Hydrothermal Vent Fluids, Siliceous Hydrothermal Deposits, and Hydrothermally Altered Sediments in Yellowstone Lake

W. C. Pat Shanks, III^{1*} | Lisa A. Morgan¹ | Laurie Balistrieri² | Jeffrey C. Alt³

¹U.S. Geological Survey, Denver Federal Center, CO ²U.S. Geological Survey, University of Washington School of Oceanography, Seattle ³Department of Geological Sciences, University of Michigan, Ann Arbor

Corresponding Author:

U.S. Ĝeological Survey 973 Denver Federal Center Denver, CO 80225

Phone: 303.236.2497 Email: pshanks@usgs.gov



ABSTRACT

Stable isotopic (δD and $\delta^{18}O$) data indicate about 13% total evaporative concentration has occurred in Yellowstone Lake, yet lake waters are enriched in dissolved As, B, Cl, Cs, Ge, Li, Mo, Sb, and W by at least an order-of-magnitude relative to the flow-weighted composition of inflowing streams. We conclude that lake water is a mixture of inflowing surface water and hydrothermal source fluid that is strongly enriched in Cl and other elements. We estimate that ~10% of the total hydrothermal flux in Yellowstone National Park (YNP) occurs in Yellowstone Lake. Geochemical and mineralogical studies of hydrothermal deposits and hydrothermally altered lake sediments (vent muds) from the active or recently active vent sites on the floor of Yellowstone Lake indicate that their formation is due to hydrothermal fluid quenching during flow through shallow conduits, or to mixing upon egress into cold bottom waters. Siliceous precipitates form conduits within the uppermost sediments, tabular deposits along sedimentary layers, and spires up to 8 m tall. These deposits are enriched in As, Cs, Hg, Mo, Sb, Tl and W. Spires, vent deposits, and conduits contain filamentous microstructures that probably represent silicified bacteria. Partly recrystallized and silicified diatoms are abundant in deposits below the sediment-water interface. Vent muds and some outer conduit walls show pervasive leaching of silica, which explains the occurrence of most sublacustrine vents in craters. Systematics of δD and Cl variations, as well as silica and cation geothermometry for hydrothermal fluids, suggest that ascending fluids boil due to depressurization to a temperature of ~220°C and then mix with pore waters prior to venting on the lake bottom. Depositional temperatures for sublacustrine silica deposits, calculated using oxygen isotope fractionation, range from 78°C to 164°C. The amorphous silica-saturated vent fluids precipitate silica to form spires or conduits largely by conductive cooling. Bacterial accumulations may have inhibited the mixing of vent fluids and bottom waters, and provided a site for silica deposition.

Key Words

 alteration

 hydrothermal

 silica

 spires

 stable isotopes

 trace elements

 vents

1.0 INTRODUCTION

Yellowstone National Park (YNP) is a region of recent and active tectonism and volcanism that is related to its current position over the Yellowstone hotspot (Pierce and Morgan 1992; Yuan and Dueker 2005). Large-volume, high-silica rhyolite ignimbrites and lava flows have erupted from overlapping and nested calderas in the Yellowstone Plateau volcanic field. The last major eruption produced the 0.64-Ma Yellowstone Caldera, which contains most of the active hydrothermal basins in the Park. Seismic studies suggest that a zone of magma is present below the caldera at a depth of about 5-6 km (Christiansen 2001; Smith and Rubin 1994). Magmatic heat drives YNP's abundant and spectacular hydrothermal activity.

Isotopic and geochemical studies indicate that the impressive subaerial thermal basins in YNP result from the interaction between deeply recharged meteoric water and a magma chamber in the upper crust beneath the Yellowstone Caldera (Fournier 1999). A deeply circulating, hot (360°C), chloride-enriched fluid reservoir (Fournier 1989; Rye and Truesdell 1993, and in press) is thought to feed most thermal fields and geyser basins in the park. Temperature and compositional variations between hot springs are due to a series of intermediate reservoirs that alter fluids by conductive cooling to surrounding rocks, steam separation and H₂S oxidation, and mixing and dilution of ascending hydrothermal fluids with colder meteoric water (Truesdell et al. 1977; Fournier 1989, and this volume). Water-rock interaction, magma degassing, and mineral precipitation also contribute to the diverse geochemical compositions of YNP hot springs.

Multiple geologic forces—volcanic, hydrothermal, and glacial—have shaped the Yellowstone Lake basin (Morgan et al. 2003; Morgan and Shanks, this volume; **Figure 1, next page**). The northern portion of the lake and West Thumb basin are within the Yellowstone Caldera (**Figure 1A**) and host numerous sublacustrine hydrothermal vent sites. In addition, large sublacustrine hydrothermal explosion events formed Mary Bay crater, Elliott's crater, Evil Twin Crater in West Thumb basin, and the unnamed crater south of Frank Island (Morgan et al. 2003). The Mary Bay hydrothermal explosion crater (Wold et al. 1977), with a diameter of about 2.6 km, is the largest known crater of this type in the world (Browne and Lawless 2001) and is still a center of intense sublacustrine hydrothermal activity (Figures 1A and 1C). Analogous large hydrothermal explosion craters formed subaerially at Indian Pond, Turbid Lake, Duck Lake, and several other locations in the Park (Muffler et al. 1971; Morgan et al. 1998; Pierce et al. 2002)

This report focuses on the geochemistry of Yellowstone Lake water, the processes that control its composition, and the supply of potentially toxic elements to the lake ecosystem by sublacustrine hydrothermal vents. Such information is critical for understanding the complex relationships between geology and biological communities in YNP. We also examine the hydrothermal processes at sublacustrine vent sites that alter lake sediments and produce lake-bottom siliceous deposits.

2.0 METHODS

During August and September of 1998, samples of surface water were collected and flow measurements were made at 44 of the 141 streams that enter Yellowstone Lake; these were the streams with highest flow. In July 1999, sampling and flow measurements were redone for 21 of the 44 streams-those established as significant contributors to the lake due to their high flow and amount of metal loading in the water. The resulting data allow calculation of flow-weighted influx for comparison with outflow at the U.S. Geological Survey (USGS) gauge of the Yellowstone River at its outlet from the lake (station 06186500; http://waterdata.usgs.gov/mt/nwis/). Samples from different depths in the water column of Yellowstone Lake were collected in Southeast Arm, West Thumb, and Mary Bay in 1997 and 1998, and near Stevenson Island in 1998, using trace-metal-clean hydro bottles and noncontaminating hydro cable.

Hydrothermal vent waters and siliceous hydrothermal deposits and sediments were collected from the lake bottom with a tethered remotely operated vehicle (ROV) designed and piloted by David Lovalvo of Eastern Oceanics, Inc. Water samples were collected in large plastic



Figure 1. Bathymetric maps of: A. Yellowstone Lake, B. West Thumb showing locations of hydrothermal sites, and C. Northern Yellowstone Lake showing locations of hydrothermal sites.

B. West Thumb



syringes attached to sampling tubes fitted, along with a temperature probe, to an articulated telescoping sampling arm. The ROV also was equipped with a motorized scoop for collecting solid and sediment samples. Some additional sediment samples were collected by gravity coring, and spire samples were collected by the National Park Service Yellowstone dive team. A typical configuration of the submersible is shown in **Figure 2**.

Alkalinity, pH, and temperature of water samples were measured in the field. Laboratory analyses for 40 major and minor elements were obtained by inductively coupled plasma-mass spectrometry (ICP-MS); Hg by cold vapor atomic fluorescence; anions by ion chromatograph; and δ^{18} O, δ D, and δ^{34} S by isotope ratio mass spectrometry calibrated to Vienna Standard Mean Ocean Water (VSMOW) or Canyon Diablo troilite (CDT). Analytical errors based on replicate analyses of standards are <0.05 per mil for δ^{18} O_{H2O}, ~1.0 per mil for δ D, and <0.2 per mil for δ^{34} S.

