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Vapor-driven sublacustrine vents in Yellowstone Lake, Wyoming, USA

Andrew P.G. Fowler[1]*, Chunyang Tan[1], Christie Cino[1], Peter Scheuermann[1], Michael W.R. Volk[1], W.C. Pat Shanks III[2], and William E. Seyfried, Jr.[1]

[1]Department of Earth Sciences, University of Minnesota, Minneapolis, Minnesota 55455, USA
[2]U.S. Geological Survey, Denver Federal Center, MS 973, Denver, Colorado 80225-0046, USA

ABSTRACT

Study of the hydrothermal dynamics of Yellowstone Lake (Wyoming, USA) is important for identifying potential changes in sublacustrine hydrothermal systems in response to external perturbations from earthquakes, seiches, large waves, and seasonal effects. Remotely operated vehicle (ROV) submersible-based investigations of hydrothermal vents offshore from Stevenson Island reveal numerous non-constructional ~10-cm-diameter orifices with diffuse fluid flow at temperatures up to 174 °C. The vent field occurs in a large roughly conical depression on the lake floor at a water depth of ~120 m. The volatile-rich composition (CO_2, H_2S) of the vent fluids is preserved by using a novel isobaric sampling system that precludes degassing effects. In addition to high temperatures, the vent fluids have high CO_2 and H_2S, but low chloride (Cl) and major element concentrations largely indistinguishable from those in ambient lake water. These results are consistent with steam addition to the sublacustrine hydrothermal system. Kaolinite- and boehmite-rich alteration indicates acidic conditions and provides a low-permeability substrate that may contribute to the development of a steam-heated upflow zone. At the scale of individual vent areas (centimeters to meters), perturbations cause bursts of steam-rich fluids that locally expel and disperse sediment and contribute to the formation of vent orifices. Here we report on chemical and physical phenomena associated with the hottest and deepest sublacustrine hydrothermal vents in Yellowstone Lake. Results indicate that vapor-dominated sublacustrine systems are fundamentally different in hydrothermal alteration and hydrothermal dynamic characteristics than their liquid-dominated counterparts.

INTRODUCTION

The Yellowstone volcanic-hydrothermal system (Wyoming, USA) is the most recent expression of a sequence of events that trace back ~16 m.y. along the track of the Yellowstone hotspot (Pierce and Morgan, 1992). Heat and non-condensable gases derived from the volcanic system interact with deeply circulating meteoric water to produce geochemically diverse and abundant hydrothermal activity (Hurwitz and Lowenstern, 2014).

Sublacustrine hydrothermal activity in Yellowstone Lake has been inferred for >100 yr (Hayden, 1878), yet direct observation and sampling of vents was first achieved comparatively recently in 1987 (Klump et al., 1988; Remsen et al., 2002). Observations from lake-floor bathymetry surveys, breccia deposits in sediment cores, and the rock record exposed around the lake establish that sublacustrine hydrothermal activity produced noteworthy hydrothermal explosions in the past (Morgan et al., 2003, 2009; Wold et al., 1977). Thus, understanding sublacustrine hydrothermal processes is important, considering that more than four million people visit Yellowstone annually (National Park Service, 2018). Hundreds of active and inactive vents have now been identified within the lake (Morgan et al., 2003), and fluids from many vents have been analyzed to better understand sublacustrine hydrothermal processes (Balistrieri et al., 2007; Gemery-Hill et al., 2007; Klump et al., 1988).

The present study is a collaborative multidisciplinary effort (Hydrothermal dynamics of Yellowstone Lake, HD-YLAKE) to understand the response of the Yellowstone Lake hydrothermal system(s) to geological and environmental perturbations (Sohn et al., 2017). Sublacustrine hydrothermal vent fluids are observed in the "Deep Hole" area east of Stevenson Island, which is the deepest (100–125 m) region of the lake. The Deep Hole is located within a NW-trending fracture zone 2 km east of Stevenson Island that is defined by large conical depressions that form linear arrays with *en echelon* offsets (Fig. 1).

