6th Biennial
Scientific Conference on the
Greater Yellowstone Ecosystem

YELLOWSTONE LAKE

HOTBED OF CHAOS OR RESERVOIR OF RESILIENCE?

Proceedings

Edited by
Roger J. Anderson and David Harmon

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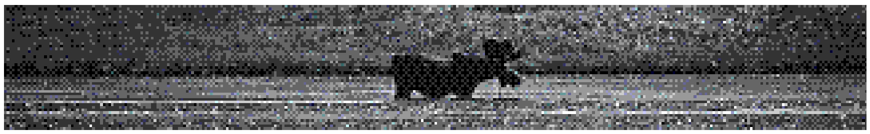
Yellowstone Lake Conference Program Committee



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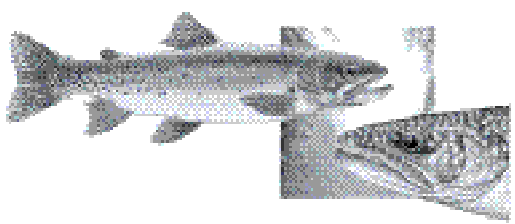

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Foreword

Since the establishment of Yellowstone National Park, its riches have largely been protected through the efforts of generation after generation of park managers and friends. The park's status as a World Heritage Site and a Biosphere Reserve affirm its international recognition as a unique place worthy of preservation. Its relatively unimpaired condition as a naturally functioning ecosystem makes it an ideal place to do research, even while its important standing in the world makes it a place charged with political and emotional controversy.

Many of us see good science as the best antidote to controversy, as so, the purpose of the greater Yellowstone conference series, instituted in 1991, is to encourage the awareness and application of wide-ranging, high-calibre scientific work on the region's natural and cultural resources. There continues to be so much interest in Yellowstone science and issues that a biennial series, with the active involvement of professional societies and other institutions, provides a perfect forum for the hundreds of researchers doing work here.

The Sixth Biennial Conference focused on a central feature of the Yellowstone ecosystem's landscape, Yellowstone Lake—from its depths, where submerged hot springs and spires emerge atop the Yellowstone caldera, to its beaches, where rare plants and evidence of prehistoric peoples erode at the mercy of wind, waves, and modern footsteps. The conference was interdisciplinary in nature and addressed management issues, natural features, and the human history associated with the Yellowstone Lake basin. Session topics included archeology, climate and environmental change, fisheries and ecosystem-level functions, and hydrothermal and geologic processes.

The conference's featured speakers included Dr. Robert Smith, a University of Utah geophysicist who has conducted research in the area for 45 years. Dr. Nigel Trewin of the University of Aberdeen discussed his studies of ancient and extinct hot springs in Scotland, and drew comparisons to fossils preserved more recently in Yellowstone's hot springs. Dr. Cathy Whitlock of the University of Oregon discussed her research examining the prehsitoric record of climate change, vegetation, and fire in the ecosystem by looking at pollen and charcoal records preserved in lakes. Dr. Pat Shanks, a research geologist for the USGS, discussed some of the remarkable spires, hot springs, and geysers that have been found on the floor of the lake.

Other conference highlights included Dr. Andrew Munro's presentation on the potential contributions of microchemistry to forensic science related to the puzzle of when and from where exotic lake trout many have been introduced to Yellowstone Lake. Dr. Russel Cuhel, from the University of Wisconsin at Milwaukee, presented an outstanding collection of photographs related to the underwater spires and thermal features of Yellowstone Lake. Renowned cinematographer Bob Landis presented film footage captured by a remote underwater camera that included Yellowstone Lake's spires and their microbial colonies, geysers erupting from the bottom of the lake, and cutthroat trout spawning up tributary streams.

Nearly 150 people attended the conference, including members of the public as well as scientists, authors, media representatives, and individuals from a number of government agencies. We hope these conferences and their proceedings continue to contribute to professional knowledge and debate on the many aspects of this extraordinary area.

John D. Varley
Director, Yellowstone Center for Resources

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Porewater and Hydrothermal Vent Water Inputs to Yellowstone Lake, Wyoming

Carmen Aguilar, Russell L. Cuhel, and J. Val Klump

Abstract

Geochemical inputs to Yellowstone Lake, Wyoming, come from a variety of sources, including hydrothermal vents, groundwater, rainwater, flux from sediments, and direct runoff. One-third of Yellowstone Lake is directly influenced by hydrothermal activity (hot-water vents and fumaroles). Geothermally heated water percolating through the chamber is highly enriched with carbonate, silicate, chloride, and methane, with some locations additionally rich in iron and sulfide. Vent waters in West Thumb typically contained sub-micromolar concentrations of Fe (iron), while those in Mary Bay and off Stevenson Island contained about 10 µM (micromolar). Water column concentrations of dissolved iron ranged from 250 to 450 nM (nanomolar) in Mary Bay, but were very low in the waters of Southeast Arm, West Thumb, and off Stevenson Island. Porewater and vent water chemistry provided evidence for lake water dilution of vents below the sediment–water interface. Significant fracturing of source water conduits was indicated by extreme differences in porewater profiles from cores less than 5 m apart in the geothermally vigorous West Thumb. Some samples approached theoretical reservoir composition for geothermally active areas of Mary Bay and West Thumb, showing chloride concentrations reaching several mM (millimolar), and, in the case of Mary Bay, extrapolate to the geothermal end member (~20 mM) at a depth of only 2–3 m. These steep concentration gradients support diffusive chloride fluxes across the sediment–water interface three orders of magnitude higher than those in non-venting depositional areas.

Introduction

Yellowstone Lake, Wyoming, is located in the caldera of the largest volcanic eruptions known, which occurred 1.2 million and 650,000 years ago at a mid-continental hot spot, rather than in the more widespread tectonic spreading centers. The Yellowstone hot spot has interacted with the North American plate for millions of years, causing widespread outpourings of basalt. Some of the basaltic melt, or magma, produced by the hot spot accumulates near the base of the plate, where its heat melts the rocks from the Earth's lower crust. As a result, the underlying structure is composed primarily of granite overlain by volcanic silica as opposed to freshly upheaved basalts. Geothermally heated water percolating through the relic chamber is highly enriched in carbonate, silicate, chloride, and methane; some locations are also enriched with iron, manganese, and sulfide. Yellowstone National Park is well known for its steaming geysers, shimmering thermal pools, and bubbling painted mudpots. Some of the greatest characteristics that are not visible are the hydrothermal vents submerged under Yellowstone Lake; hydrothermal activity in the form of springs and fumaroles are described by Remsen et al. (1990) and Marocchi et al. (2001).

The magma chamber encompasses the northern part of Yellowstone Lake, while the Yellowstone River inflow and the southern half of the lake (South and Southeast arms) are outside the caldera. Previous work has shown active hydrothermal venting (geothermal hot springs and fumaroles) in several areas of the lake, which strongly influences the chemical composition of the lake water (Cuhel 1998; Klump et al. 1988). This is also observed in deep-sea hydrothermal vents, where vigorous plumes mix with deep water (Butterfield et al. 1997; Cowen et al. 1986), but the large receiving volume defies budget closure, which is one of the goals of past work in Yellowstone Lake (Aguilar et al. 1999).

Previous investigations of thermal waters from the Norris–Mammoth corridor have used different approaches to identifying sources of hydrothermal fluids. These have included the use of natural isotope tracers (e.g., H, He, Li), elemental abundances (e.g., S, Cl, Na, Ca), and the number of dissolved species present (Fournier 1989; Palmer and Sturchio 1990; Kharaka et al. 1991; Bullen and Kharaka 1992; Fournier et al. 1992; Kharaka et al. 1992, Rye and Truesdell 1992; Sturicho et al. 1992; Lewis et al. 1997). Based on all these studies we can compare recent results with those performed several years ago in order to have a better understanding of the changing environment in the Yellowstone Lake area and other areas in the caldera.

The interactions of the geothermal systems with biology have an important role in understanding the processes of the origins of early life. The high-temperature systems may be relevant to understanding extreme environments on Earth as well as on other planets and moons in our solar system.

Study Area

Sampling sites on Yellowstone Lake. Yellowstone Lake is located in the southeast section of Yellowstone National Park, in an area with frequent tectonic activity. The lake comprises an area of 341 km^2 and it is the largest high-altitude lake in North America. The northwestern area of the lake lies inside the caldera, whereas the southern area as well as South and Southeast arms are located outside the caldera (Figure 1). Several areas have been sampled through the years, but all the collections mentioned in this paper were from 1998. There are areas with evident geothermal activity, such as Mary Bay, Sedge Bay, Steamboat Point, Stevenson Island, and West Thumb. All these areas have been sampled frequently, as have others such as the Yellowstone River inlet (located outside the caldera, Southeast arm) and outlet (inside the caldera).

Methods

Use of a remotely operated vehicle. The use of a remotely operated vehicle (ROV) is critical for general surveying of and sampling hydrothermal vent systems in Yellowstone Lake (Figure 2). The ROV designer and operator, Dave Lovalvo of Eastern Oceanics, is a former pilot of *DSRV Alvin* (deep sea research

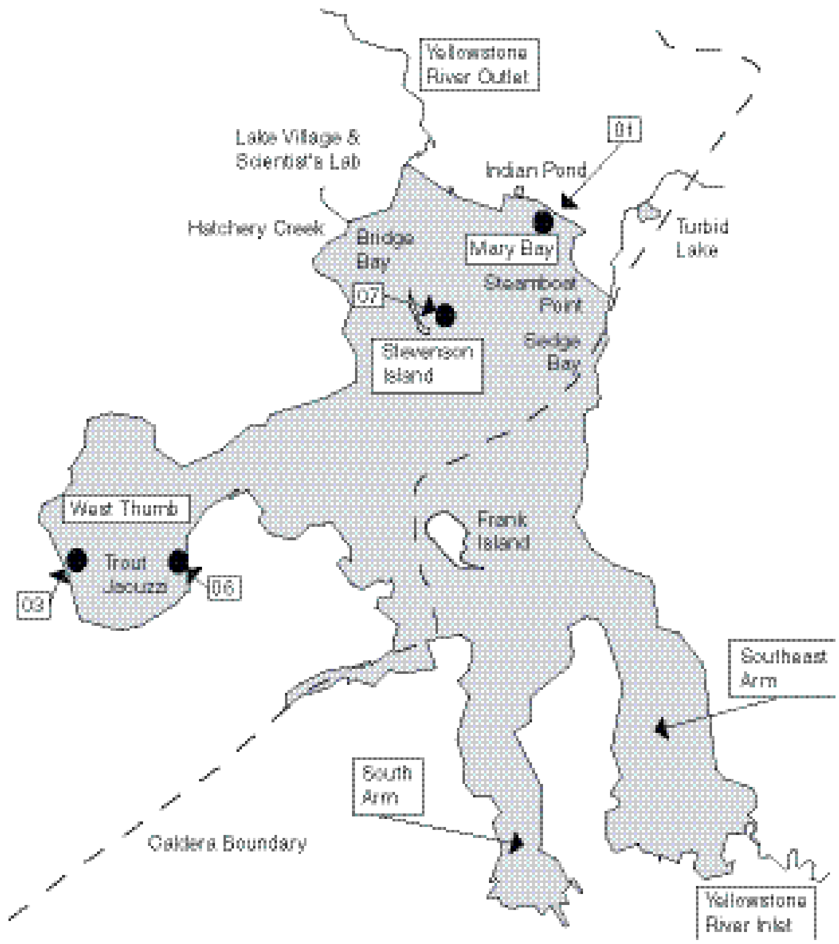

Figure 1. Map of Yellowstone Lake showing selected sampling areas: West Thumb, Mary Bay, Stevenson Island, Southeast Arm, and Yellowstone River inlet and outlet. The rim of the caldera is depicted by the dotted line. Core collection sites are in solid circles, as follows: 01 = Mary Bay 01 core, 03 = West Thumb 03 core, 06 = West Thumb 06 core, and 07 = Stevenson Island 07 core. Map from Marocchi et al. 2001; reproduced by permission.

