chloride, sulfate and bicarbonate concentrations on a ternary diagram. Acid, neutral chloride and soda springs waters are the three broad classification types. The MH-2B sample plots within the acid water region (Fig. 4b). This is curious given that the water is alkaline, but is consistent with the volcanic rocks the water has interacted with. The results of both the ThermoChem and UVDL analyses plot in almost the exact same location and, thus, only the ThermoChem sample is plotted in Fig. 4b.

Geothermometers

The geothermometers that have been applied to the chemical results of the MH-2B water sample are chalcedony and quartz (Fournier 1973, 1977), Na/K (Fournier 1979), Na/K (Giggenbach 1988), Na–K–Ca (Fournier and Truesdell 1973), Na–K–Ca–Mg (Fournier and Potter 1979), and K^2/Mg (Giggenbach 1988). There are a few other geothermometers that are widely used, such as Na/Li and Mg/Li (Kharaka and Mariner 1989), but one of the elements required for them is lithium (Li), and the MH-2B sample was not analyzed for this element.

The equilibrium temperatures calculated for the MH-2B sample using the seven geothermometers are summarized in Table 3. The geothermometry results support the idea that this area has good geothermal potential. Six of the seven geothermometers predict equilibrium temperatures above 133 °C. The K^2/Mg (Giggenbach 1988) geothermometer