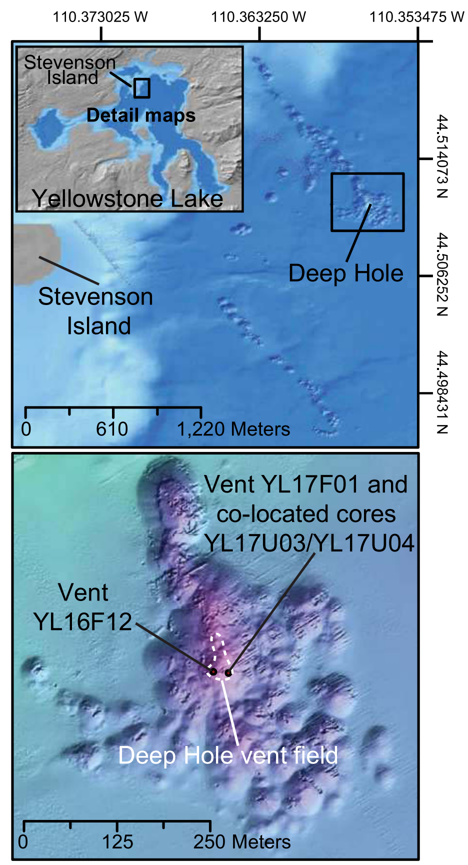

Figure 1. Location of Deep Hole sublacustrine vents (east of Stevenson Island, Yellowstone Lake, Wyoming, USA). Bathymetry and digital elevation data modified from Morgan et al. (2003) and Sohn et al. (2017). Coordinates are relative to the World Geodetic System 1984 (WGS84).

*E-mail: afowler@umn.edu

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Hot liquid and gas bubbles exit through nonconstructional centimeter-scale orifices in sediments that are sparsely populated by white bacterial mats (Fig. DR1 in the GSA Data Repository[1]). *In situ* geochemical sensor measurements show that the hydrothermal fluid is acidic, with an *in situ* pH at the vent temperature, $pH_{(T)}$, of 4.2–4.5, and is notably reducing (−0.2 to −0.3 V) (Tan et al., 2017). A maximum temperature of 174 °C was measured with a titanium-sheathed temperature probe inserted ~10 cm into one vent (Tan et al., 2017), making these the hottest sublacustrine vent fluids reported to date in Yellowstone Lake or elsewhere.

In comparison, the highest measured vent-fluid temperature in New Zealand's Lake Taupo is 45 °C (de Ronde et al., 2002). While high-temperature sublacustrine vent fluids are also likely present in New Zealand's Lake Rotomahana based on heat-flow measurements, water-column temperature anomalies, shoreline hot-spring fluid geothermometry results, and vigorous shallow vent activity (de Ronde et al., 2016; Stucker et al., 2016; Tivey et al., 2016; Walker et al., 2016), vents on the lake floor have not been directly measured or sampled.

In the present study, a newly designed gas-tight (isobaric) sampling system, constructed entirely of titanium and with real-time temperature monitoring (Wu et al., 2011), was used to acquire hydrothermal-vent fluid samples (See File DR1 for detailed sampling and analytical procedures). The isobaric capability means that lake-bottom pressure is maintained up to the point of subsampling at the surface, permitting acquisition of unaltered gas-rich fluid samples from sublacustrine vents for the first time.

RESULTS AND DISCUSSION

Absolute and relative concentrations of many dissolved constituents in vent fluids are remarkably similar to those of Yellowstone Lake water (Fig. 2). However, elevated CO_2 and H_2S concentrations in all samples and the noteworthy correspondence between dissolved gases and temperature (Table 1), combined with stable-isotope systematics, provide clear evidence of the dominating influence of a hydrothermal component. The high-temperature vent fluids have lower δD (Fig. 3) and Cl relative to lake water (with as much as 17% less Cl in the highest-temperature sample), suggesting that steam is being added to the sublacustrine system and providing the heat to achieve high temperatures while diluting conservative species, such as Cl, in the entrained lake water. Steam-heated CO_2-rich waters are relatively common in subaerial geothermal systems (Hedenquist, 1990),

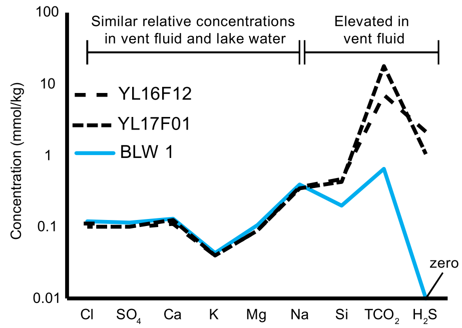

Figure 2. Major and trace element concentrations (logarithmic scale) of two offshore Stevenson Island (Yellowstone Lake, Wyoming, USA) hydrothermal vent fluid samples (YL16F12 and YL17F01) compared to typical sample of bottom lake water (BLW 1). Refer to Table 1 for values. TCO_2—total carbon as CO_2.

but have not previously been thoroughly characterized in a sublacustrine setting.