vessel) and *ROV Jason*, and has produced a practical array of modular instruments for water and solid phase sampling, as well as cameras for still pictures and video (Buchholz et al. 1995; Klump et al. 1992). The areas of interest are hard to sample by conventional means. Visual observations of shimmering surface waters are always important clues to exploring the bottom of the lake. When looking for evidence of vents on the surface waters, we rely on vigorous bubbling that is visible from a distance on a calm day (Figure 3).

Field methods. Vent samples were collected with the ROV on board the *R/V Cutthroat*, using an articulated arm outfitted with a thermistor probe at the end to

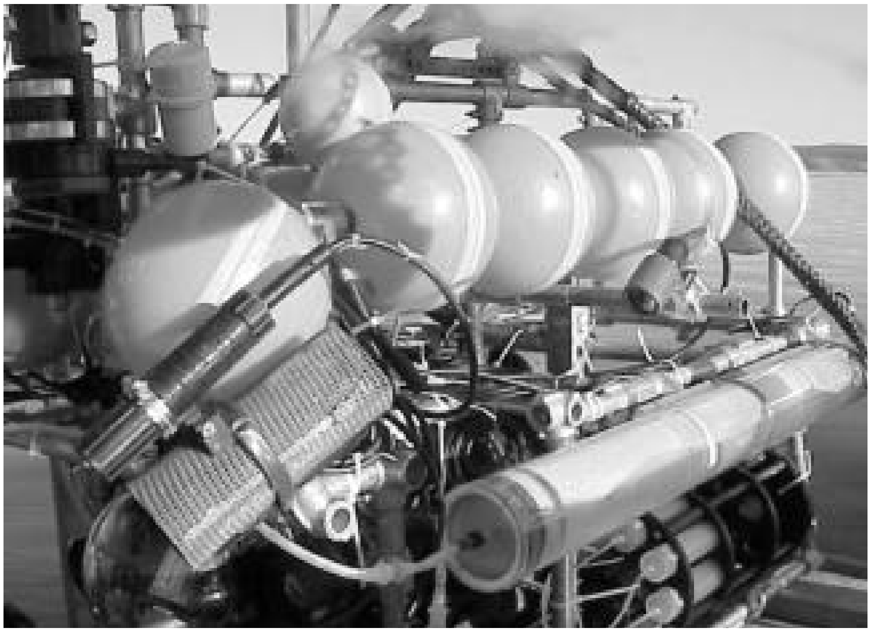

Figure 2. Remotely operated vehicle from Eastern Oceanics used to collect vent and bot - tom water.

Figure 3. Bubble field on surface waters of Mary Bay. On a calm day they can be seen from a distance. The bubbles are used to find new vent activity in different areas of the lake.

measure the temperature of the water as it was collected. Water was collected into 2-L polycarbonate syringes; samples were then retrieved and put into smaller, all-plastic syringes through a three-way valve. Samples were then transported in a cooler to the laboratory for analysis and preservation.

Cores were collected from the *Cutthroat* with a 3-inch Benthos gravity corer with cellulose acetate butyrate liners (Figure 4). Sediment was then transported to the laboratory and transferred with a hydraulic extruder to the Jahnke squeez-

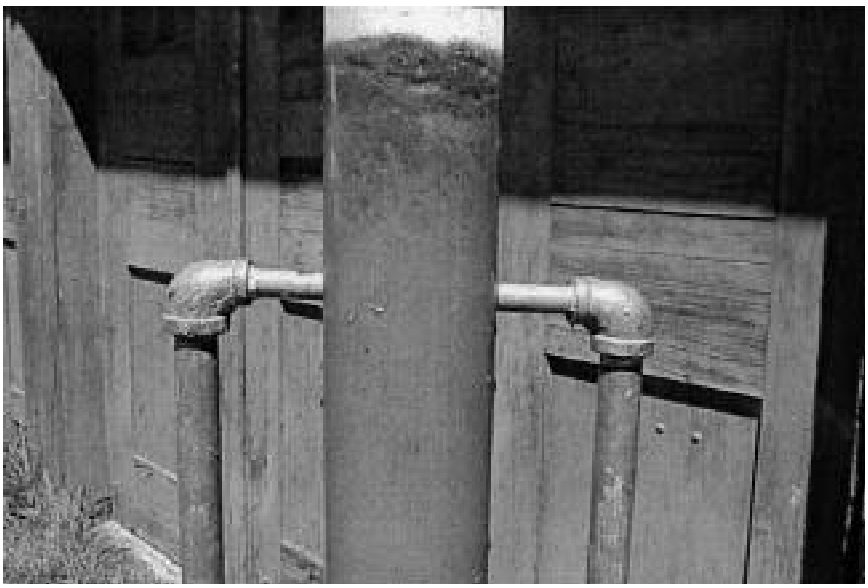

Figure 4. Core from West Thumb inside a core liner. Notice the darker sediment water–interface. This core is on the extruder, ready to be transferred into the squeezer liner.

er (Jahnke 1988) to subsequently obtain porewater (Figure 5). Porex inserts (a porous polyethylene rod to "guide" the water through while being pushed out by the action of the piston) were acid-washed and rinsed through many changes of E-Pure water (18-meg ohm/cm resistance) to zero residual chloride. The last rinses with E-Pure water were done in a Coy anaerobic chamber (90% N_2, 10% H_2) with water devoid of oxygen. All parts contacting the sample were acid-washed and those inserted were maintained anaerobically (in sealed serum vials) until the instant of use. The in-line 25-mm filters (0.2-µm pore size) used were ion chromatography-approved ultraclean commercial units (IC Gelman Acrodiscs), and all-polypropylene syringes received the sample. Components for reduced sulfur analysis were prepared in an anaerobic chamber, with dilution blanks, standards, and reagents in serum vials. Samples for trace metals were acidified with trace metal-certified nitric acid and stored in acid-washed polypropylene tubes. The samples for routine chemical analysis were stored at 4°C in polypropylene tubes. Core processing (sectioning, squeezing) was accomplished in a protected part of the National Park Service garage.

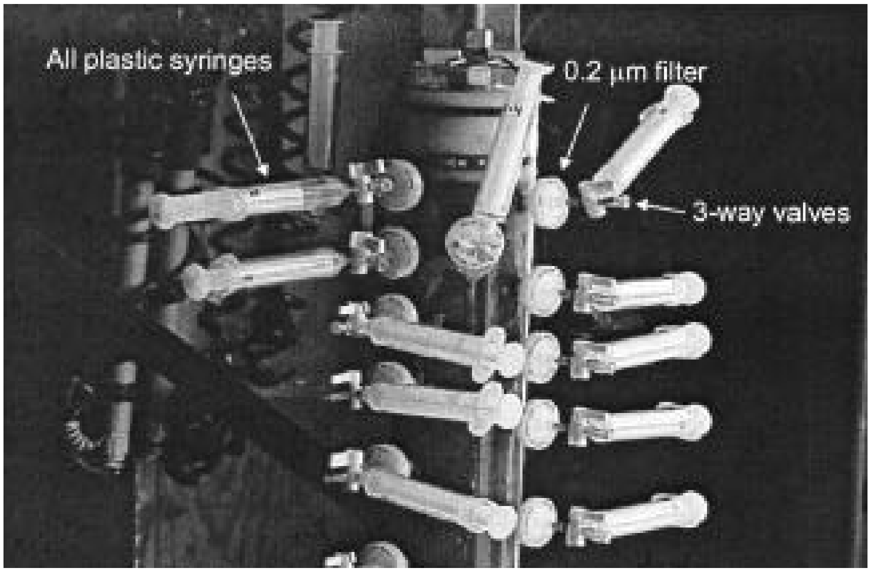

Figure 5. Porewater squeezer used to obtain porewater by applying pressure vertically; the water tends to be forced horizontally ("guided") by the porex inside the sediment at the end of the filter. The picture shows how the squeezer is put together, showing the depth intervals to obtain porewater from different depths in the core.

Chemical analyses. In the laboratory, samples were filtered through 0.2-µm filters (Supor, Nuclepore) and water was aliquotted for the different analyses. Dissolved mineral compounds were measured in the field laboratory by several methods: flow injection analysis (FIA; silicate, SiO_2), ion chromatography (IC: chloride, Cl^-, sulfate, $SO_4^=$), and spectroscopy (ammonium, NH_4^+), all according to standard methods (APHA 1992). Reduced and total iron was also determined in the field by the ferrozine spectrophotometric method of Stookey (1970), with (total iron) and without (reduced iron, FeII) reductant extraction. Total carbon dioxide, ΣCO_2, was analyzed by the Teflon–membrane flow injection method of Hall and Aller (1992). Reduced sulfur compounds (hydrogen sulfide, H_2S, thiosulfate, $S_2O_3^=$, sulfite, $SO_3^=$) were quantified by a scaled-up modification of the micro-bore high-performance liquid chromatographic (HPLC) method of Vairavamurthy and Mopper (1990), using dithio-bis-nitropyridine (DTNP) derivatization. The analytical equipment was transported to Yellowstone National Park, where all labile species were analyzed on site within one day of collection and analytical preparation.