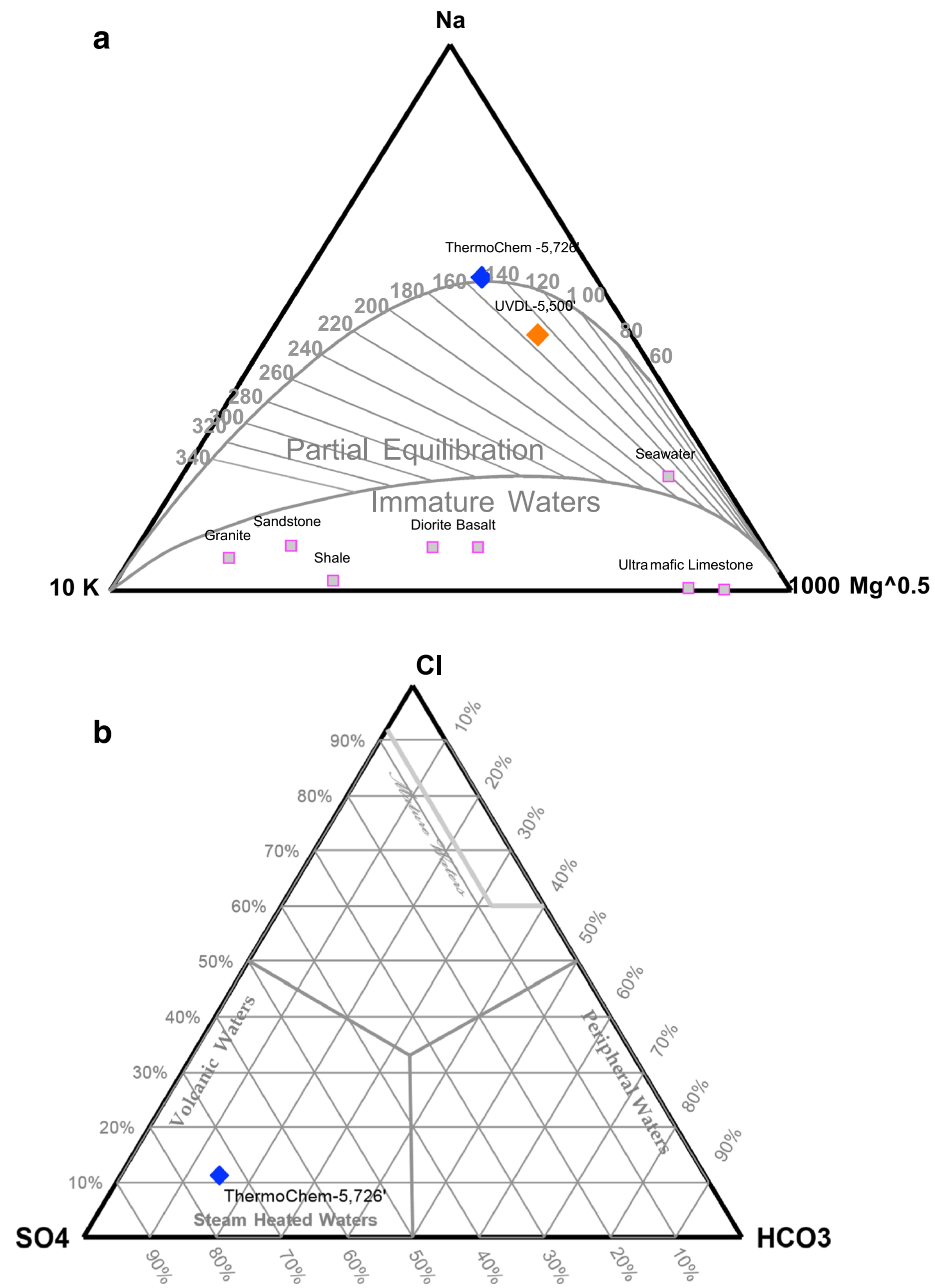

Fig. 4 MH-2B sample plotted on: **a** Giggenbach (1988) ternary diagram; **b** CL, SO_4 and HCO_3 diagram (Giggenbach 1988)

Table 3 Geothermometer calculations for MH-2B (all values in °C)

Chalcedony (Fournier 1977)	Quartz (Fournier 1977)	Na/K (Fournier 1979)	Na/K (Giggenbach 1988)	Na–K–Ca (Fournier and Truesdell 1973)	Na–K-Ca–Mg (Fournier and Potter 1979)	K^2/Mg (Giggenbach 1988)
157	179	134	154	139	133	117

provides a result of 117 °C, which is lower than the maximum measured temperature. On the other hand, the quartz (Fournier 1977) geothermometer predicts an equilibrium temperature of nearly 180 °C, but this disagrees with the other geothermometers and seems unreasonably high.

UCS experiments

Based on the results of the unconfined uniaxial compressive stress (UCS) experiments, the six deepest core samples, which were obtained from depths of 1738 to 1819 m, have been grouped together as a single, mechanical unit. The three shallower samples, which were obtained from depths of 1708 to 1735 m, have been grouped into a second mechanical unit. The mean UCS for the six deepest core samples was 113.7 ± 42.1 MPa, while the mean UCS for the three shallower samples was only 44.4 ± 30.3 MPa (Table 4).

Based on these results, the lower mechanical unit has been classified as being very brittle, while the shallower unit is classified as being ductile. In addition to sustaining the largest stress loads, the six deepest core samples experienced a relatively small amount of ductile deformation after exceeding the elastic limit and before failure. The three shallower samples show a small elastic window and experience a relatively long period of ductile deformation before fracture, if the sample fractured at all before loss of function of one or both of the strain gauges.

Physical description of core

The water sample was collected from the MH-2B corehole when it was flowing. It is assumed that the sample came from a depth of 1745.3 m, which was the depth at which the hole began to flow. The core at this depth was basalt (Fig. 5), and core recovery was low, which suggests significant porosity. Note that in Fig. 5 the core box covers a length of 5.1 m. The boxes hold approximately 3 m of core. This supports the idea that there is a fracture zone or zone of higher porosity at this depth.

The lower mechanical unit (Unit 1) has a high fracture density. Cores indicate the presence of large vugs that may be contributing to fluid storage. The rocks are strong, brittle, aphanitic basalt rich in feldspar (labradorite) with some minerals indicating hydrothermal alteration (Walton and Shiffman 2003), including sulphides and smectite clay (saponite). Some minor vesiculation is present and sealed fractures are seen near

Table 4 Results of unconfined uniaxial compressive stress experiments

Unit	Depth (m bgs)	First UCS (MPa)	Second UCS (MPa)	Avg UCS (MPa)	Unit Avg UCS (MPa)	Unit Std Dev (MPa)
2	1708	90.5	83.6	87.1		
2	1719	20.6	20.6	20.6	44.4	30.3
2	1735	26.4	24.6	25.5		
1	1738	153.9	148.4	151.1		
1	1763	84.0	85.2	84.6		
1	1788	110.8	120.6	115.7	113.7	42.1
1	1806	80.7	106.8	93.7		
1	1807	55.6		55.6		
1	1819	175.7	187.3	181.5		