Minerals were characterized by X-ray diffraction (XRD), scanning electron microscopy (SEM), and by chemical



Figure 2. Photo of the Eastern Oceanics, Inc. remotely operated vehicle (ROV) for submersible studies in Yellowstone Lake.

(X-ray fluorescence and ICP-MS) and isotopic analyses in the USGS laboratories in Denver, CO. Silicate samples for oxygen isotope analysis were reacted with BrF₅ following the Clayton and Mayeda (1963) technique. Sulfur-bearing phases were analyzed for δ^{34} S using an automated elemental analyzer interfaced to an isotope ratio mass spectrometer



(Giesemann et al. 1994).

3.0 CHEMISTRY OF LAKE WATERS

3.1 Evaporation

Hydrogen (\deltaD) and oxygen $(\delta^{18}O)$ isotope analyses indicate that Yellowstone Lake waters and hydrothermal vent fluids plot off the global meteoric water line of Craig (1961), along evaporation trends (Craig 1963) with slopes of about 5 (Figure 3). In contrast, samples from the majority of streams that drain into Yellowstone have Lake isotope values of typical atmospheric waters that plot



		Stream	SE Arm	WT	SI	MB	wт	SI	MB-nearshore	MB-deep hole
	Units	Inflow*	DW	DW	DW	DW	vents	vents	vents	vents
temperature	°C	14.6	4.8	7.3	9.3	12	8.7-68	15-106	28.3-93	30-103
рН		5.7	7.5	7.3	7.4	6.9	5.4-8.6	5.1-7.1	5.4-7.3	4.8-6.9
СІ	μM	8.7	120	160	140	170	50-1150	130-140	120-140	140-170
SiO ₂	μM	170	170	210	190	200	180-1600	160-330	150-350	150-400
В	μM	1.1	7.4	8.1	7.5	9.7	3.2-68	5.7-8.3	6.5-9.2	7.4-13
Li	μM	0.8	5.7	7.9	6.5	8.1	8.8-88	6.2-7.8	4.9-7.2	4.9-8.5
Na	μM	72	350	470	400	440	440-3900	360-420	300-390	270-430
К	μM	16	31	38	36	36	17-200	36-41	33-61	31-51
Rb	nM	13	56	69	60	68	61-550	56-69	47-96	55-85
Cs	nM	0.4	24	31	22	31	22-630	17-24	17-280	8.3-660
Mg	μM	42	98	110	110	110	8.2-120	90-130	74-140	66-120
Са	μM	59	130	130	130	130	87-140	120-160	100-210	90-140
Sr	nM	230	500	490	490	520	75-550	470-730	410-1140	380-730
Ва	nM	41	61	59	60	65	36-120	71-590	29-1240	57-490
As	nM	2.9	160	270	190	240	120-2800	130-290	88-230	49-720
Ge	nM	0.1	2.7	5.5	3.3	3.9	5.5-140	2.7-5.5	2.7-4.1	2.7-5.5
Hg	рМ	<25	<25	55	<25	<25	<25-800	<25-850	<25-160	<25-140
Мо	nM	0.4	11	16	11	11	18-380	0.4-21	9.5-33	1-28
Sb	nM	<0.2	4.1	6.3	4.9	6.5	0.8-140	<0.2-7.8	<0.2-90	<0.2-107
W	nM	0.9	7.3	11	6.9	9.5	87-440	5.4-10	6.5-260	7.1-540
ΣCO ₂	mM	0.25	0.62	0.69	0.69	0.79	0.76-5.5	0.64-9.8	0.92-2.4	0.83-27
HCO ³	μΜ	240	560	680	620	610	510-3040	460-700	400-720	230-620
SO4	μM	21	76	78	82	89	21-130	78-120	71-150	78-150

 Table 1. Temperature and average chemical composition of Yellowstone Lake water, streams that enter the lake (flow-weighted average composition), deep lake water (DW; >25 m) in Southeast Arm (SE Arm), in West Thumb (WT), near Stevenson Island (SI), and in Mary Bay (MB), and lake-bottom hydrothermal vent fluids in West Thumb, near Stevenson Island, and in Mary Bay.

* Flow-weighted average composition of stream inflow

on or near the global meteoric water line. Examination of the data for lake water reveals three important observations: (i) lake water is progressively more evaporated with increased distance from the Yellowstone River inlet, which is at the south end of Southeast Arm (**Figure 1**); (ii) sublacustrine hydrothermal vent water is mainly lake water, probably due to mixing in the shallow subsurface or entrainment of lake water during sampling of the hydrothermal vent fluids; and (iii) vent water samples and water column samples above vent sites plot along nearly vertical arrays that indicate mixing between local bottom water and hydrothermal waters. Balistrieri et al. (in press) used $\delta^{18}O$ systematics and climatic data to calculate that Yellowstone Lake water has evaporated approximately 13% during the 14±3-year residence time of the water in the lake. Hostetler and Giorgi (1995) determined a net evaporation of about 16% from meteorological data for Yellowstone Lake. Furthermore, Hostetler and Giorgi (1995) calculated that the volume of water lost due to evaporation and gained from precipitation is 3-4 times less than the volume of water flowing into and out of the lake. Thus, evaporation has a significant but limited effect on the stable isotopic and elemental composition of Yellowstone Lake water.

3.2 Element Enrichment Due to Hydrothermal Activity

Geochemical data for stream waters, lake water, and hydrothermal vent fluids indicate that the chemical compositions of Yellowstone Lake waters are significantly different from meteoric waters surrounding the lake (Balistrieri et al. in press). Lake water is a variable mixture of riverine inflow water and hydrothermal vent fluids; and vent fluids are, in turn, variable mixtures of lake water and deep-source hydrothermal fluids. Hydrothermal vent samples for this study were collected in West Thumb basin and in the northern lake in the summers of 1996 through 2004 (Figures 1B and 1C). West Thumb vent samples were collected from several vent fields at depths of 29-53 m. Vent fluids from depths of 7-10 m were also collected near Steamboat Point and Pelican Creek, and from a deep hole in Mary Bay at depths of 48-54 m. Samples collected near Stevenson Island were from the deepest lake vents (95-110 m). Complete chemical data for lake, stream, and vent waters are available in Gemery-Hill et al. (in press).

Mass balance calculations using the flow-weighted average composition of stream influx (**Table 1; Figure 4**) indicate that Yellowstone Lake water is substantially enriched in some elements and species (As, B, Cl, Cs, Cu, Ge, Li, Mo, Sb, and W) relative to concentrations in inflowing riverine waters (Balistrieri et al. in press). This enrich-



Figure 4. Flow-weighted balance of elements in Yellowstone Lake.

ment includes water in Southeast Arm that is outside of the caldera and away from known hydrothermal activity; thus, Yellowstone Lake is relatively well-mixed. Some elements such as Hg, Tl, and H_2S are strongly enriched in vent fluids and hydrothermal deposits but are not present above our detection limits in lake or stream waters. Finally, some elements (Ba, Ce, Fe, La, Mn, Sc, and U) are lower in Yellowstone Lake waters than in flow-weighted inflow waters due to precipitation or other removal mechanisms. Some of the enriched elements (As, Hg, Mo, Sb, and Tl) are potentially toxic and could impact biota. The potentially toxic elements, and B, Cs, Li, and W, represent a chemical suite typical of ore fluids associated with epithermal Au and Ag mineralization.