Porewater flux was calculated from porewater concentration profiles, and concentration gradients at the sediment–water interface were used to calculate fluxes via Fick's first law of diffusion (Berner 1980): $J = D_S \cdot \phi \cdot dC/dz$, where J is the flux of the different components; D_S is the whole sediment molecular diffusivity corrected for tortuosity (Li and Gregory 1974); ϕ is the porosity at the sediment–water interface; and dC/dz is the slope of the concentration gradient.

Results

Porewater. Since almost a third of Yellowstone Lake is directly influenced by hydrothermal activity, it is important to measure chemical components that can provide a proxy for geothermal activity in the lake. Chloride is an important indicator of geothermal activity, and the Yellowstone River inlet provides a low-chloride concentration (<7 μM). The subsurface deep reservoir containing fluids that feed the thermal basins in Yellowstone National Park is thought to have concentrations of about 20 to 21 mM chloride (Truesdell et al. 1977; Fournier 1989).

Porewater profiles in Figures 6–12 depict distinct sites in Yellowstone Lake, with all cores being collected during the 1998 season. The Mary Bay 01 core (01-MB; shown as open squares in the figures) was taken from a vent field in the bay, and smelled of hydrogen sulfide as we brought it onto the vessel. This core was close to one that melted the plastic core liner (temperature >135°C) moments before. The West Thumb 03 core (03-WT; open circles) was collected near the West Thumb geyser basin. The West Thumb 06 core (06-WT; closed circles) was collected in the West Thumb deep basin. The Stevenson Island 07 core (07-SI; closed squares) was collected from the deep canyon east of the island (refer to locations in Figure 1).

Chloride is a conservative and non-reactive ion that is used as a geothermal tracer. Chloride concentrations in Mary Bay sediments reached 10 mM, the highest concentration measured in porewater (Figure 6). A concentration of about 5 mM was also found in a core from West Thumb; all the other sites measured showed a concentration lower than 1 mM.

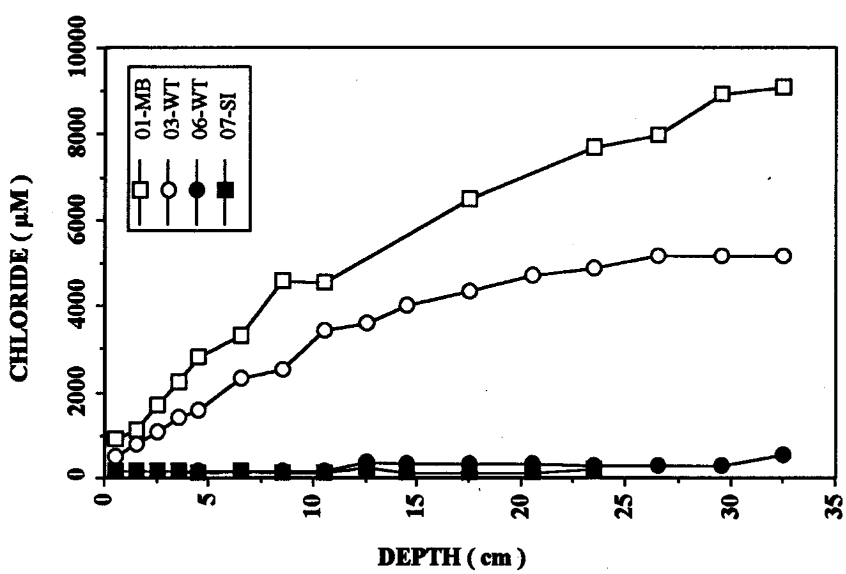

Figure 6. Porewater profile depicting chloride concentration (μM, micromolar) with depth in four different cores from Mary Bay, West Thumb, and Stevenson Island.

Diatoms (algae) require silica to produce frustules (skeletons made of silica). These organisms can settle to the bottom of the lake by different processes; the frustules then begin to undergo dissolution. Evidence of this process is found in the porewater profiles from the sediments from different areas of the lake. Silica is a compound that is non-conservative and biologically reactive. Silicate reflects the diagenetic/dissolution control in the water and sediments, where decomposition takes place without geothermal influence. In addition, vent water seepage into sediments adds additional silicate, and there are some examples of porewater profiles that show this influence. Mary Bay 01 and West Thumb 03 had the highest concentrations, about 2.5 mM SiO_2, whereas non-geothermally influenced cores peaked at 1 mM (Figure 7). Silicate shows a higher concentration than expected from a diagenetically generated profile, showing the influence of vent activity in the area. The values for the Southeast Arm reach a concentration of 750 µM, similar to that of West Thumb 06 and Stevenson Island 07.

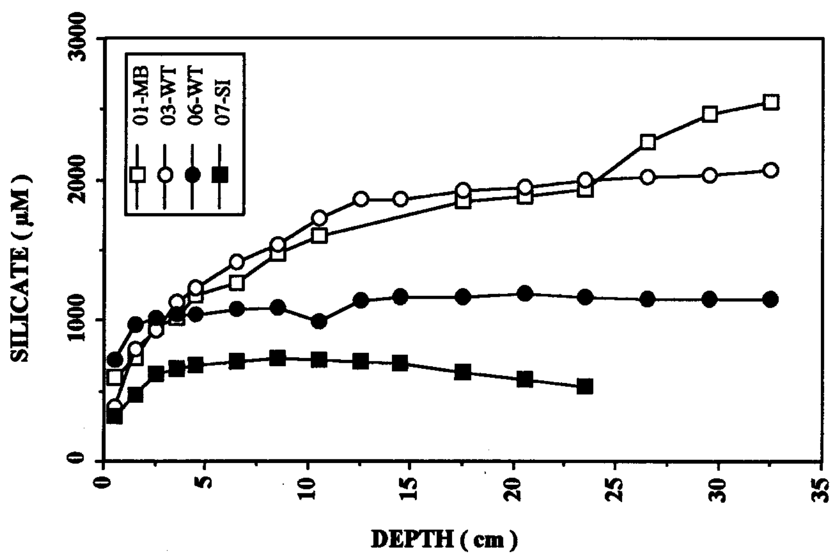

Figure 7. Porewater profile depicting silicate concentration (µM, micromolar) with depth in four different cores from Mary Bay, West Thumb, and Stevenson Island.

Hydrogen sulfide is a compound that we refer to as the "smell of success" since it is a great marker for reducing conditions in sediments as well as vent water. It is a readily distinguishable reduced component that will be present in an area where there is usually little oxygen present. It is also a characteristic of geothermally derived vent waters. Sulfate reduction from bacteria is an important component in the production of this reduced compound. Except for methane, hydrogen sulfide is the most inefficient to produce. Hydrogen sulfide concentration was highest, 550 µM, in Mary Bay 01 (Figure 8). The concentration in the other cores was less than 10 µM, which is significantly lower than that in the active areas. Hydrogen sulfide has been found consistently in Mary Bay.

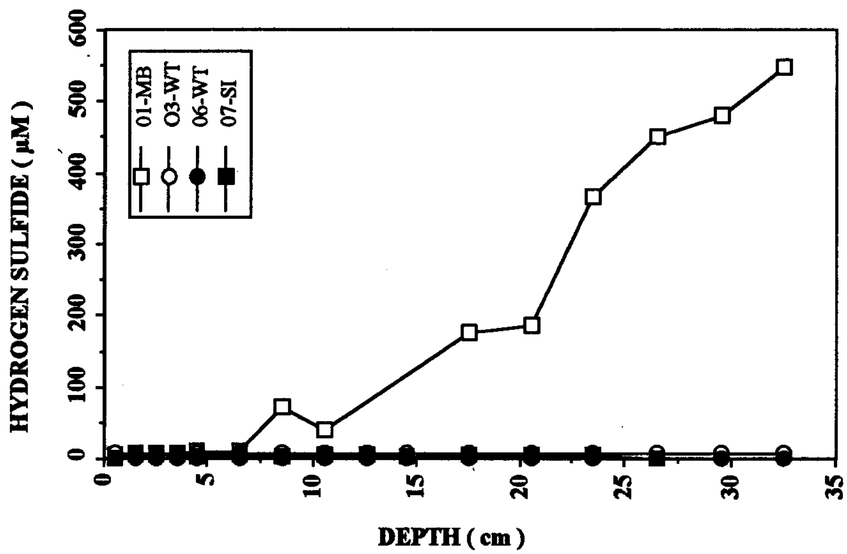

Figure 8. Porewater profile depicting hydrogen sulfide concentration (µM, micromolar) with depth in four different cores from Mary Bay, West Thumb, and Stevenson Island.

Bacterial sulfate reduction is a process of organic matter decomposition, where sulfate is used as an energy source by bacteria, by which sulfate is reduced to hydrogen sulfide. Hence, sulfate reduction tends to decrease with water column depth because less organic matter reaches those sediments. This process occurs in the absence of oxygen. Sulfate was highest, 200 µM, at Stevenson Island, whereas the concentrations in the other cores were less than 80 µM (Figure 9). West Thumb 03 showed a very shallow gradient compared with the gradient from Mary Bay 01.

Reduced iron concentrations were highest in Stevenson Island 07, as well as in West Thumb 06; that core, taken from the deep basin, had a concentration of 37 µM (Figure 10). Iron laminations are found extensively in the West Thumb area. Typically, vent water lacks reduced iron in the effluent, but some areas in the sediment show evidence of iron oxides.

Ammonium is released to porewater from the decomposition of labile organic nitrogen compounds contained within the bulk of the organic matter deposited in sediments (2–4% organic carbon and 0.3–0.5% total nitrogen). Porewater concentrations of ammonium produced by organic matter decomposition can reach 600 µM in the high-deposition areas of the lake (Figure 11). Profiles observed in these locations are consistent with a diagenetic source, but the steep gradient measured in Mary Bay could result in part from geothermally influenced processes.

Though produced by organic matter decomposition, its main source of enrichment is the extraordinarily high concentrations (to 25 mM) in vent reservoir fluids. Carbon dioxide is another indicator of geothermal activity. High con-

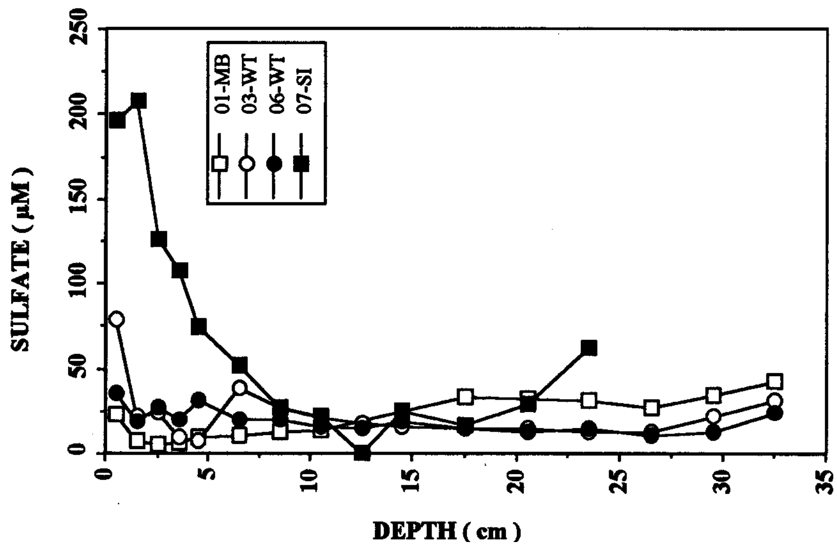

Figure 9. Porewater profile depicting sulfate concentration (µM, micromolar) with depth in four different cores from Mary Bay, West Thumb, and Stevenson Island.