The proportion of steam required to heat lake water to the sampling temperature of 150 °C for sample YL17F01 was estimated using enthalpy values from steam tables (Wagner and Kretzschmar, 2008), assuming binary conservative mixing, as follows:

$$\text{Mixture} = x \cdot \text{component A} + (1 - x) \cdot \text{component B}. \quad (1)$$

The enthalpy corresponding to a temperature of 188 °C was used in the calculation, the temperature of steam condensation for pure water at the lake-floor pressure of 1.2 MPa (Wagner and Kretzschmar, 2008). While the temperature of the vapor source is unknown, using steam enthalpy values at liquid-steam saturation corresponding to temperatures from 188 °C to the critical point for pure water makes only a minor (3%) difference in the calculated mixing fraction. The result shows that condensation of 19% steam into 4 °C lake water produces a vent fluid at a sampling temperature of 150 °C. This mixing ratio is in close agreement with the chloride dilution factor of 17% calculated for sample YL17F01 and suggests minimal conductive cooling or mixing with lake water for this sample following steam condensation.

Consistent with dissolved-species concentrations, vent-fluid oxygen isotope ($\delta^{18}O$) and hydrogen isotope (δD) values indicate limited reaction between the lake-floor substrate and vent fluids or high water-to-rock ratios in an upflow zone. Should the sampled steam-heated lake water have reacted extensively with lake sediments at low water-to-rock ratios, vent fluid $\delta^{18}O$ would be shifted to heavier values as is typical for thermal waters relative to local meteoric water recharge (Fig. 3). Instead, sublacustrine vent fluids are shifted to lower $\delta^{18}O$ and δD values, suggestive of mixing with isotopically light fluid. The $\delta^{18}O$ and δD values of isotopically light sublacustrine steam can be calculated by mass balance (Equation 1) using a 17% steam fraction and stable isotope values listed in Table 1 for sample YL17F01. The result ($\delta^{18}O$ = −20.7‰ and δD = −148.1‰) falls within the range of values of subaerial fumaroles in Yellowstone (Fig. 3).

The dominant gases in Yellowstone fumaroles after steam (H_2O) are CO_2 and H_2S (Lowenstern et al., 2015), and enrichments of these gases in vent-fluid samples relative to ambient lake water (Fig. 2) further support our vapor-source model. Ubiquitous gas bubbles observed exiting vents (Video DR1) and *in situ* pH values are consistent with vent fluids being CO_2 saturated (Tan et al., 2017). Using CO_2 solubility relations in the CO_2-H_2O system (Duan and Sun, 2003), CO_2 in vent-fluid sample YL17F01 is consistent with saturation at 180 °C and 1.2 MPa pressure. This temperature estimate lies between the maximum measured vent temperature of 174 °C and the liquid-vapor transition temperature of 188 °C for pure water at 1.2 MPa.

Yellowstone research drill hole Y-11 at the subaerial Mud Volcano thermal area, completed