Fig. 5 Core from 1743.5 to 1748.6 m

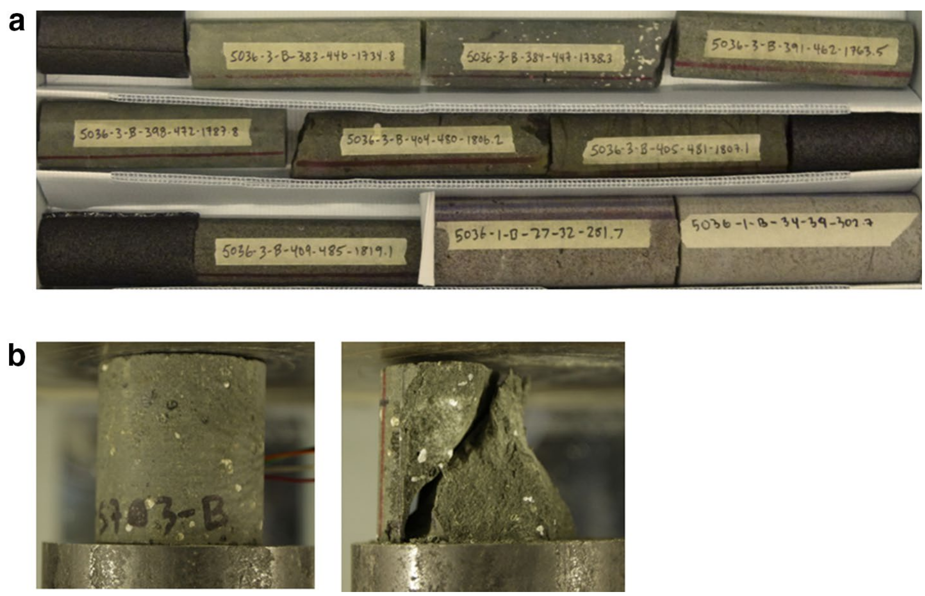

Fig. 6 Pictures of Unit 1: **a** core; **b** sample before and after UCS experiment

the bottom 10 m of the unit (Fig. 6a) with a montmorillonite/chlorite fill. The samples failed catastrophically (Fig. 6b) near the bottom of the unit.

Unit 2 is the shallower ductile unit. It lacks fractures. The core samples show fine-grained, highly altered basalt with minor silica-filled voids (Fig. 7a). The presence of smectite clays (saponite) indicates hydrothermal alteration, and the presence of feldspar (labradorite) and other silicates may indicate the preservation of original material that has been reworked and redeposited in this unit. Some samples show reworked basaltic sediments that appear to have been deposited in a secondary environment from their original volcanic deposition. The stress–strain relationship shows that the samples exhibited ductile deformation until a fracture developed late in the experiment (Fig. 7b).

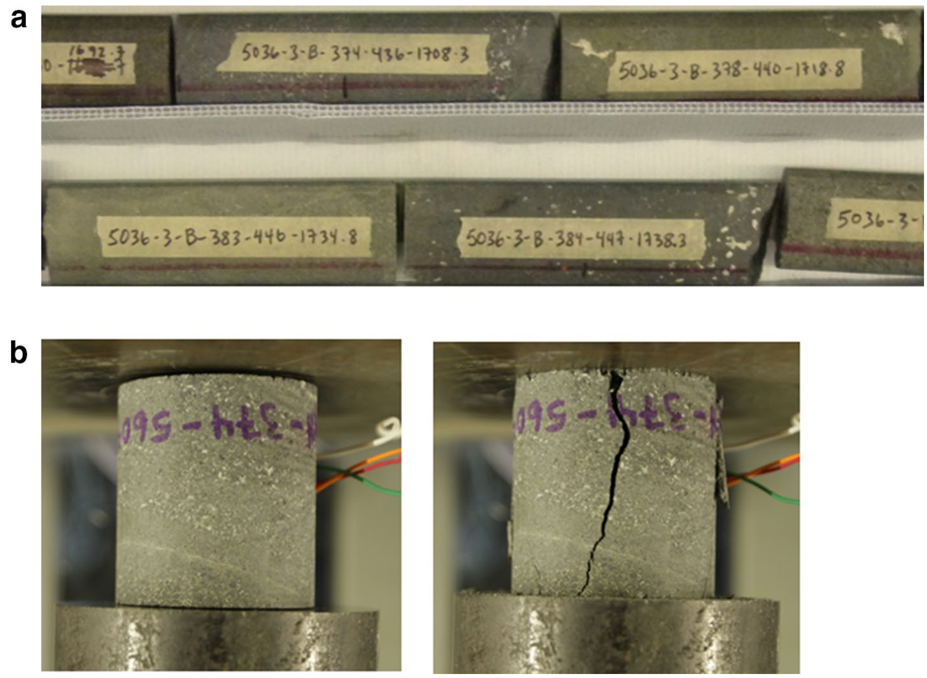

Fig. 7 Pictures of Unit 2: **a** core; **b** sample before and after UCS experiment

This unit had one sample fail during preparation due the weak nature of the rock and the reduced strength and cohesion when it got wet during the grinding process.