3.3 Hydrothermal Elements: Mixing of End-Member Solutions

Geochemical interpretations of subaerial geyser basin fluids in YNP indicate that the subsurface deep-reservoir fluids contain about 8.7 mM (310 mg/kg) Cl (Truesdell et al. 1977; Fournier 1989). Chloride is an excellent tracer of hydrothermal water in Yellowstone Lake because Yellowstone River, the major source of water to the lake, contains almost no Cl (<6 μ M). The flow-weighted inflow of all streams for August and September of 1998 and July of 1999 had Cl concentrations of 15 and 9 μ M, respectively (**Table 1**). Those values are at least three orders-of-magnitude smaller than Cl concentrations in the deep source fluids.

Sublacustrine hydrothermal vent fluids and lake water are both enriched in Cl relative to the inflowing stream waters. However, the vent fluids, with a few exceptions, have about the same concentration of Cl as the lake water, and that concentration (100-200 μ M) is substantially lower than dissolved Cl concentrations in deep thermal water (10 mM). Thus, most vent fluids are dominated by lake water, with only a small component of deep source fluids. Linear

relationships between Cl and many elements or species in vent fluids and lake water indicate end-member mixing is occurring. The end members that define the chemical composition of Yellowstone Lake water are riverine inflow water and deep hydrothermal source fluids.

4.0 HYDROTHERMAL SOURCE FLUIDS

4.1 ^(b)D and CI: An Estimate of the Concentration of CI in the Hydrothermal Source Fluid

Truesdell et al. (1977) developed an elegant graphical treatment illustrating the effect of subsurface boiling on the hydrogen isotopic (δD) and Cl composition of subaerial hydrothermal water in YNP. Their calculations showed that the δD values of hydrothermal fluids are a function of the boiling mechanism, which is approximated using 2 modelssingle-stage steam separation, and continuous steam separation (Figure 5). One assumption of these calculations is that there is a single, deep, thermal reservoir containing fluid with the following characteristics: 360°C, 310 mg/kg Cl (8.7 mM Cl), and -149 per mil δD . This deep reservoir fluid is isotopically lighter than present-day surface waters in the caldera, and the distribution of δD values in YNP recharge waters indicates either that the thermal areas have a remote recharge area in the Gallatin Range in the northwest corner of the Park or, more likely, there is a residual component of



↑ Figure 5. Plot of δD versus dissolved Cl concentrations in Yellowstone hydrothermal fluids.

water from the last glacial event in the deep reservoir (Rye and Truesdell 1993, and in press).

We have plotted our isotope data for lake waters, vent fluids, pore waters from vents, and flow-weighted stream inflow on **Figure 5**. This plot clearly shows that vent fluids are not simply a mixture between ascending deep thermal water and lake water and/or local meteoric waters as represented by flow-weighted inflow. Instead, vent and pore water data define a trend that intersects the boiling curves for deep thermal water at the 220°C mark. We believe this is strong evidence that deep thermal water has boiled to ~220°C on ascent and then mixed with lake water at depth to form the lake bottom vent fluids.

Is 220°C a reasonable boiling temperature for the hydrothermal fluids entering the bottom of Yellowstone Lake? Using the relationship between boiling point and depth (or pressure) in Henley et al. (1984), we calculate that the boiling-point temperatures at the depths of the lake bottom vents are 105°C for the shallow (7–10 m) vents in Mary Bay; 158–160°C for vents in the deep crater of Mary Bay; 140–160°C for vents at depths of 29–53 m in West Thumb; and 180–185°C for the deep (95–110 m) vents near Stevenson Island. The higher boiling temperature of the hydrothermal source fluid derived from **Figure 5** (220°C) suggests that mixing with lake water occurs in the subsurface beneath

Element or species	Units	predicted composition of geothermal source fluid to YL	predicted composition of deep thermal reservoir fluid	Porkchop Jul-99	Black Pool Sep-98	Black Pool Jul-99	Vandalized Pool Sep-98
temp.	°C	220	360	57	ND	72.3	ND
рН		ND	ND	6.6	8.2	7.9	8.2
CI	mM	16	8.7	17	8.5	8.5	8.7
SiO ₂	mM	16	8.7	6.8	6.0	4.8	5.3
В	μΜ	920	500	860	ND	320	ND
Li	μM	950	510	1,400	620	560	520
Na	mM	37	20	17	16	18	16
К	μM	1,000	570	1,460	490	500	310
Rb	μM	7.4	4.0	5.7	1.8	2.3	1.2
Cs	μM	9.0	4.8	4.4	1.8	2.3	0.60
Mg	μM	ND	ND	0	0	0	0.4
Са	μM	ND	ND	130	19	22	17
Sr	nM	ND	ND	150	21	23	18
Ва	nM	ND	ND	76	0	0	0
As	μM	32	20	41	21	32	21
Ge	μM	1.6	1.0	0.55	0.44	0.74	0.44
Мо	μM	4.6	2.8	2.9	0.93	1.1	1.0
Sb	μM	1.7	1.1	1.2	0.82	0.82	0.82
w	μΜ	5.5	3.4	0.87	1.3	2.1	1.4
HCO ₃ *	mM	13	ND	0.12	7.0	9.0	7.0
SO4	mM	5.1	ND	0.33	0.41	0.47	0.49

 Table 2. Comparisons of predicted chemical compositions of boiled hydrothermal source fluid to Yellowstone Lake water (YL) and

 deep thermal reservoir fluid with measured compositions of subaerial geothermal waters in Norris Geyser Basin (Porkchop Geyser) and West Thumb Geyser Basin (Black Pool and Vandalized Pool Geysers). Modified from Balistrieri et al. (2006).

ND = not determined

*Calculated by charge balance

the lake bottom. The hydrostatic boiling curve indicates a total depth of about 225 m for a boiling temperature of 220°C. Thus, mixing between ascending deep source fluid and lake water is estimated to occur at ~100–200 m below the lake floor based on the total hydrostatic pressure of the column of water. If pressures are above hydrostatic due to lithostatic loading, then the depth of boiling at 220°C will be shallower.

4.2 Concentrations of Selected Elements and

Species in Boiled Hydrothermal Source Fluid

If our assessment of the Cl-δD relationships and pore-water data is correct, then we can estimate the concentrations of elements in the hydrothermal source fluid by linear extrapolation of element concentrations in lake water and vent fluids (Balistrieri et al. in press) to Cl concentrations equal to the 220°C boiled fluid (16 mM or 570 mg/kg; **Figure 5**) or the 360°C deep source fluid (8.7 mM or 310 mg/kg). The predicted concentrations of selected elements and species in the boiled hydrothermal source fluid are similar to the observed compositions of selected subaerial geyser fluids that are thought to approximate deep seated fluids in YNP (Table 2). These comparisons indicate that Porkchop Geyser is most similar to the predicted 220°C boiled source fluid. Comparing these two directly, predicted As, B, K, Li, Rb, Sb concentrations are all within ~40% of the measured values in Porkchop Geyser. Cs, Ge, HCO₂, Mo, Na, SO₄, SiO₂, and W are all depleted in the Porkchop water relative to the predicted 220°C water. Volatile components, bicarbonate and sulfate (which is derived from H₂S oxidation) are the most strongly depleted relative to the predicted value. The Black Pool and Vandalized Pool samples (Table 2) most closely reflect the composition of the neutral chloride 360°C deep thermal reservoir fluid. Comparing these analyses to the predicted deep reservoir fluid, predicted concentrations of As, K, Li, Na, and Sb are within 34% of the average values for the real springs. Cs, Mo, Rb, and W are strongly depleted relative to the predicted 360°C water composition. The degree of agreement between the predicted fluids and actual springs is remarkable given that both the lake vents and the subaerial vents have undergone a long series of complicated boiling, cooling, and reaction processes.