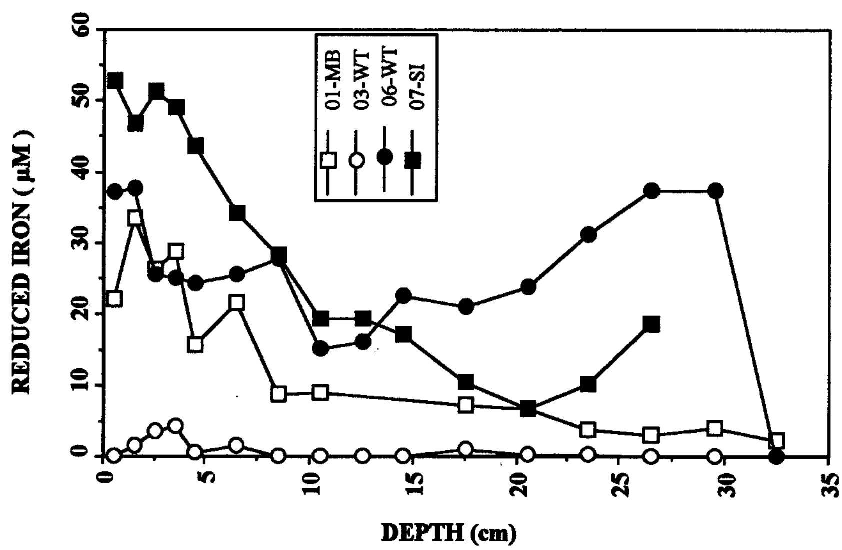

Figure 10. Porewater profile depicting reduced iron concentration (µM, micromolar) with depth in four different cores from Mary Bay, West Thumb, and Stevenson Island.

centrations were measured in the Mary Bay 01 and West Thumb 03 cores (Figure 12), both showing evidence of active geothermal influence, based on the chloride concentration.

Vent water. Vents are very heterogeneous, with temperatures ranging from 20°C to 112°C and pH values from 4 to 8.6, as well as having chemistry that

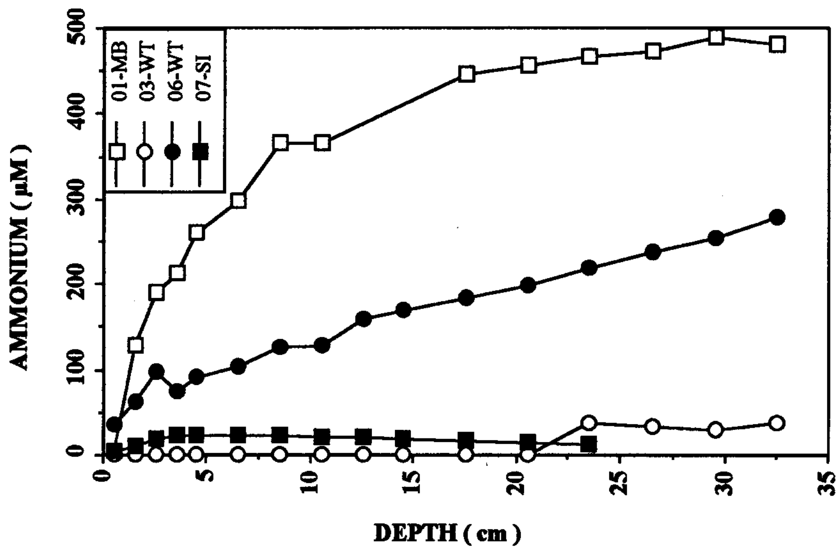

Figure 11. Porewater profile depicting ammonium concentration (µM, micromolar) with depth in four different cores from Mary Bay, West Thumb, and Stevenson Island.

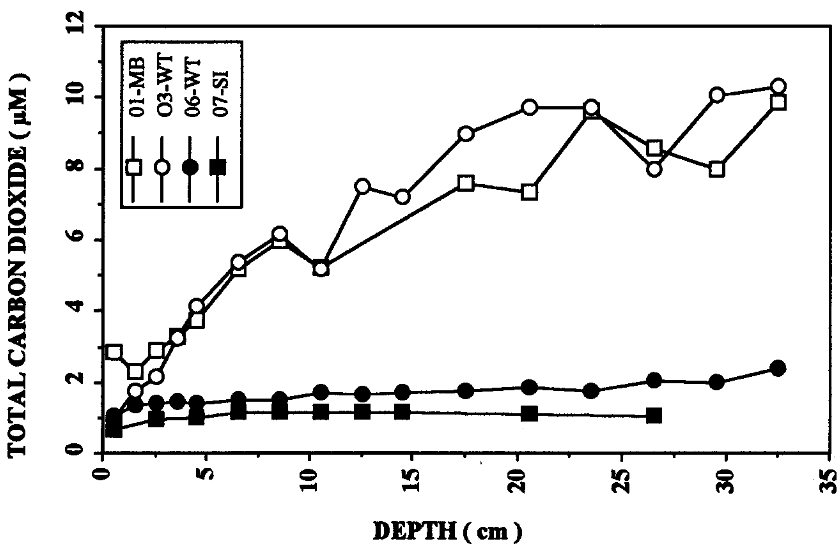

Figure 12. Porewater profile depicting total carbon dioxide concentration (µM, micro - molar) with depth in four different cores from Mary Bay, West Thumb, and Stevenson Island.

varies with location. Chemical differences from vents in different areas have allowed us to group the different characteristics into domains (see Cuhel et al., this volume). Vent waters from West Thumb and Mary Bay showed enrichment in chloride and silicate, although they were highly variable (Table 1). Reduced iron was present in vents from Stevenson Island and Mary Bay, where the reduced species can remain in the water for at least 24 hours (data not shown).

Lake water. Lake water collected in a deep vent area (near Stevenson Island) showed chemical enrichment in several constituents—chloride, silicate, sulfate, sodium, etc.—when compared with surface water collected at the Southeast Arm inlet and the Yellowstone River outlet (Table 1). When lake water values were compared with those of vents of the different areas, it becomes evident that, for

Table 1. Selected chemistry of Yellowstone National Park vents, Yellowstone River inlet and outlet, and water column values.

Location	pH	Cl (µM)	Fe (µM)
WT vents	5.5–8.6	50–1,147	<0.18–0.54
MB vents	4.9–5.9	144–169	0.23–9.3
SI vents	5.0–6.2	136–148	1.7–8.1
SE Arm water column	7.45	120	<0.18
WT water column	7.3	154	<0.18
MB water column	6.75	179	0.25–0.45
SI water column	7.4	141	<0.18
YR-inlet	7.05	7	0.5
YR-outlet	7.29	126	0.197

MB = Mary Bay, SI = Stevenson Island, WT = West Thumb, YR = Yellowstone River

example, Mary Bay has water that still reflects the hydrothermal composition of the vents.

There were distinct differences in the composition of hydrothermal vent fluids from different parts of Yellowstone Lake. For example, vents from the West Thumb area were rich in chloride but poor in sulfur compounds, as compared with vents from Stevenson Island which were rich in sulfur but poor in chloride. In contrast, chimney structures from these vents record times that the vent fluids must have been different in composition because they contain precipitates that could not have formed from the vent fluids that currently emanate from these sites; chimney structures from Stevenson Island contain sulfur crystals as well.

Flux from the sediment into the overlying water can be calculated from the porewater chemistry from Mary Bay, West Thumb, and Stevenson Island. Table 2 shows the calculated flux from chloride as the geothermal activity tracer, and silica as the dissolution/diagenetic control in porewater. Chloride flux was highest (two orders of magnitude) from the Mary Bay and West Thumb hot cores; other cores and areas such as Stevenson Island as well as Southeast Arm (which is outside the caldera) do not provide chloride to the receiving lake water. Silica does not show such a dramatic difference, but the same cores have high standing silica concentrations throughout, probably controlled by the solubility of amorphous silica (diatoms) which makes up to ~50% of the sediment mass.

Table 2. Porewater concentrations and flux from cores obtained in Mary Bay, West Thumb, Stevenson Island, and Southeast Arm, showing values for chloride, a “geothermal tracer,” and silica, a “dissolution/diagenetic control” parameter.

	Chloride "geotheramal tracer"			Silica "dissolution/diagenetic control"		
Station Porewater chemistry	[conc] @ $z = \infty$ mmol/L	Grad µM cm^{-1}	Flux Mol $m^{-2} y^{-1}$	[conc] @ $z = \infty$ mmol/L	Grad µM cm^{-1}	Flux Mol $m^{-2} y^{-1}$
Mary Bay "hot" core	12.5–20.0	450	2.41	2,000	200	0.80
W. Thumb "hot" core	7.5	360	1.93	2,050	224	0.90
W. Thumb	0.185	5.5	0.017	1,200	165	0.47
Stevenson Island	0.180	-0.6	-0.002	720	311	0.89
Southeast Arm	0.172	0.34	0.001	900	140	0.40

Discussion

Geochemical inputs to Yellowstone Lake come from a variety of sources, namely: hydrothermal vents, groundwater, rainwater, flux from sediments, and direct runoff (including from tributaries). Approximately one-third of the lake is directly influenced by hydrothermal activity through hot-water vents and fumaroles. Surveys of lake water, vent water, and sediment pore water gradients established zones of direct and subsurface inputs of geochemically altered fluids. Vent water intrusion into the surrounding sediments is evident in some of the profiles. In some instances, chloride approaches theoretical reservoir concentrations (20 mM) and the silicate concentration at depth seems greater than that expected from diagenesis alone. Porewater and vent water chemistry provides evidence for lake water dilution of vents below the sediment–water interface.