TABLE 1. AQUEOUS SAMPLE ANALYTICAL DATA, OFFSHORE STEVENSON ISLAND, YELLOWSTONE LAKE, WYOMING, USA

SAMPLE	Vent YL16F12	Vent YL17F01	Lake water BLW 1
Latitude (WGS84)	44.510690	44.510725	44.511110
Longitude (WGS84)	−110.356660	−110.356544	−110.356590
Date collected	17 August 2016	10 August 2017	19 August 2016
Depth (m)	114	115	–
Temperature (°C)	110–114	150	4
Cl (mmol/kg)	0.11	0.10	0.12
SO_4 (mmol/kg)	–	0.10	0.11
Ca (mmol/kg)	0.11	0.12	0.13
K (mmol/kg)	0.039	0.039	0.042
Mg (mmol/kg)	0.09	0.09	0.10
Na (mmol/kg)	0.36	0.35	0.39
Si (mmol/kg)	0.45	0.42	0.20
TCO_2 (mmol/kg)	7.0	17.8	0.63
H_2S (mmol/kg)	2.1	1.0	–
H_2 (mmol/kg)	<	0.031	<
$\delta^{18}O$ ‰ (VSMOW)	−15.53	−16.06	−15.12
δD ‰ (VSMOW)	−124.7	−126.6	−122.0

Note: WGS84—World Geodetic System 1984; TCO_2—total carbon expressed as CO_2; VSMOW—Vienna standard mean ocean water. Dash (–) represents not analyzed; < represents not detected.

[1]GSA Data Repository item 2019081, File DR1, Figures DR1–DR6, and Video DR1 (brief footage of gas bubbles exiting a sublacustrine hydrothermal vent), is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

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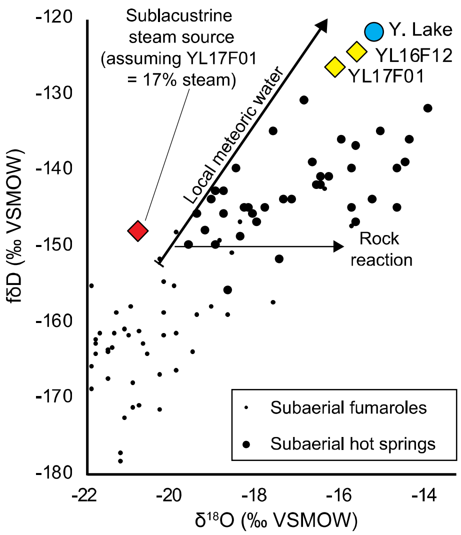

Figure 3. Oxygen and hydrogen isotope relationships for sublacustrine vent fluids from the Deep Hole east of Stevenson Island, Yellowstone Lake, Wyoming, USA (yellow symbols) and subaerial thermal waters and fumaroles from throughout Yellowstone National Park (black symbols). Yellowstone meteoric water line is from Kharaka et al. (2002); subaerial fumaroles and thermal waters are from Bergfeld et al. (2014). The Y. Lake sample represents a bottom-water sample collected near the Stevenson Island deep hydrothermal vents and analyzed in this study (blue circle). The theoretical oxygen and hydrogen isotope values for steam that contributes to sublacustrine vents is calculated assuming sample YL17F01 is a mixture between bottom lake water and 17% steam (red symbol). VSMOW—Vienna standard mean ocean water.

during 1967 and 1968 (White et al., 1975), provides insight into rock alteration in a vapor-dominated zone under similar pressure, temperature, and f_{O_2} conditions to those in the Deep Hole off Stevenson Island. Hole Y-11 encountered a 165 °C subsurface steam zone where kaolinite and pyrite are the most abundant alteration products (White et al., 1971). Kaolinite in hole Y-11 rocks formed from acidic CO_2-saturated steam condensate that altered silicate minerals, while H_2S in the steam combined with rock-derived Fe to form pyrite (White et al., 1971). Similar to hole Y-11 and steam-heated areas elsewhere (e.g., Hedenquist, 1990; Simmons and Browne, 2000), the vent substrate at the Deep Hole contains ~90% kaolinite, with pyrite and pyrrhotite. Additionally, boehmite, mixed-layer clay, diatoms, and quartz are present (Figs. DR2–DR5).

The occurrence of a dominantly kaolinite substrate is critical for sustaining the steam zone. In porous media, steam zones can develop when a permeability contrast is imposed by the presence of a low-permeability cap (Ingebritsen and Sorey, 1988; Schubert et al., 1980). Permeability values for kaolinite (Al-Tabbaa and Wood, 1987; Olsen, 1966) are generally within the range required for a steam cap (e.g., Raharjo et al., 2016), particularly when contrasted to the high permeability values expected for fracture-controlled fluid flow evidenced from the broader structural setting of the Deep Hole vents. We suggest that the occurrence of kaolinite and other alteration minerals in surficial Deep Hole sediments may enhance steam zone development and prevent gravitational flooding of the underlying steam by overlying lake water.