Chemical geothermometers (Fournier 1981; Kharaka and Mariner 1988) indicate equilibrium temperatures for the boiled source fluid of 158°C (Na-K), 202°C (amorphous SiO₂), 277°C (quartz with maximum steam loss), and 331°C (chalcedony). The amorphous silica geothermometer is most consistent with the 220°C predicted from δ D-Cl systematics, which is consistent with the observation that vent deposits and the underlying lake sediments contain abundant amorphous silica.

The fraction of hydrothermal source fluid that is in the water column of Yellowstone Lake is due to the flow of water from hydrothermal vents into the lake, and this can also be assessed using Cl concentrations. The flow of water from hydrothermal vents is estimated by mass balance, assuming Cl behaves as a conservative element (Balistrieri et al. in press). This calculation indicates that the flow of hydrothermal source fluid to the lake is 0.006-0.009 km³ of water per year or about 8 x 10⁹ kg of water

per year. Although the flow rate of hydrothermal source water to the lake is small compared to the flow rate of water from streams, the flux or loading of elements to the lake from sublacustrine vents is significant because of the high concentrations of Cl and other elements in the hydrothermal source water.

Using the same procedure as Balistrieri et al. (in press), we can also estimate the flux of hydrothermal water in terms of the deep (360°C) thermal reservoir fluid. Chloride mass balance calculations on inflow and outflow water yields a discharge from the deep thermal reservoir of 0.01-0.02 km³ of water per year or about $1.5 \ge 10^{10}$ kg of water per year. Studies of Cl in streams indicate that in 1999 there was a total flux of deep thermal water of about 16 x 10¹⁰ kg/yr from all thermal areas in the Park (Friedman and Norton 2000, and in press). This means that sublacustrine vents in Yellowstone Lake account for ~10% of the total flux of deep thermal reservoir water in the Park. This estimate is similar to that of Fournier et al. (1976) based on Cl content at the lake outflow at Fishing Bridge in 1972. Because we estimate that 41 million kg/d of deep hydrothermal fluid flows into the lake, and recent studies have revealed the presence of more than 650 hydrothermal features on the lake bottom (Morgan et al. in press), Yellowstone Lake should now be considered one of the most important thermal basins in the Park.

5.0 OCCURRENCE AND MINERALOGY OF HYDRO-THERMAL DEPOSITS IN YELLOWSTONE LAKE

We have collected hydrothermal deposits from a range of environments in Yellowstone Lake (**Figure 1**) including shallow-water (<15m) near-shore locations in West Thumb, Mary Bay, off Steamboat Point, and in Sedge Bay; at moderate-depths (29–53 m) in West Thumb and in the Mary Bay hydrothermal-explosion-crater complex; and in the deepest part of the lake (95–110 m) off Stevenson Island.

Most sublacustrine hydrothermal vents in Yellowstone Lake occur within localized bathymetric pits or craters, here called vent craters, which are commonly \sim 1–10 m wide and \sim 10–20 m deeper than the surrounding lake



sublacustrine photos by David Lovalvo, Eastern Oceanics Inc.

Figure 6. Photographs of hydrothermally altered sediments and hydrothermal deposits: A. Silicified mud fragments near hydrothermal vent in Mary Bay. B. Silicified, semi-lithified layered muds showing slumping in vent crater wall in Mary Bay. C. Disoriented fragments of laminated hydrothermally altered muds at the base of a vent crater wall in Mary Bay D. Silicified hydrothermal conduits protruding above the lake floor in West Thumb at 33 m depth. E. Flat and branching plates of siliceous vein deposits along joints and fractures atop sediment in West Thumb at 33 m depth. F. Irregular, bulbous conduit that terminates in a surficial, layer of silicified sediments from 22 m depth in West Thumb. G. Irregular conduit structure from 51 m depth in Mary Bay. Walls are coated with semi-lithified lake sediments. H. Siliceous, iron-oxide-stained conduit showing main orifice and smaller orifices branching off the sides from 50 m depth in West Thumb. I. Portion of 4-cm-diameter conduit with silica-rich walls and ~2-cm-diameter main conduit, filled with buff-colored sediment, from 42 m depth in Mary Bay. J. Mushroom-shaped conduit from West Thumb at 51 m depth. Upper portion of sample is semi-indurated and stained red-brown by Fe-oxides. Base of sample consists of softer gray-buff sediment. Central 2.5- to 4.0 cm-diameter conduit is lined with amorphous silica and native sulfur (not visible in photo). K. SEM photomicrograph of outer surface of conduit with detrital material and diatoms. L. Portion of silicified conduit from Mary Bay with partly silicified buff-gray lake sediment adhering to outer walls, and partly stained by iron-oxides. M. SEM photomicrograph of outer surface of conduit with detrital material and bitoms. L. Portion of silicified conduit from Mary Bay with partly silicified buff-gray lake sediment adhering to outer walls, and partly stained by iron-oxides.

floor. High-resolution bathymetric mapping has located more than 650 vent structures in Yellowstone Lake (Morgan and Shanks, this volume; Morgan et al. in press). The largest of the vents is near Stevenson Island (**Figure 1C**) and is about 220 m wide and 50 m deeper than the surrounding lake bottom. It contains numerous individual vents, as indicated by ROV exploration and sampling.

Altered sediments (referred to as vent muds) exposed in the walls of vent craters commonly are laminated, semiindurated, fractured, and jointed, and typically break into angular centimeter- to decimeter-sized blocks (**Figure 6A-C**). Unconsolidated but often strongly altered sediment occurs on floors of the craters near active hydrothermal vents in Mary Bay and West Thumb, and southeast of Stevenson Island (**Figure 1C**).

5.1 Siliceous Vent Deposits

Hydrothermal precipitates occur on the lake bottom near active hydrothermal vents and at vent sites that are now inactive. Hydrothermal deposits in Mary Bay, in West Thumb, and southeast of Stevenson Island are characterized by centimeter- to decimeter-sized siliceous tubular and branching structures representing fluid conduits (Figure 6D-J). Most common are 1- to 8-cm-diameter irregular tubes with 1- to 5-cm-diameter openings that are, in some cases, filled with sediment or silica (Figure 6G-J). Individual conduit samples are as much as 40 cm long. The outer surface of many conduits consists of soft to friable sediment mainly comprised of diatoms, as well as minor quartz, albite, smectite, and illite (Figure 6G, H, K, L). Toward the inner wall of the conduit, the diatoms are progressively recrystallized and cemented by amorphous silica. Conduit centers are coated or clogged with amorphous silica, the texture of which indicates precipitation from hydrothermal fluids (Figure 6M).

Siliceous hydrothermal conduits or tabular deposits occur on the bottom and walls of the hydrothermal vent craters, either protruding from the sediment or lying flat on the sediment surface. In one upright conduit rising above the sediment in West Thumb, native sulfur occurs as thin layers within the walls and lining the inner wall of the open conduit (**Figure 6J**). This mineral probably results from microbial oxidation of H_2S in hydrothermal fluids. The outer surface of a conduit sample from the Stevenson Island site is coated with gypsum and yellowish natrojarosite that results from oxidation of hydrothermal sulfide minerals within the conduit walls.

In Mary Bay, irregularly shaped conduits are commonly perched on the walls of the explosion crater (**Figure 6D and G**). Field observations suggest that these features have formed within soft sediment during fluid seepage through fractures in the underlying sediment, and have subsequently been exposed by winnowing or slumping of soft sediment. An alternative explanation is that the conduits grew as chimneys above the sediment surface, but this is inconsistent with the occurrence of layered diatomaceous sediments within conduit walls (**Figure 6D, G, H, K**).

The occurrence, morphology, and mineralogy of the tubular and tabular siliceous structures suggest that they formed as fluid conduits within the sediment and that the sediment between the conduits was subsequently removed, in some places exposing the deposits at the sediment surface where many have toppled over. Holocene sediments are diatom-rich, and accumulation rates are 60-100 cm/ka (Tiller 1995) suggesting that the now inactive hydrothermal conduit deposits formed within the last few hundred years.