Reduced sulfur compounds are important components of the vent waters in Mary Bay and Stevenson Island, while in the West Thumb these compounds were usually undetectable. The vent fluids exhibit a highly variable concentration of dissolved minerals in different areas of the lake as well as for different years of sampling. This is shown, for example, in the solid phase from West Thumb (Figure 13), where highly laminated iron–manganese oxide crusts are found in areas that typically do not contain sulfide, methane, or other reduced compounds.

Strong evidence for vent fluid seepage was found in the hot-core porewater measurements of chloride (10 mM), total CO_2 (to 11 mM), and silicate (2.8 mM), all highly enriched in deep reservoir fluids. Some areas of the lake contain high concentrations of sulfide (500 µM) and of iron (50 µM). Because inorganic nitrogen (ammonium) is virtually absent from the water column and vent fluids, diagenetic production of ammonium from organic matter may provide more growth-

Figure 13. Solid phase sample collected from West Thumb. Note the laminations on the surface of alternating manganese and iron oxides.

promoting habitats in surrounding sediments than in aqueous environments.

One of the factors that may have influenced the vent activity throughout the lake was the lake stage or water level, which directly affects the hydrostatic pressure on vent systems. There seemed to be a correlation between high activity in the vents when water levels were low, and low activity when water levels were high. This is one of the factors that will benefit from long-term studies of the different vent areas in the lake.

Comparing data from the inlet of the Yellowstone River (in Southeast Arm) and its outlet (in the northern part of the lake), it is clear that there is a significant hydrothermal influence in the lake (Figure 14). Chloride is virtually absent in the inlet waters. Hence, much higher values of lake water provide strong evidence for an external source of the ion. During three years of piezometer studies to measure the groundwater inputs to the lake, we concluded that the source is not sufficient to explain the lake water enrichment. Chloride, then, contributes another piece of evidence that points to a geothermal influence in the concentration of key components (see Klump et al., this volume). There are also sources and sinks of other elements, but having mentioned just a few we can see that this is a very dynamic geoecosystem, in which different sources of chemicals are found and where microbiology is an important component.

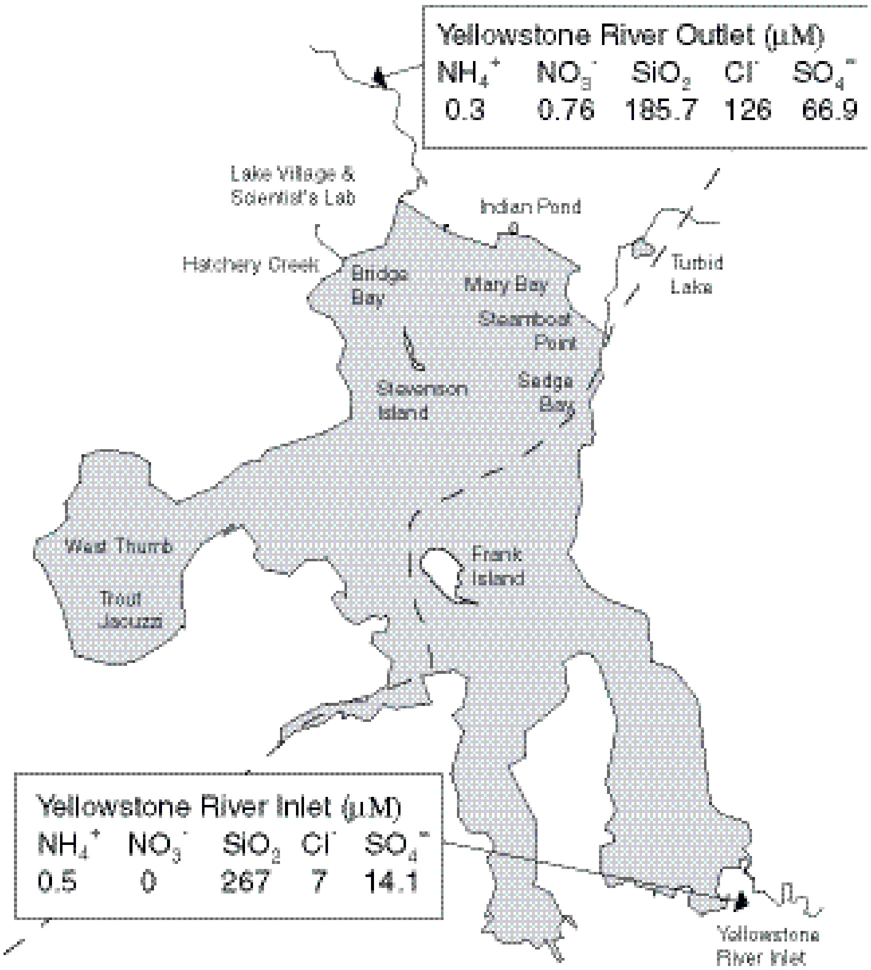

Figure 14. Yellowstone Lake map showing different concentrations of selected compounds and the changes incurred from the source of the water coming into the lake outside the caldera region to the Yellowstone River outlet.

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Yellowstone Lake Cutthroat Trout Hemoglobin Polymorphism

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Abstract

Hemoglobin polymorphism was observed in Yellowstone Lake cutthroat trout. Variation occurred only in the cathodally migrating hemoglobin components. Eight of the ninety-three trout sampled displayed an electrophoretic pattern identical to that of adult rainbow trout.

Introduction

Data presented in this paper were published previously (Braman et al. 1980). The text is extensively revised with additional references cited to support the contention that hemoglobin polymorphism is a unique characteristic of Yellowstone Lake cutthroat trout.

Yellowstone Lake cutthroat trout *(Oncorhynchus clarki bouvieri)* represent a "keystone species" in the Yellowstone Lake ecosystem (Plumb and Koel 2001). Bald eagle *(Haleaeetus leucocephalus),* white pelican *(Pelecanus occidentalis),* osprey *(Pandion haliaetus),* otter *(Lutra canadensis),* black bear *(Ursus americanus)* and grizzly bear *(Ursus arctos)* prefer cutthroat trout to exotic lake trout *(Salvelinus namaycush)* as a food source (Plumb and Koel 2001). Piscivorous lake trout, discovered in Yellowstone Lake in 1994, and the Whirling Disease parasite, found in several Yellowstone Lake cutthroat trout in 1998, threaten to collapse the cutthroat trout population (Koel et al. 2001). Decimation of cutthroat trout may result in a "catastrophic shift" to an altered Yellowstone Lake ecosystem state that would require drastic and expensive intervention for restoration (Scheffer et al. 2001). Scheffer et al. propose that "building and maintaining resilience of desired ecosystem states is likely to be the most pragmatic and effective way to manage ecosystems in the face of increasing environmental change."

Building resilience into the Yellowstone Lake ecosystem might involve propagating Yellowstone Lake cutthroat trout variants that demonstrate increased resistance to the Whirling Disease pathogen and/or improved survival rate following bursts of vigorous physical activity when avoiding predators and during spawning. Identifying variants possessing biochemical systems with unique properties that confer survival advantage under extremes of physical activity is the research emphasis described in this paper. Studying the underlying molecular and physiological mechanisms responsible for improved fitness is the ultimate goal of this research.

Hemoglobin is a biochemical system adapted to bind and release oxygen under a wide range of environmental and physiological conditions (Hochachka and Somero 1973), allowing fish to exploit a variety of habitats and adapt to adverse conditions. Therefore, Yellowstone Lake cutthroat trout expressing hemoglobin with unique oxygen-binding properties might demonstrate increased resiliency to the extremes of physical activity described above.

Multiple Hemoglobin Components in Cutthroat and Rainbow Trout

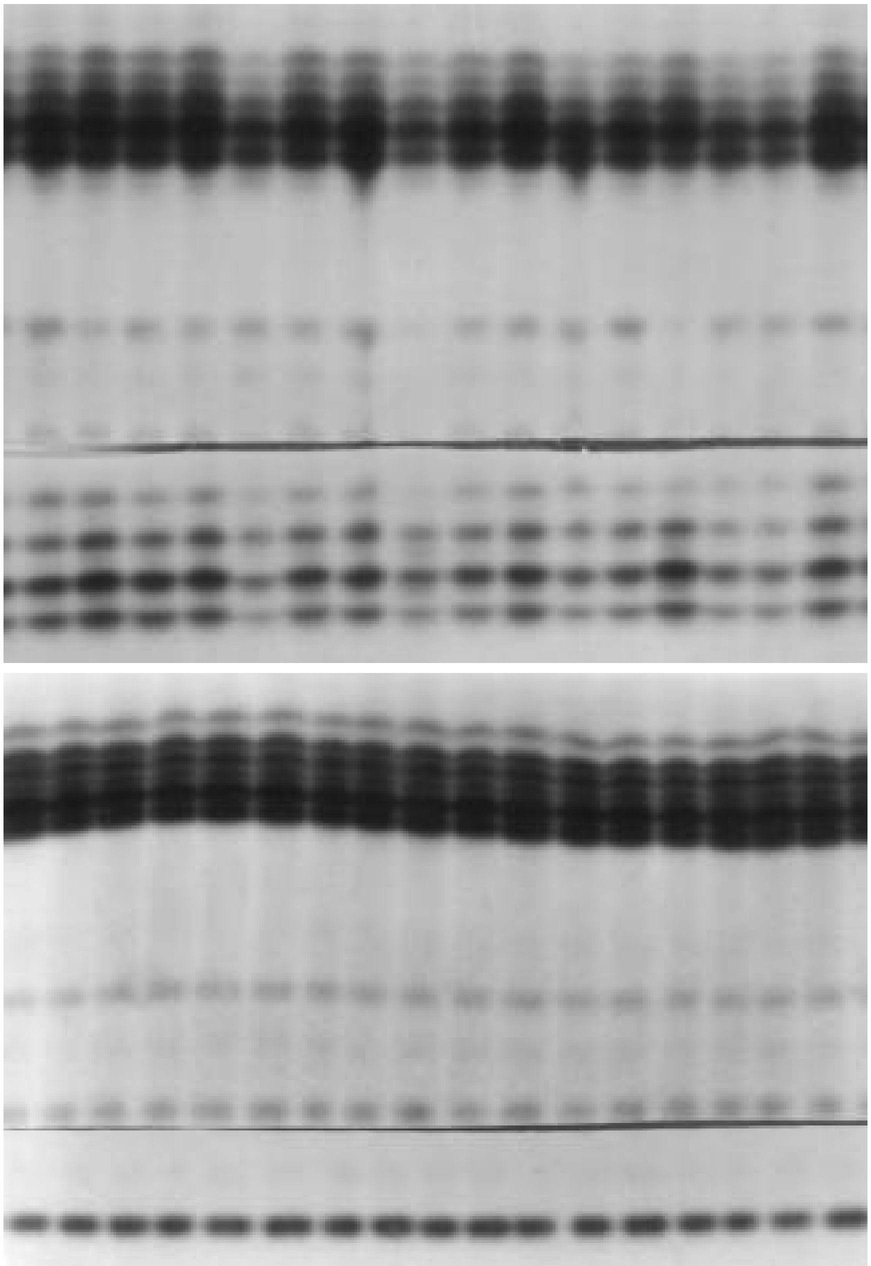
Multiple hemoglobin components in fish is a well-documented phenomenon, with cutthroat trout having twelve (Figure 1a) and rainbow trout having nine (Figure 1b) hemoglobin components (Braman et al.1977). A high-resolution starch gel electrophoresis method was developed to resolve eight negatively charged hemoglobin components from both species, all of which migrate coincidentally toward the positive electrode (anode). Rainbow trout have one and cutthroat trout have four positively charged hemoglobin components migrating toward the negative electrode (cathode). The single positively charged rainbow trout hemoglobin component migrates coincidentally with one of the four positively charged cutthroat trout hemoglobin components.