Discussion

In addition to water, the two other components of a hot-water geothermal system are heat and permeability. The corrected maximum temperature estimated for the MH-B corehole of 149.4 °C, the nearly linear geothermal gradient of 73 °C (Fig. 2), and the equilibrium temperatures calculated using five geothermometers of between 133 and 157 °C (Table 3) all indicate that the Mountain Home site has sufficient heat to warrant further geothermal exploration. Furthermore, the two Giggenbach (1988) diagrams (Fig. 4) indicate that the water is close to being fully equilibrated and is representative of volcanic and/or steam-heated waters.

The possibility of high-temperature fluid flow through large fracture networks and fault zones indicates the potential for geothermal energy development (Gudmundsson et al. 2002; Gupta and Roy 2007; Kattenhorn and Schaefer 2007). The flowing artesian zone encountered at 1745.3 m is an important indicator of such permeability. The high porosity evidenced by the low core recovery supports the idea that the corehole intersected a significant fracture zone at this depth. Additionally, the UCS experiments indicate that this fracture zone exists within a very brittle mechanical unit (Unit 1), and inspection of the core from this unit shows that it has a high fracture density and contains large vugs that contribute to its high porosity.

There is one other component of the hydrothermal system at the Mountain Home site that contributes to its desirability as a potential geothermal resource, namely the existence of a ductile mechanical unit (Unit 2) immediately overlying the very brittle unit in which the flowing artesian zone was encountered. Unit 2 appears to act as a cap or seal for the geothermal reservoir contained within Unit 1. This ductile unit likely plays a vital role in establishing the potential geothermal reservoir by trapping hydrothermal fluids in the underlying fractured unit. This cap is facilitated by hydrothermal alteration that is centered on the zone of fluid entry (Walker and Wheeler 2016; Atkinson et al. 2017).

The effectiveness of Unit 2 in keeping the thermal water confined at depth in Unit 1 is evidenced by the chemistry of the water. It is a sodium-sulfate type of water, which is unusual in this region, and it also has a high pH, although both the EC and alkalinity are low (Table 2). It plots far from the GMWL, indicating that it probably is not meteoric water. Finally, its low tritium content suggests that the water is relatively old, with the majority having been isolated from the atmosphere for at least 65 years.

Conclusions

Based on the MH-2B corehole, the Mountain Home area appears to warrant further exploration for geothermal resources. All the components of a hot-water geothermal system (water, heat and permeability) are present at this site. The high geothermal gradient as well as the relatively high measured maximum temperature and estimated equilibrium temperatures calculated using the geothermometers all indicate the presence of sufficient heat. Perhaps most importantly, though, is the presence of a significant fracture zone at 1745.3 m that produced flowing geothermal water at the surface. This fracture zone lies within a very brittle mechanical unit that is at least 81 m thick (1738 to 1819 m) and is characterized by high fracture density and high porosity. This unit appears to constitute a desirable potential geothermal reservoir. Finally, a ductile mechanical unit at least 27 m thick (1708 to 1735 m) immediately overlies this potential reservoir and seems to act as an effective cap or seal which prevents the hydrothermal fluids from escaping upward toward the surface. All these attributes suggest that the subsurface conditions in the Mountain Home area may well prove to contribute to a valuable geothermal resource.

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Author's contributions

TEL and TGF collected the water samples and interpreted the results of their chemical analyses. JAK, JPE, XC and DRS conducted the uniaxial compressive stress experiments and interpreted their results. JFB and DDB made the thermal conductivity measurements and heat flow calculations. DLN interpreted the temperature log. JWS and JPE served as the principal investigators. All authors read and approved the final manuscript.

Availability of data and materials

The datasets supporting the conclusions of this article are available in the Utah State University Libraries Digital Commons repository at http://digitalcommons.usu.eud/.

Ethics approval and consent to participate

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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