In West Thumb, flat and branching plates of siliceous material, <1 cm thick by as much as tens of centimeters across, occur locally atop the sediment along with other hydrothermal deposits (**Figure 6F**, **J**). This platy material is essentially identical to the walls of the tubes described above and probably formed as surface crusts or veins within the sediment. Lacy, network-like conduits along joints and fractures in West Thumb hydrothermal fields must have formed beneath the sediment-water interface. Many of the inactive siliceous conduits are stained red to dark brown by coatings of Fe oxyhydroxides.

5.2 Siliceous Spires

A major type of inactive hydrothermal deposit consists of hard, porous siliceous chimneys, referred to herein as spires, which occur only in Bridge Bay (**Figure 1C**). A group of 12–15 spires, extending to 8 m in height and 10 m in diameter, project above the lake floor at a water depth of 15 m (Figure 7). No presently-active hydrothermal vents are observed associated with spire fields. Spire samples consist of white or tan, porous, punky opaline silica with a distinctly red-brown to black outer zone and surface. Scanning electron microscope studies reveal that the spire interiors consist of interconnecting masses, cylinders, and tubes of aggregated silica globules (Figure 7). The individual globules are 5-10 μ m in diameter. These textures are similar to those observed for silica in active submarine hydrothermal deposits from mid-ocean ridges (Alt et al. 1987; Juniper and Fouquet 1988). Tiny $(\sim 1 \,\mu m)$ holes in the silica globules are probably dissolution effects and could be microbial in origin. The overall texture resembles the precipitation of silica on bacterial filaments as documented in New Zealand hydrothermal systems (Jones and Renaut 1996; Jones et al. 1997). Bacterial mats surrounding shallow, active hydrothermal vents in Yellowstone Lake are commonly observed. Diatoms are present in the spire walls and especially abundant in spire "roots" that extend below the sediment-water interface.

The Bridge Bay spires are chimney-like features formed in place at lake-bottom hydrothermal vents, which are analogous to sulfide-sulfate-rich chimneys formed at ocean ridges. No active hydrothermal venting associated with spires has been observed in Yellowstone Lake, and the only known spires are in Bridge Bay. Preliminary studies using uranium-isotope disequilibria suggest the spires formed about 11 ka (N. Sturchio 1998, written communication), shortly after the last glacial recession about 16 ka. Investigations of post-glacial Yellowstone Lake shorelines (Meyer 1986; Meyer and Locke 1986; Pierce et al. 2002) indicate that the lake was above present level during most of this period. Moreover, the upright spire structures could not have formed subaerially above a lower lake level and survived submergence with the attendant wave activity and seasonal ice flows.

5.3 Geochemistry of Yellowstone Lake Sediments and Altered Vent Sediments

Hydrothermally altered and unaltered sediments were sampled at several sites in the lake. Unaltered, unconsolidated lake sediment consists almost entirely of



opal (diatoms) as well as trace amounts of quartz, albite, smectite, illite, and pyrite.

Altered, semi-consolidated, laminated, gray sediment exposed in the walls of hydrothermal vent craters in West Thumb consists of fine-grained quartz, smectite, and chlorite, as well as traces of illite, albite, and pyrite. Sediment in the outer walls of inactive silicified conduits within the craters consists of opal, minor quartz, albite, smectite, illite, and pyrite. Altered gray-brown and olivebrown muds at active and inactive vents in vent craters east of Stevenson Island consist of chlorite and quartz in addition to lesser albite, smectite, illite, and pyrite. Opal has been recrystallized to quartz, and chlorite may be derived from hydrothermal-alteration processes. OliveTable 3. Average major, minor, and trace element data for sublacustrine hydrothermal vent deposits, spires, and vent muds compared to subaerial West Thumb sinter and unaltered West Thumb surficial sediments. Oxide data are in wt.% and elemental data are in mg/ kg (ppm).

Oxide or element	Vent conduit deposits	Bridge Bay spires	West Thumb sinters	Hydrothermal vent muds	West Thumb sediments
SiO ₂	81.5	83.6	92.4	69.7	85.2
Al ₂ O ₂	5.78	4.64	0.54	13.9	3.72
CaO	1.19	0.64	0.10	1.52	0.62
Fe.O.	1.88	3.00	0.11	4.71	1.87
K O	0.00	0.40	0.09	1.45	0.52
K ₂ O	0.88	0.40	0.09	1.45	0.52
MpO	0.53	0.41	< 0.10	0.12	0.65
Na O	1.06	0.04	0.01	1.10	0.10
	0.07	0.44	0.32	1.13	0.40
P ₂ O ₅	0.27	0.48	0.07		0.54
TiO ₂	0.25	0.12	0.03		0.13
S wt %	0.33	0.20		0.04	0.17
Ag	0.24	0.17	0.06	0.15	0.30
As	442	563	7.13	220	360
Ba	536	1780	43.2	696	281
Be	1.29	17.8	29.9	2.16	3.71
Bi	0.09	0.06	0.06	0.13	0.18
Cd	0.26	0.55	0.02	0.17	0.29
Co	6.10	13.3	0.24	17.9	6.73
Cr	37.6		29.0	118	
Cs	34.7	4.83	82.2		13.5
Cu	11.3	14.0	7.90	32.9	17.3
Ga	11.3	8.73	117	26.2	
Ge	2.60	2.70	1.88	3.26	15.5
Hf	1.57	0.60	1.10		1.14
Hg	5.38			16.0	1.92
Li	10.0	21.7	6.32	39.1	13.6
Mo	4.18	15.6	0.41	11.8	13.9
Nb	8.37	8.75	1.43		5.21
Ni	21.2	143	4.80	59.3	33.0
Pb	12.5	5.63	1.40	28.1	6.94
Rb	34.0	12.9	13.7	48.3	20.0
Sb	6.48	11.4	39.5	12.7	37.2
Sc	4.94	2.00			3.44
Se	0.30			0.60	1.00
Sn	1.26	0.70		3.02	0.96
Sr	239	119	5.63	276	88.2
la	0.57	0.10	0.20	40.0	0.30
	4.28	2.03	0.46	10.8	3.49
	0.83	9.10	0.12	0.91	0.31
0	1.29	2.13	0.22	3.44	1./8
V	39.0	66.3	1.40	108	48.3
W	59.4	137	3.58	//.6	40.4
Y	10.9	9.05	1.18	07.0	12.9
Zn	23.5	24.0	14.0	67.9	35.6
l ∠r	89.8	21.7	0.40		/0.6

green to black muds sampled at active 60–120°C vents in Mary Bay by ROV and by gravity coring contain quartz, albite, smectite, illite, and minor gypsum. Gypsum may have formed from oxidation of H_2S in hydrothermal fluids or pore waters or from oxidation of fine-grained pyrite. Opal in these sediments has also been completely recrystallized to quartz.

Altered sediments in cores taken in hydrothermal vent areas in Mary Bay and West Thumb (Balistrieri et al. in press) smelled of sulfide and, in some cases, petroleum-like hydrocarbons. Plastic core liners, which melt at ≥135°C, were partially melted and strongly deformed,

reflecting high temperatures in the very shallow subsurface (<1 m). Analyses of pore waters from these cores, discussed above, indicates high-Cl contents (up to 9.1 mM or 318 ppm) that record mixing of lake water and endmember hydrothermal fluids in the very shallow subsurface (Balistrieri et al. in press).