Hemoglobin Polymorphism in Yellowstone Lake Cutthroat Trout

Hemoglobin polymorphism due to allelic variation (Sick 1961; DeLigney 1969; Fyhn and Sullivan 1974; Fyhn and Sullivan 1975; Bonaventura et al. 1975; Perez and Rylander 1985; Giles and Rystephanuk 1989; Fyhn and Withler 1991) and ontogenetic variation (Wilkins 1968; Iuchi and Yamagami 1969; Giles and Vanstone 1976; Koch 1982; Wilkins 1985; Giles and Rystephanuk 1989) has been described in a variety of fish species, but not in cutthroat trout. Several cutthroat trout populations in the Intermountain West were examined for hemoglobin polymorphism by the starch gel electrophoresis method described above. All fish demonstrated the prototypical cutthroat trout phenotype with twelve hemoglobin components (Figure 1a). Yellowstone Lake cutthroat trout collected from the Peale Island area were also examined for hemoglobin polymorphism. Blood samples were collected on two occasions (September and October 1974) from a total of ninety-three fish. Variation in hemoglobin components migrating toward the cathode was observed in fish collected on both occasions (Braman et al. 1980; Figure 2). The polymorphism is complex in that there are concentration differences in hemoglobin components within a given sample in addition to variation in the number and concentration of hemoglobin components between samples. It is interesting to note that eight of the ninety-three fish sampled possessed the rainbow trout phenotype, with a single hemoglobin component migrating toward the cathode. These fish were not, by all apparent outward characteristics, cutthroat–rainbow (cuttbow) hybrids.

Additional Observations Made of Yellowstone Lake Cutthroat Trout

Fish sampled near Peale Island appeared to be adults ranging in size from 30 to 40 cm in length. Many of the fish were infested with unidentified ectoparasites on the body and, in particular, on the fins, where considerable damage was inflicted. A third sample of 50 cutthroat trout was collected one year later (1975)



Figures 1a and 1b. Starch gel electrophoresis of adult cutthroat trout (1a) and adult rain - bow trout (1b) hemoglobin components. Electrophoresis was performed as described in Braman et al. (1976). The anode (positive electrode) of the electrophoresis chamber is located at the top of the photo. The visible horizontal line running across the width of the gel in the photo represents the origin where hemoglobin samples were applied.

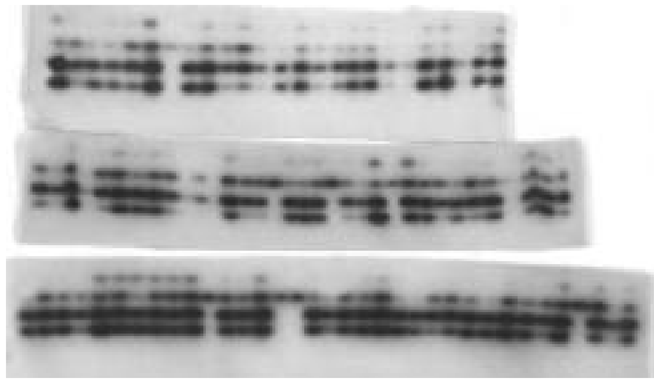


Figure 2. Three starch gel sections showing hemoglobin components migrating toward the cathode (negative electrode). Samples are from 93 adult Yellowstone Lake cutthroat trout. Electrophoresis was performed as described in Braman et al. (1980). Each section is oriented so that the origin is positioned at the top and the cathode is positioned at the bottom of each segment.

from a site approximately five miles north of Peale Island. These fish were also 30 to 40 cm in length, were not infested with ectoparasites, and did not demonstrate hemoglobin polymorphism. This second group of Yellowstone Lake cutthroat trout had the characteristic phenotype (i.e., having twelve hemoglobin components) shown in Figure 1a.

Plausible Explanations for the Observed Hemoglobin Polymorphism

Observed protein variation when using starch gel electrophoresis may result from artifacts generated during sample preparation and storage (Utter et al. 1974; Reinitz 1976). This is an unlikely explanation for hemoglobin polymorphism in Yellowstone Lake cutthroat trout because variation occurred exclusively in the hemoglobin components migrating toward the cathode. Hemoglobin components migrating toward the anode did not vary in number and concentration. If sample preparation and storage caused the polymorphic hemoglobin electrophoretic patterns, then all hemoglobin components from every population of fish would likely demonstrate variation, not just the hemoglobin components migrating toward the cathode, as in the Peale Island group of Yellowstone Lake cutthroat trout. In practice, identical electrophoretic patterns were obtained with freshly prepared and three-week-old hemoglobin samples. A hemoglobin sample stored longer than three weeks demonstrated degradation of all hemoglobin components, as evidenced by streaking of the entire electrophoretic pattern.

Another explanation for hemoglobin polymorphism in Yellowstone Lake cutthroat trout is ontogenetic variation (Wilkins 1968; Iuchi and Yamagami 1969; Giles and Vanstone 1976; Koch 1882; Wilkins 1985; Giles and Rystephanuk 1989). This hypothesis is unlikely because all fish examined appeared to be adults, 30 to 40 cm in length.

Hemoglobin polymorphism in Yellowstone Lake cutthroat trout could be attributed to allelic variation and is complicated by the fact that rainbow trout genetic material was introduced into the Yellowstone Lake cutthroat trout gene pool as a result of stocking prior to 1915 (Jack L. Dean, personal communication). Allelic variation in cathodal hemoglobin components has been described for Arctic charr *(Salvelinus alpinus;* Giles and Rystephanuk 1989) and in anodal hemoglobin components for chinook salmon *(Oncorhynchus tshawytscha;* Fyhn and Withler 1991). Allelic variation resulting in polymorphic hemoglobin components of Yellowstone Lake cutthroat trout has not been confirmed. Breeding Yellowstone Lake cutthroat trout having known hemoglobin phenotypes, as well as performing crosses of Yellowstone Lake cutthroat trout with rainbow trout and scoring the phenotypes of the resulting offspring, will establish if the polymorphism is genetically based.

A further influence of rainbow trout genetic material on phenotypic expression of Yellowstone Lake cutthroat proteins is worth mentioning. The extent of introgression of anadromous rainbow trout *(Oncorhynchus mykiss irideus)* and coastal cutthroat trout *(O. clarki clarki)* was recently investigated by screening populations of these fish with amplified fragment length polymorphic (AFLP) and mitochondrial (mt) DNA markers (Young et al. 2001). Results of this work confirm that rainbow–cutthroat F_1 hybrids are produced from females of both species. Rainbow and cutthroat backcross hybrids were also detected, indicating that F_1 hybrids mate successfully with both rainbow and cutthroat parents. Hybrids were not found in all populations sampled and hybrid swarms were not evident. The data are consistent with the hypothesis that complete introgression of these two species is not possible due to an environment-dependent reduction in hybrid fitness. Screening Yellowstone Lake cutthroat trout with AFLP and mt DNA markers will aid in determining the extent and persistence of rainbow trout introgression due to stocking that occurred many years ago. AFLP markers are sensitive for identifying rainbow trout genetic material in cutthroat trout populations because, for the markers used by Young et al., rainbow trout did have cutthroat trout-diagnostic AFLP markers, while native cutthroat trout did not display any rainbow trout-diagnostic AFLP markers. Limiting the extent of introgression does not eliminate the possibility that Yellowstone Lake cutthroat trout harbor remnant rainbow trout hemoglobin alleles.

A second piece of circumstantial evidence obtained using a different experimental approach further reduces the importance of rainbow trout influence. Two-dimensional gel electrophoresis of serum proteins was used to distinguish native rainbow and cutthroat trout from cuttbow hybrids (Rourke and Wallace 1978). Results of these experiments show that serum protein profiles are different for native rainbow and cutthroat trout, but are equivalent for cuttbow and native cutthroat trout, suggesting that rainbow trout genetic material does not measurably alter the expression pattern of native cutthroat trout serum proteins.

Physiological stress represents another plausible explanation for the observed polymorphic hemoglobin patterns (Utter et al. 1974; Koch 1982). Circumstantial evidence in favor of this explanation is that Peale Island fish were infested with ectoparasites and had polymorphic hemoglobin components, while fish collected one year later five miles north of Peale Island were not infested with ectoparasites and did not have polymorphic hemoglobin components. However, a mechanism is lacking that links stress with variation in Yellowstone Lake cutthroat trout hemoglobin components migrating toward the cathode, and with the fact that several fish expressed the characteristic rainbow trout phenotype (i.e., having nine hemoglobin components).

Future Research

Cutthroat trout, rainbow trout, and other salmonids contain multiple hemoglobins that are divided into two groups. The anode group migrates toward the positive electrode during starch gel electrophoresis and contains hemoglobin components with relatively low isoelectric points. They are characterized by oxygen equilibria that are strongly dependent on pH, temperature, and ATP (adenosine triphosphate). The cathode group migrates toward the negative electrode during starch gel electrophoresis and contains hemoglobin components that are largely unaffected by pH, temperature, and ATP (Southard et al. 1986). Analogous anode and cathode groups of hemoglobin components are found in other teleost fishes, and it is hypothesized that the cathode group allows efficient uptake of oxygen at the gills as blood pH lowers during and following strenuous exertion (Powers and Edmundson 1972). Yellowstone Lake cutthroat trout demonstrate polymorphism in the cathode group of hemoglobin components. The physiological significance of this phenomenon deserves further investigation.

Yellowstone Lake cutthroat trout collected near Peale Island, many of which were infested with unidentified ectoparasites, demonstrated hemoglobin polymorphism. Fish sampled from a location approximately five miles north of Peale Island were not infested with ectoparasites and did not demonstrate hemoglobin polymorphism. It will be instructive to investigate whether hemoglobin polymorphism is a widespread occurrence in Yellowstone Lake cutthroat trout or if it is limited to fish confined to certain locations.