Why do the offshore Stevenson Island vents lack constructional amorphous silica features found at some inactive sites in Yellowstone Lake (Shanks et al., 2007)? The Si concentration in the sampled vent fluids is above ambient lake water values (Table 1), but is undersaturated with respect to amorphous silica at any temperature or with respect to quartz above 74 °C. This is consistent with steam-heated lake water enhancing silicate mineral dissolution rather than precipitation. Indeed, dissolution of diatomaceous material that constitutes unaltered Yellowstone Lake sediment may have contributed to the formation of conical depressions at an earlier stage in the formation of the Deep Hole vents (Shanks et al., 2007).

Trace pyrrhotite is present in all samples (Fig. DR5), however the high $H_2S_{(aq)}/H_{2(aq)}$ log ratio of 1.52 for fluid sample YL17F01 is well within the pyrite stability field at any reasonable temperature. Clearly, pyrrhotite formed under more reducing conditions at some time in the past based on its occurrence in vent muds (Fig. DR5), and the current system has moved toward equilibrium with pyrite based on the occurrence of pyrite replacing pyrrhotite (Fig. DR2). The common association of pyrrhotite with steam zones is noted in other areas and in epithermal mineral deposits where $H_2S_{(aq)}/H_{2(aq)}$ ratios are lower (Browne and Ellis, 1970; Hedenquist, 1990; Simmons and Browne, 2000), which suggests a similar association in the Deep Hole area.

The ~16-cm-long YL17U03 push core, located 1 m from a vent orifice (Fig. DR6), recovered a clast supported semi-lithified mud breccia, likely the buried equivalent of angular slabs (up to 10 cm long) observed scattered around vent orifices (e.g., Fig. DR1). The breccia is capped with a distinct 4–5-cm-thick layer of sediment with similar mineralogy to breccia clasts lower in the core, but is coarser and contains large (up to 0.3 mm) hexagonal pyrrhotite crystals (Fig. DR2). The 4–5 cm sediment cap may be material exhaled from deeper (centimeters to meters) within the sediments during a disturbance to the steam zone.

The occurrence of a sublacustrine steam zone warrants investigation into potential hydrothermal explosion mechanisms. In a liquid-dominated system at the boiling point, a pressure drop triggers the downward propagation of a steam-liquid interface that will manifest as a hydrothermal explosion if mechanical energy from the volume change overcomes rock strength (Browne and Lawless, 2001; Montanaro et al., 2016; Morgan et al., 2009; Muffler et al., 1971; Smith and McKibben, 2000). The hydrothermal explosion potential is exacerbated by the addition of dissolved gases that lower the liquid stability limit (Hurwitz et al., 2016).

Studies of hydrothermal explosion deposits at Waiotapu, New Zealand, suggest that the existence of a steam zone perched beneath a low-permeability cap provides a locus for the accumulation of non-condensable and compressible gases such as CO_2 (Hedenquist and Henley, 1985), which may enhance the vulnerability of such systems to hydrothermal explosions. In addition to water-level changes modifying the pressure regime, seismic events might affect cap-rock permeability or provoke rapid depressurization, releasing non-condensable gases with sufficient force to cause rock fragmentation and debris ejection (Hedenquist and Henley, 1985). Although differences exist in hydrothermal explosion mechanisms for sublacustrine hot-water and vapor zones, each is still poorly understood in Yellowstone and similar active hydrothermal terrains.

CONCLUSIONS

The identification of a vapor-rich zone beneath the Deep Hole east of Stevenson Island in Yellowstone National Park presents a previously unappreciated phenomenon associated with sublacustrine hydrothermal activity. Vent-fluid chemistry, stable-isotope, and enthalpy constraints are consistent with sublacustrine steam mixing with lake water prior to venting. Vent sediments are dominated by kaolinite, boehmite, and pyrite, and are compatible with a CO_2-saturated, H_2S-bearing, and mildly acidic steam condensate–lake water mixture. A steam zone with accumulated gases may respond to lake-level changes or seismic activity, perhaps with localized hydrothermal explosions, or other changes to hydrothermal dynamics of sublacustrine hydrothermal processes.

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