Average major, minor, and trace element data for sublacustrine hydrothermal vent deposits, spires, and vent muds and, in contrast, subaerial West Thumb sinter and unaltered West Thumb surficial sediments, are compiled here (**Table 3**). Complete data sets are available in Shanks et al. (in press). Unaltered lake sediments have high SiO₂ (81.3–86.4 wt.%) and Al₂O₃ (2.8–5.5 wt.%), and minor total iron (1.6–2.6 wt.% as Fe₂O₃) and MgO (0.5–1.2 wt.%). CaO, Na₂O, and K₂O are very low (<1 wt.%). In contrast, altered muds from hydrothermal vents have lower contents of SiO₂ and greater Al₂O₃, CaO, Na₂O, K₂O, Fe₂O₃, and MgO than the modern diatom-rich sediments.

Major element variations in individual samples of altered vent muds, unaltered sediments, and hydrothermal deposits are illustrated on a ternary diagram of SiO_2 - Al_2O_3 -CaO (**Figure 8**). This projection shows that the vent mud samples are progressively depleted in SiO_2 , strongly enriched in Al_2O_3 , and somewhat enriched in CaO relative to unaltered Yellowstone Lake sediment. Silica dissolution and its affect on sediment chemistry, calculated by mass



Figure 8. Ternary diagram of SiO₂-Al₂O₃-CaO for siliceous deposits and Yellowstone Lake sediments

balance (Shanks et al. in press), indicates that dissolution of 63 wt.% SiO₂ from normal unaltered lake sediments produces solids that are remarkably similar to the analyzed vent muds. This calculation slightly underestimates the amount of Al₂O₃ and Na₂O in altered muds and overestimates CaO, K2O, MgO, and Na2O, especially for Stevenson Island vent muds. Also, Fe₂O₃ is enriched in Stevenson Island vent muds compared to the calculated values. These results suggest that, in West Thumb and Mary Bay vent muds, silica leaching is accompanied by the addition of Na₂O and Al₂O₃. In the Stevenson Island vent field, silica leaching is accompanied by the addition of Fe₂O₃ and the removal of CaO, K₂O, and MgO, and Na₂O. These trends are consistent with the more intense alteration observed in Stevenson Island vent muds, which contain abundant chlorite.

Could these chemical trends be produced or enhanced by physical entrainment of fine-grained sediments, as apparently occurs to produce a water column sediment plume over some north lake vents (Morgan and Shanks, this volume)? The indicated removal of alkalis and alkaline-earth elements from the Stevenson Island muds, coupled with the addition of iron to form chlorite, favors a chemical process. In addition, chemical variation in hydrothermal conduits (**Figure 8**) ranges from nearly pure silica for deposits filling the conduit interiors to SiO₂-Al₂O₃-CaO abundances in the outer walls of conduits that are similar to vent muds (Shanks et al. in press). Because physical winnowing is precluded in the conduit wall, where original sedimentary layering is often preserved, we conclude that these variations are due to chemical-leaching. Vent muds show more extreme chemical changes than conduits, which is most likely due to more intense chemical leaching. Physical entrainment is unlikely to produce the chemical shifts we observe.



Figure 9. Plot of oxygen isotope values of hydrothermal silica deposits versus calculated temperatures assuming formation from vent fluid with δ¹⁸O similar to present-day Yellowstone Lake water. Lake floor boiling temperatures, which are upper limits, are noted for deposits from different depth environments.

Siliceous hydrothermal conduits and spires are

enriched in As, Hg, Mo, Tl, and W relative to West Thumb sinter or unaltered sediments (**Table 3**). Hydrothermally altered vent muds are enriched in Ba, Co, Cu, Fe, Ni, Tl, V, W and Zn relative to unaltered sediments. Most of these elements are strongly enriched in hydrothermal vent fluids (**Tables 1 and 2**; **Figure 4**), and we conclude they are deposited due to hydrothermal vent processes.

Hydrothermal vent muds are also depleted in As, Mn, Mo, and Sb (**Table 3**) suggesting these elements may be derived from alteration of subsurface sediments. However, the minor and trace elements concentrated in hydrothermal fluids appear to be similar throughout YNP, especially within the caldera (Gemery-Hill et al. in press), suggesting that subsurface reaction with underlying rhyolitic lava flows (Morgan and Shanks, this volume) must be the ultimate source of many of these elements.

6.0 STABLE ISOTOPE SYSTEMATICS

6.1 Oxygen Isotopes in Siliceous Deposits and Altered Sediments

Oxygen isotope values of silica in sublacustrine conduits, spires, and vent mud samples range from -3.5 to 20.3 per mil (Shanks et al. in press), with the lower values indicating

formation at higher temperatures. Unaltered West Thumb sediments have δ^{18} O values from 15.0 to 17.3 per mil, and subaerial West Thumb sinter samples have values from 20.6 to 21.4 per mil.

Calculated oxygen isotope fractionation temperatures of sublacustrine hydrothermal deposits, assuming reaction of amorphous silica deposits with normal lake water ($\delta^{18}O = -16.5$), indicates a range from 78–164°C (**Figure 9**). The progression of temperatures in **Figure 9** is generally consistent with those expected for the different environments. For example, subaerial West Thumb sinter, which forms from thin sheets of hot-spring waters flowing across the surface of the sinter terraces, must form at temperatures between boiling (94°C at the altitude of West Thumb Geyser Basin) and ambient air temperature. Our calculated temperatures are 51–55°C based on silicawater oxygen isotope fractionation.

Similarly, the spires must form at moderately low temperature because they occur in shallow water where the boiling point limits fluid temperature to about 120°C, and they appear to contain abundant remains of bacteria which cannot live at temperatures above 114°C (Jorgensen et al. 1990). Moreover, the spires protrude into the water column and would effectively radiate heat. Calculated oxygen isotope temperatures are 80-96°C.

At the other end of the spectrum, sinter and vent mud samples from Mary Bay and Stevenson Island, where boiling temperatures are 140°C or higher, give δ^{18} O temperatures generally from 127—164°C (**Figure 9**). Thus, the oxygen isotope fractionation temperatures for silica deposits are generally consistent with their geologic settings but are probably underestimated because δ^{18} O values for actual vent fluids may be higher than –16.5 per mil (ambient lake water) due to sediment-fluid interaction on ascent.

6.2 Sulfur Isotopes in Lake Water, Vent Fluids, and Vent Deposits

Sulfur isotope values of Yellowstone Lake sulfate are quite uniform at 2.5 per mil (±0.7 per mil). Two sources of sulfur to Yellowstone Lake are possible: (i) vent-related sulfide that oxidizes to SO4 in the lake (vent H2S has measured $\delta^{34}S_{_{\rm H2S}}$ values of –0.5 to 3.6 per mil with an average value of 2.2 per mil), or (ii) SO_4 in streams that drain into the lake. Yellowstone River and tributaries that flow into Yellowstone Lake have $\delta^{34}S_{SO4}$ values that range from -3.6 to 10.7 per mil with an average of 2.6 per mil. Vent mud δ^{34} S values of sulfides range from -3.8 to 5.7per mil and average 2.7 per mil, similar to the range and average in stream waters. These overlapping data do not distinguish the proportion of sulfur contribution from surface discharge or sublacustrine hydrothermal vents. It is likely, however, that vents make a significant contribution to the sulfur budget of the lake because H₂S is present in most vent fluids and minor pyrite precipitation is common in altered sediments.

7.0 PROCESSES OF SPIRE DEVELOPMENT

Shanks et al. (in press) used geochemical reaction modeling to show that conductive cooling is very effective in precipitating amorphous silica from saturated solutions, and that silica precipitation during advective mixing with cold bottom water occurs only at mixing temperatures >145°C. Under the conditions encountered at Yellowstone Lake, conductive cooling is the more effective process for silica precipitation.