It is also important to establish whether hemoglobin polymorphism in the lake's cutthroat trout is due to allelic variation or is the result of stress.

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Underwater Domains in Yellowstone Lake Hydrothermal Vent Geochemistry and Bacterial Chemosynthesis

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J. Val Klump, and David Lovalvo

Abstract

Reduced inorganic compounds of geothermal-origin hydrogen sulfide (H_2S), iron (Fe[II]), and methane (CH_4) were common but not ubiquitous components of hydrothermal vent fluids of Yellowstone Lake at concentrations capable of supporting chemolithoautotrophic (geochemical-oxidizing, carbon dioxide (CO_2)-fixing) bacterial growth. Closely linked to the presence of reduced geochemicals was abundance of chemosynthetic bacteria and dark CO_2 fixation activity. Pronounced productivity at vent sites in the northern basin (Mary and Sedge Bays, Storm and Steamboat Points, and east of Stevenson Island) was accompanied by reduced sulfur stimulation in near-vent receiving waters, while none of these characteristics were found in West Thumb vent fields. Per-liter bacterial productivity at vents (to 9.1 µgC/L/hour) could reach algal photosynthesis in surface waters (to 8.9 µgC/L/hour). Thermophilic (heat-loving) sulfur- and methane-oxidizing bacteria were isolated from vent orifice waters, and CO_2 fixation incubations at 50°C indicated that the majority of chemosynthesis within the vents themselves was optimal at high temperatures. Receiving waters had much less activity at 50°C than at ambient temperature (4–20°C), distinguishing populations of mesophilic (moderate-temperature) bacteria that had also responded to the input of geochemicals from vents. Strong evidence for mineral-dependent bacterial productivity was obtained, with limited data suggesting an influence of lake stage or outflow on vent and productivity characteristics.

Introduction

For decades the colorful mats of bacteria and algae surrounding bubbling vents and fumaroles at Yellowstone National Park have been a focus of both touristic and scientific interest. It is with no small wonder that people look upon the growth of microorganisms in the often very hot, very corrosive fluids. Yet the interaction of biology with geothermal and geochemical energy may be more ancient than any other ecology. Prior to the mid-1970s, many scientists favored the theory of organic matter formation in the atmosphere and initial biological activity in surface brine pools using lightning energy as the primary catalyst (c.f. Miller 1953; Oro et al. 1990). Following the discovery of deep-sea hydrothermal geoecosystems in the mid-1970s, an additional hypothesis was developed, invoking organic matter formation and biological assembly in the high-temperature (to

350°C), high-pressure (>200 atm) deep-sea vents and surroundings. Both theoretical and experimental evidence supporting each theory exist, and in fact the two concepts are not mutually exclusive.

Early life certainly was microbial, at least tolerant of high temperatures, and predominantly made use of chemical energy for metabolic needs. At present, the highest temperatures for growth range to 113°C (Stetter 1999) and the isolated organisms are involved in methane and sulfur transformations. Yellowstone National Park offers a variety of habitats from hot (but <96°C), dissolved geochemical-laden (often to saturation with silicate or carbonate) surface springs and geysers with high microbial diversity (Barns et al. 1994) to hotter (to 130°C), dissolved geochemical-rich (but not saturated) waters and gases of Yellowstone Lake underwater vents and fumaroles. From a biogeochemical and ecological point of view, Yellowstone Lake is appealing because observed maximum vent-fluid temperatures range around or just above the limits for microbial life (Huber et al. 1989; Jørgensen et al. 1992), yet many of the same physical and geochemical characteristics of marine vents are preserved. Other freshwater hydrothermal sites have been identified, including massive sulfide deposits in Lake Tanganyika, East Africa (Tiercelin et al. 1989, 1993); hot-water vents in Lake Baikal, Russia (Crane et al. 1991; Shanks and Callender 1992), and deep microbial mats in Crater Lake, Oregon, USA (Dymond et al. 1989). Given the geochemically derived source of nutrition and the typically harsh physicochemical habitats in which they thrive, it is understandable that the bacteria known as lithotrophs (literally “rock eaters”) are usually the dominant forms of life in such environments. While they provide further rationale for the study of freshwater systems, few are as tractable as Yellowstone Lake for accessibility to study.

The Yellowstone caldera underlies the northern half of Yellowstone Lake, while the Yellowstone River inflow and the southern half of the lake lie outside the caldera boundary. Within the caldera, geothermally heated subsurface water percolating through hot rocks above the magma chamber becomes enriched in carbonate, silicate, and chloride, with some locations additionally rich in methane, iron and sulfide. The park is world-renowned for its geothermal activity. This provides a significant opportunity to delineate vent geochemical effects on bulk lake water composition, because enrichment occurs far from the most significant surface inflow, which is the Yellowstone River in the Southeast Arm (Figure 1). The northern half of Yellowstone Lake is strongly influenced by underwater geothermal hot springs and gas fumaroles. These features release water with high concentrations of silicate and bicarbonate as well as reduced materials of mineral origin, including hydrogen sulfide, Fe[II], methane, and, more rarely, ammonia into the bottom waters. While the vents of Yellowstone Lake resemble deep-sea hydrothermal systems in some important respects, the nearly closed nature of the basin and the relatively small volume of receiving waters provides additional opportunities for process research. Because riverine inputs and outputs may be estimated, Yellowstone Lake geothermal and biogeochemical activities are amenable to budgeting by mass balance (inputs + change = outputs).

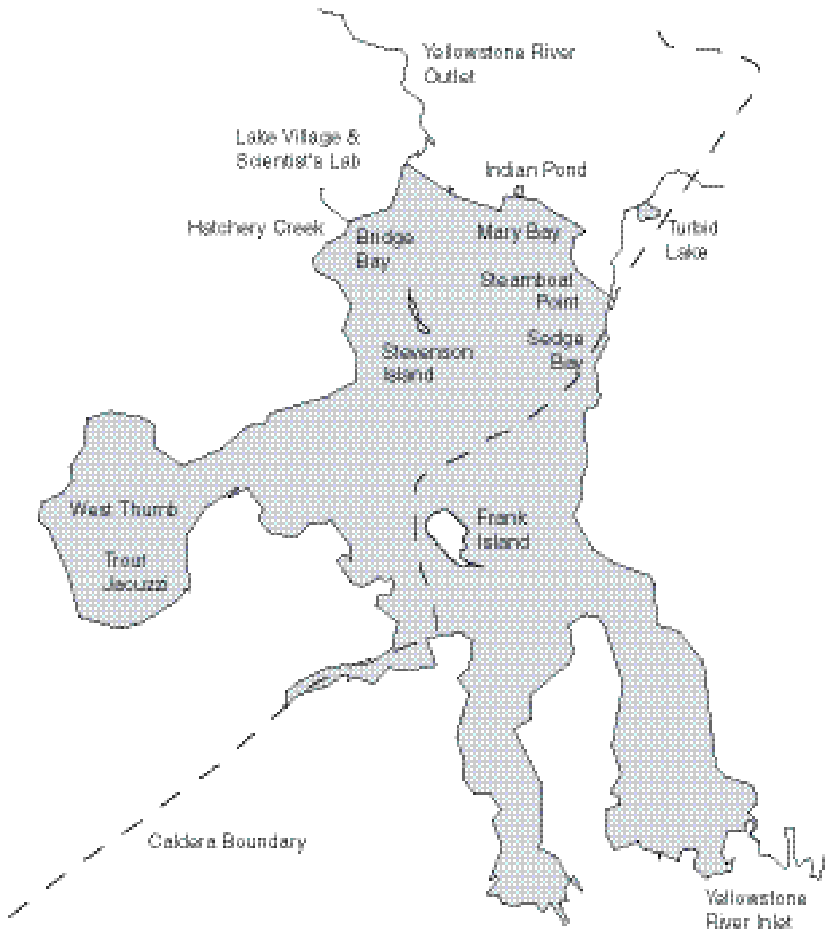

Figure 1. Map of Yellowstone Lake showing areas of underwater hydrothermal features sampled by ROV. West Thumb samples ring the entire basin, and Mary Bay, Sedge Bay, Steamboat Point, and Storm Point samples were also within 300 m of shore. Stevenson Island collections were made in the deep canyons just east of the island. Southeast Arm samples were taken midway down the arm (65–90 m water depth). Yellowstone River inlet samples were taken by NPS personnel well upstream of the mouth.

Work over the last 10 years on the development of remotely operated vehicle (ROV) survey and sampling technology (Marocchi et al. 2001; Remsen et al., this volume) demonstrated the absolute necessity of remote sampling of the deep, hot, seemingly inhospitable fluids of Yellowstone Lake vents. Starting with a simple Mini-Rover system consisting of video and still cameras and a claw with small pump-driven sipper tube, photographic surveys and water samples suitable for limited dissolved geochemical (Cl^-, SiO_2, $SO_4^=$, Na^+, etc.) and dissolved gas (CH_4, CO_2, ^{222}Rn) analysis were obtained (Klump et al. 1988). Combining the submersible results with surface-collected samples from the inlet at Southeast

Arm and the outlet at Fishing Bridge, it became apparent that aqueous species and gases found in vent fluids were also significantly enriched in lake water relative to surface inflows (Table 1) and in some cases comparable to marine vent-

Table 1. Mineral content of mid-Atlantic Ridge seawater and marine vents compared with Yellowstone Lake inflow, outflow, and freshwater vents, 1994–1998 sampling results.

Parameter	Units	Maximum or Minimum	Marine Hydro-thermal Fluids (TAG, 26°N)[a]	Mid-Atlantic Seawater[a]	Yellowstone River Inflow	Yellowstone Lake Vent Fluids	Yellowstone River Outflow
Temperature	°C	Maximum	365	2	22	120	20
Acidity	pH	Minimum	3.35	7.8	7.05	4.92	7.29
Dissolved oxygen	mg/L	Minimum	0	7.6	9.0	0	8.5
Hydrogen sulfide	mM	Maximum	3.5	0	0.0004	0.9	0.0006
Sodium	mM	Maximum	537	464	0.078	3.360	0.341
Potassium	mM	Maximum	17.1	9.8	0.022	0.076	0.034
Calcium	mM	Maximum	0.031	0.01	0.093	1.032	0.136
Magnesium	mM	Minimum	0	52.7	0.057	0.025	0.087
Silica	mM	Maximum	20.75	0.2	0.333	1.283	0.223
Chloride	mM	Maximum	636	541	0.007	1.146	0.126
Sulfate	mM	Minimum	0	27.9	0.012	0.054	0.070
Manganese (II)	µM	Maximum	680	0	<0.20	0.87	<0.20
Iron (II)	µM	Maximum	5590	0.0015	<0.02	1.5	0.05

[a] Marine data from summary of Humphris and McCollom 1998.

ing systems. Although near-surface groundwater may contribute to enrichment, exceptionally strong signals from such geochemical indicators as radon-222 (derived from deep-rock degassing) and high flux rates of methane across the air–water interface imply a major role for submarine vents and fumaroles.