The formation of silica deposits is conceptualized in Figure

10 (next page). Venting of hot silica-rich fluids on the cold lake floor causes precipitation of amorphous silica in the sediment and at the sediment-lake water interface (Figure 10). Smaller conduits, including vertical pipe and horizontal flat tabular deposits, form within near-surface sediments along cracks and joints and permeable horizons. We suggest that spires form by precipitation on bacterial masses, which are commonly observed by ROV around active sublacustrine vents, and are abundant as silicified filaments within the spires (Figure 7). This could provide a semi-permeable barrier to mixing, which would enhance conductive cooling and encourage additional silicification and spire growth. Once the outer shell of the spire is established, additional vent fluids traveling up the central portion of the structure can be cooled by conductive heat loss, consistent with the 80-94°C estimated temperatures of formation (Figure 9). Conductive cooling causes rapid silica precipitation and upward growth of spires from the lake bottom. Diatoms in surrounding sediments and in the water column are incorporated into the precipitating spire structure.

Why do large spires occur in shallow water near Bridge Bay and not elsewhere in the lake? Relevant observations are: (i) spires are not associated with present-day hydrothermal activity; (ii) high resolution bathymetric mapping (Morgan et al. 2003) shows conclusively that large spires occur only in the Bridge Bay area; (iii) spires contain abundant silicified filamentous masses (Figure 7); (iv) chemical and isotopic studies indicate that spires are hydrothermal; and (v) bathymetric images show the spires form within hydrothermal craters on the lake bottom in shallow water (<15 m). Many presently active hydrothermal vents on the floor of Yellowstone Lake are in shallow-water settings similar to the Bridge Bay spire field, yet do not appear to be forming spires. Observations of the silica-encased filamentous textures suggest the original thermophilic bacteria may have been cyanobacteria, which have an upper temperature limit of 73°C and are photosynthetic. We speculate that the spires require a site shallow enough to be in the photic zone so cyanobacteria can flourish around the periphery of the vents. In order to carry and deposit abundant silica, the spires must form from hot water (not steam or gas) vents. This may be a rare combination because most shallow-water vents are very gas-rich and therefore are poor transporters of silica.

8.0 CONCLUSIONS

Geochemical studies of stream, lake, and hydrothermal vent waters indicate that Yellowstone Lake is enriched in a suite of elements (As, B, Cl, Cs, Cu, Ge, Li, Mo, Sb, and W) derived from hydrothermal processes. Cl- δ D systematics indicate that lake bottom vent fluids are a mixture of lake water with deep source fluid that has boiled on ascent from ~360°C to ~220°C and has mixed with lake water in the shallow subsurface. Mass-balance calculations indicate that the flow of hydrothermal source fluid into the lake is about 1.5 x 10¹⁰ kg/yr or about 10% of the total flux of deep thermal fluid in YNP. Thus the Yellowstone Lake Basin represents one of the Park's most important thermal areas.

Hydrothermal vent processes on the floor of Yellowstone Lake result in a variety of siliceous hydrothermal deposits, including conduits and spires, as well as the development of vent craters where active venting occurs or has occurred in the past. Tubular siliceous conduits form in recent sediments just below the sediment-water interface, and are typically filled with amorphous silica.

Spires composed mainly of silica grew as chimneys above lake-bottom hydrothermal vents. Ascending hot and Clrich waters react with silica-rich volcanic glass and diatomrich lake sediments in the subsurface, resulting in saturation with amorphous silica. Cooling of the silica-saturated hydrothermal vent fluids at the lake floor causes silica precipitation. Spires contain abundant silicified masses that are probably bacteria, and bacterial concentrations at vents sites are probably important in the spire growth process.

Hydrothermal vents in Yellowstone Lake almost invariably occur in hydrothermal craters on the lake bottom localized near the edges of rhyolitic lava flows (Morgan and Shanks, this volume). Geochemical analyses of altered vent muds indicate that vent craters are most likely formed by hydrothermal dissolution of silica in sediments. Sediment entrainment and physical winnowing by vent fluids also occurs, but is considered to be less important.





This work could not have been done without the support of the National Park Service, especially Mike Finley, John Varley, Tom Olliff, Paul Doss, Dan Reinhart, Rick Fey, John Lounsbury, Dan Mahoney, Jim Ruzycki, Todd Koel, and the Aquatic Resources Group at Lake Station. We are particularly indebted to Dave Lovalvo of Eastern Oceanics, Inc., who designed, built, and piloted the ROV and the research vessel (R.V. Cutthroat), and generously shared his incredible knowledge of Yellowstone Lake. We thank Kate Johnson, Ed du Bray, Geoff Plumlee, Pat Leahy, Steve Bohlen, Tom Casadevall, Linda Gundersen, Denny Fenn, Elliott Spiker, and Dick Jachowski for supporting this work. We thank Dan Reinhart, Paul Doss, Ann Deutch, Christie Hendrix, Pam Gemery, Rick Sanzolone, Al Meier, Pete Theodorakos, Eric White, Jim Bruckner, Brie Burdick, Steve Harlan, Kirk Miller, Jim Waples, Bob Evanoff, Wes Miles, Rick Mossman, Gary Nelson, and many others for assistance with field and laboratory studies. We especially thank Greg Lee and Mike Webring of the USGS for turning raw data into beautiful maps. We thank Val Klump, Russell Cuhel, Tony Remsen, and Carmen Aguilar of the University of Wisconsin-Milwaukee for introducing us to Yellowstone Lake vent studies and for sharing samples. The U.S. Geological Survey and the National Park Service provided financial support for this research. Randy Koski and Ian Ridley provided constructive reviews that substantially improved the manuscript.

REFERENCES

- Alt, J.C., P. Lonsdale, R. Haymon, and K. Muehlenbachs. 1987. Hydrothermal sulfide and oxide deposits on seamounts near 21°N., East Pacific Rise: *Geol Soc Am Bull* 98:157–168.
- Balistrieri, L.S., W.C. Shanks, III, R.L. Cuhel, C. Aguilar, and J.V. Klump. In press. The influence of sublacustrine hydrothermal vents on the geochemistry of Yellowstone Lake. In *Integrated Geoscience Studies in the Greater Yellowstone Area: Volcanic, Hydrothermal, and Tectonic Processes in the Yellowstone Geoecosystem*, ed. L.A. Morgan. US Geol Surv Prof Pap.
- Browne, P.R.L., and J.V. Lawless. 2001. Characteristics of hydrothermal eruptions, with examples from New Zealand and elsewhere. *Earth Sci Rev* 52:299–331.
- Christiansen, R.L. 2001. The Quaternary and Pliocene Yellowstone Plateau volcanic field of Wyoming, Idaho, and Montana. US Geol Surv Prof Pap 729-G.
- Clayton, R.N., T.K. and Mayeda. 1963. The use of bromine pentafluoride in the extraction of oxygen in oxides and silicates for isotopic analysis: *Geochim Cosmochim Acta* 27:43–52.
- Craig, H. 1961. Isotopic variations in meteroic waters. *Science* 133:1702–3.
- Craig, H., L.I. Gordon, and Y. Horibe. 1963. Isotopic Exchange Effects in the Evaporation of Water. J Geophys Res 68:5079-87.
- Fournier, R.O. 1981. Application of water geochemistry to hydrothermal exploration and reservoir engineering. In *Geothermal* systems—Principles and case histories, ed. L. Rybach and L.J.P. Muffler, 109-43. New York: John Wiley and Sons.
- Fournier, R.O. 1989. Geochemistry and dynamics of the Yellowstone National Park hydrothermal system. Ann Rev Earth Planet Sci 17:13–53.
- Fournier, R.O. 1999 Hydrothermal processes related to movement of fluid from plastic into brittle rock in the magmatic-epithermal environment. *Econ Geol* 94:1193–1212.
- Fournier, R.O., D.E. White, and A.H. Truesdell. 1976. Convective heat flow in Yellowstone National Park. Proc 2nd U.N. Symp Development and Use of Geothermal Resources, San Francisco, 1975, 731–9.
- Friedman, I., and D.R. Norton. 2000. Data used for calculating chloride flux out of Yellowstone National Park for the water years 1983-1999: US Geol Surv Open-File Rep 00-0194.
- Friedman, I., and D.R. Norton. In press. Is Yellowstone losing its steam?: Chloride flux out of Yellowstone National Park. In Integrated Geoscience Studies in the Greater Yellowstone Area: Volcanic, Hydrothermal, and Tectonic Processes in the Yellowstone Geoecosystem, ed. L.A. Morgan. US Geol Surv Prof Pap.
- Gemery-Hill, P., W.C. Shanks, III, and L.S. Balistrieri. In press. Geochemical Data for selected rivers, lake waters, hydrothermal vents and sub-aerial geysers in Yellowstone National Park, Wyoming, and vicinity, 1996-2002. In *Integrated Geoscience*

Studies in the Greater Yellowstone Area: Volcanic, Hydrothermal, and Tectonic Processes in the Yellowstone Geoecosystem, ed. L.A. Morgan. US Geol Surv Prof Pap.

- Giesemann, A., H.-J. Jager, A.L. Norman, H.R. Krouse, and W.A. Brand. 1994. On-line sulfur-isotope determination using an elemental analyzer coupled to a mass spectrometer. *Anal Chem* 66:2816–19.
- Henley, R.W., A.H. Truesdell, P.B. Barton, Jr., and J.A. Whitney. 1984. Fluid-mineral equilibria in hydrothermal systems. *Reviews in Economic Geology*, vol 1, Society of Economic Geologists.
- Hostetler, S.W., and F. Giorgi. 1995. Effects of a 2 X CO₂ climate on two large lake systems: Pyramid Lake, Nevada, and Yellowstone Lake, Wyoming. *Global Planetary Change* 10:43–54.
- Jones, B., and R.W. Renaut. 1996. Influence of thermophilic bacteria on calcite and silica precipitation in hot springs with water temperatures above 90 degrees C; evidence from Kenya and New Zealand. *Can J Earth Sci* 33:72–83.
- Jones, B., R.W. Renaut, and M.R. Rosen. 1997. Biogenicity of silica precipitation around geysers and hot-spring vents, North Island, New Zealand. J Sediment Res 67:88–104.
- Jorgensen, B.B., L.X. Zawacki, and H.W. Jannasch. 1990. Thermophilic bacterial sulfate reduction in deep-sea sediments at the Guaymas Basin hydrothermal vent site (Gulf of California): *Deep-Sea Res* 37:695-710.
- Juniper, S.K., and Y. Fouquet. 1988. Filamentous iron-silica deposits from modern and ancient hydrothermal sites. *Can Mineral* 26:859–69.
- Kharaka, Y.K., and R.H. Mariner. 1988. Chemical geothermometers and their application to formation waters from sedimentary basins. In *Thermal history of sedimentary basins—Methods and case histories*, ed. N.D. Naeser and T.H. McCulloh, 99-117. New York: Springer-Verlag.
- Meyer, G.A. 1986. Genesis and deformation of Holocene shoreline terraces, Yellowstone Lake, Wyoming. Master's thesis, University of Wyoming.
- Meyer, G.A., and W.W. Locke. 1986. Origin and deformation of Holocene shoreline terraces, Yellowstone Lake, Wyoming. *Geology* 14:699–702.

Morgan, L.A., W.C. Shanks, III, D. Lovalvo, S.Y. Johnson, W. Stephenson, K.L. Pierce, S. Harlan, C. Finn, G. Lee, M. Webring, B. Schulze, J. Duhn, R. Sweeney, and L. Balistrieri. 2003.
Exploration and Discovery in Yellowstone Lake: Results from High-Resolution Sonar Imaging, Seismic Reflection Profiling, and Submersible Studies. J Volcanol Geotherm Res 122:221-42.

Morgan, L.A., W.C. Shanks, III, D. Lovalvo, G. Lee, M. Webring, W.J. Stephenson, and S.Y. Johnson. In press. The Floor of Yellowstone Lake is Anything but Quiet: New Discoveries from High-Resolution Sonar Imaging, Seismic Reflection Profiling, and Submersible Studies. In *Integrated Geoscience* Studies in the Greater Yellowstone Area: Volcanic, Hydrothermal, and Tectonic Processes in the Yellowstone Geoecosystem, ed. L.A. Morgan. US Geol Surv Prof Pap.

- Morgan, L.A., W.C. Shanks, K.L. Pierce, and R.O. Rye. 1998. Hydrothermal explosion deposits in Yellowstone National Park—Links to hydrothermal processes. *EOS Trans AGU* Abstract 79:F964.
- Muffler, L.J.P., D.E. White, and A.H. Truesdell. 1971. Hydrothermal explosion craters in Yellowstone National Park. *Geol Soc Am Bull* 82:723-40.
- Pierce, K.L., and L.A. Morgan. 1992. The track of the Yellowstone hot spot; volcanism, faulting, and uplift. In *Regional geology of eastern Idaho and western Wyoming*, ed. P.K. Link, M.A. Kuntz, and L.B. Platt, 1-53. Geological Society of America Memoir 179.
- Pierce, K.L., K.P. Cannon, G.A. Meyer, M.J. Trebesch, and R. Watts. 2002. Post-glacial inflation-deflation cycles, tilting, and faulting in the Yellowstone caldera based on Yellowstone Lake shorelines. US Geol Surv Open-File Rep 02-142.
- Rye, R.O., and A.H. Truesdell. 1993. The question of recharge to the geysers and hot springs of Yellowstone National Park. US Geol Surv Open-File Rep 93-384.
- Rye, R.O., and A.H. Truesdell. In press. The question of recharge to the deep thermal reservoir underlying the geysers and hot springs of Yellowstone National Park. In *Integrated Geoscience Studies in the Greater Yellowstone Area: Volcanic, Hydrothermal, and Tectonic Processes in the Yellowstone Geoecosystem*, ed. L.A. Morgan. US Geol Surv Prof Pap.
- Shanks, W.C., III, J. Alt, and L.A. Morgan. In press. Geochemistry of sublacustrine hydrothermal deposits in Yellowstone Lake: hydrothermal reactions, stable isotope systematics, sinter deposition, and spire growth. In *Integrated Geoscience Studies in the Greater Yellowstone Area: Volcanic, Hydrothermal, and Tectonic Processes in the Yellowstone Geoecosystem*, ed. L.A. Morgan. US Geol Surv Prof Pap.
- Smith, R.B., and A.M. Rubin. 1994. Rapid reversal of uplift to subsidence at the Yellowstone caldera by magmatic processes imaged by earthquakes. *Seismol Res Lett* 65:56.
- Tiller, C.C. 1995. Postglacial sediment stratigraphy of large lakes in greater Yellowstone- Scenarios of tectonic and climate forcing. Master's thesis, University of Minnesota.
- Truesdell, A.H., M. Nathenson, and R.O. Rye. 1977. The effects of subsurface boiling and dilution on the isotopic compositions of Yellowstone thermal waters. J Geophys Res 82:3694–704.
- Wold, R.J., M.A. Mayhew, and R.B. Smith. 1977. Bathymetric and geophysical evidence for a hydrothermal explosion crater in Mary Bay, Yellowstone Lake, Wyoming. *J Geophys Res* 82:3733–8.
- Yuan, H., and K. Dueker. 2005. Teleseismic P-wave tomogram of the Yellowstone plume. *Geophys Res Lett* 32:L07304, doi:10.1029/ 2004GL022056