Visual evidence of a long history of submarine geothermal activity is abundant in West Thumb, Mary Bay, Sedge Bay, Steamboat Point, and even in the very deep waters (120 m) off Stevenson Island, all within the caldera boundary (Marocchi et al. 2001). "Vent hole with white ppt. (323'); large relic pipe (176'); sponge attached to relic structure (176'); sulfide seeps, white ppt. (106'); bacterial mat on relic (110'); hot water vent with leeches (143'); sulfide fumaroles with white ppt. (143'); shimmering water with zooplankton swarm (310'); fish near hot water vent (128'); probe in 120°C hot vent—black smoker! (131')" are a few of the annotations from still and video images catalogued from the last few years (Remsen et al., this volume).

Submersible observations reveal some significant similarities and some major differences between the freshwater Yellowstone Lake hydrothermal systems and marine deep-sea hydrothermal vents (Humphris et al. 1995). Both show powerful, highly localized geochemical process signals in solid-phase deposits and dissolved chemical species. Both demonstrate finite lifetimes through existence of relic vent fields. Both act as focal points for biological activity (Page et al. 1991; Toulmond et al. 1994; Nelson et al. 1995), particularly in the microbial community (Cary et al. 1993; Cavanaugh 1994; Stetter 1999), with biomass significantly higher than surrounding areas and of distinct composition (Jannasch and Mottl 1985). Low hydrostatic pressure and hence lower maximum temperature, freshwater source material, and continental basement rock composition result in substantially different mineral content of emanating fluids at Yellowstone Lake, however. Biological community development is also far less complex because of the evolutionarily-short existence of the system. One of the most important differences is that Yellowstone Lake has definable, measurable inflows and outflows (compared with, for example, the eastern Pacific Ocean).

Biogeochemical reactions both form and consume reduced minerals, and as the term implies both biotic (microbiological) and abiotic (chemical) mechanisms are involved. Because the reactions have negative free energy, they may be accomplished spontaneously, often under conditions of extreme temperature, pressure, and reactant concentration, or they may be facilitated by enzymes contained within the cytoplasm of the microorganisms known for these reactions. Biogeochemical transformations and a model net reaction are given in Table 2, along with a representative microbial genus or genus prefix that biologically undertakes the transformation (cf. Brock and Madigan 1991).

Biological transformations of dissolved inorganic nutrients occur almost exclusively in the domain of microorganisms (algae, bacteria, fungi) and plants.

Table 2. Biogeochemical transformations, model net reactions, and representative microbial genus or genus prefixes.

Reductive-component model reactions	
Methanogenesis	$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ (*Methano** spp.)
Sulfate reduction	$SO_4^{=} + 4H_2 \rightarrow S^{=} + 4H_2O$ (*Desulfo** spp.)
Iron reduction	$Fe[III] + 2e^- \rightarrow Fe[II]$ (heterotrophic respiration; e.g., *Shewanella* spp.)
Manganese reduction	$Mn[IV] + 4e^- \rightarrow Mn[II]$ (as iron above)
Oxidative-component model reactions	
Methane oxidation	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ (*Methylo** spp.)
Reduced sulfur oxidations	$H_2S + \frac{1}{2}O_2 \rightarrow S^0 + H_2O$ (*Thio** spp., *Beggiatoa* spp.) $H_2S + 2O_2 \rightarrow H_2SO_4$ $2S^0 + 3O_2 + H_2O \rightarrow 2H_2SO_4$ $S_2O_3^{=} + 2O_2 + 2H^+ \rightarrow 2H_2SO_4$
Iron oxidation	$Fe(II) + \frac{1}{4}O_2 \rightarrow Fe(III) + H_2O$ (*Ferroglobulus* spp., *Gallionella* spp.)
Ammonia oxidation	$NH_3 + 1\frac{1}{2}O_2 \rightarrow HNO_2 + H_2O$ (*Nitroso** spp.)

* Denotes multiple genera in a group.

In most aquatic environments, microbial activity is restricted to photoautotrophs (photo = energy from light, auto = cellular carbon from CO_2 fixation; algae) and heterotrophs (hetero = organic matter decomposition providing both energy and cellular carbon; bacteria and fungi), with chemolithoautotrophy (chemo = energy from reduced inorganic chemicals, litho = chemicals of geologic origin, auto = CO_2 fixation; bacteria) restricted to the very bottom waters and upper few cm of sediments (Jørgensen and Fenchel 1974). In hydrothermally influenced systems, injection and mixing of relatively stable reduced geochemicals (e.g., CH_4, Fe[II], NH_4^+, H_2S, and intermediate sulfur oxidation products) provides an opportunity for accentuated chemosynthesis and population growth of bacteria responding to the available energy sources (CH_4: Distel and Cavanaugh 1994; Cheng et al. 1999; Fe: Cowen et al. 1986; Hafenbradl et al. 1996; Emerson and Moyer 1997; Mn: Mandernack and Tebo 1993; H_2: Brysch et al. 1987; Nishihara et al. 1990; H_2S: Nelson et al. 1989; Hallberg and Lindstrom 1994). Lithotrophic bacteria require the same inorganic nutrients for biomass production as photoautotrophs and many heterotrophs, and hence compete with them in nutrient cycling. The elemental stoichiometries (mol:mol) of tissue are approximately the same in all these microbes, i.e., $C_{106}\ N_{16}P_1\ S_{0.5}$.

Bacterial growth and metabolism occurs in proportion to the amount of usable nutrients in the environment, while the presence of bacteria depends upon previous access to nutrients. In the context of this work, both the presence and activity of specific bacterial types (e.g., nitrifiers, sulfur oxidizers, methane oxidizers) indicate that the respective nutrient substances are available. By utilizing an appropriate suite of metabolic measurements coupled with enumeration of specific bacterial populations, an independent confirmation of hydrothermal contributions to lake geochemistry is possible, and the extent of biological transformations in geochemical cycling may be elucidated. This paper summarizes efforts to characterize microbial community function specifically in underwater hydrothermal emanations of the Greater Yellowstone Geoecosystem.

Sampling Locations and Methods

Underwater hydrothermal vents have been sampled in Yellowstone Lake for over 15 years (Marocchi et al. 2001; Remsen et al., this volume). Three areas have been repeatedly studied: the West Thumb basin; the northern basin, including Mary Bay, Steamboat Point, Storm Point, and Sedge Bay; and the deep waters just west of Stevenson Island. Suspected vent areas were identified by observations of bubbling, hot-water upwelling, shimmering water, presence of bacterial mats or apparent mineral precipitates, or inappropriately warm water at depth. Due to the limited amount of ROV dive time and weather difficulties on the lake, most effort was focused on reliable vent areas around the above-mentioned features. On occasion, surveys with the ROV delved into unexplored flanks of active regions.

Vent samples have been collected using traditional water sampling bottles over visible bubblers, by wading with hand-held sample bottles, by SCUBA diving with sample bottles and syringe arrays (Buchholz et al. 1995), and by ROV equipped with a variety of water and solid-phase sampling implements (Klump et al. 1992). For SCUBA samples, divers identified features of interest, then opened the cap of a sample bottle as close to the orifice as possible. In some cases, 60- or 140-cc syringes were filled from the emanating water. For the ROV samples, a progressively more refined mechanism has been developed over the years (Marocchi et al. 2001; Remsen et al., this volume). Initially, the submarine's claw arm held a piece of tubing leading to a peristaltic pump on the surface vessel. The inlet was placed close to a feature and pumped water collected for chemical analysis. Later, a more independent, multiple-closed-loop sampling system was deployed (Klump et al. 1988), yielding more and deeper samples, but of limited volume (a few mL). Subsequently, larger samples were collected using multiple-syringe arrays. Syringes imparted the additional benefit of reducing sample contamination with atmospheric gases and lake water. As a result, measurement of more difficult analytes (e.g., reduced iron, hydrogen sulfide, methane, etc.) could be undertaken. Prior to each day's sampling, the entire sipper system was flushed with ultra-pure deionized water; residual dead-volume was about 30 mL. In a 8 x 140-mL sample this represented only 2–3% dilution, not intolerable for most geochemical analyses or even biological rate measurements, but somewhat more problematic for redox-sensitive analytes (iron and sulfur compounds in particular) and pure culture isolations.

On board the surface vessel, the National Park Service *R/V Cutthroat,* subsamples for sensitive analytes (dissolved gases, sulfur compounds, reduced metals, biological rate parameters, etc.) were taken by syringe (60 or 140 cc) without exposure to air or any non-plastic parts. When possible, derivatization or other means of sample preservation were taken aboard the vessel.

Chemical Analyses

Principal dissolved inorganic compounds were measured by flow injection analysis (FIA; SiO_2, NO_3^-, NO_2^-); ion chromatography (IC; Cl^-, $SO_4^=$); spectroscopy ($HPO_4^=$, NH_4^+), gas chromatography (GC; CH_4), or atomic absorption spectroscopy (AAS; Ca^{++}, Mg^{++}, Na^+, K^+, Fe, Mn) according to standard methods (APHA 1992). Iron was also determined by the ferrozine spectrophotometric method of Stookey (1970) with (total Fe) and without (Fe^{++}) reductant extraction. Total CO_2 was analyzed by the Teflon-membrane FIA method of Hall and Aller (1992). Beginning in 1997, reduced sulfur compounds (H_2S, $S_2O_3^=$, $SO_3^=$) were quantified by a scaled-up modification of the micro-bore high-performance liquid chromatographic (HPLC) method of Vairavamurthy and Mopper (1990) using dithio-bis-nitropyridine (DTNP) derivatization. Much of the analytical equipment was transported to the park, and all labile species were analyzed on site, usually within one day of sampling and preparative stabilization.

Biological Measurements

Bacterial isolates were obtained from vent water samples by enrichment, dilution, and growth on liquid or solidified media using inorganic nutrient supplements (CH_4, Fe[II], H_2S, $S_2O_3^=$, polysulfide) according to a variety of standard approaches. Enrichment and growth were accomplished at three temperature ranges reflecting types of bacteria expected in these geochemically and geothermally altered habitats (cf. Henry et al. 1994). Mesophiles (bacteria growing at temperatures lower than 40°C) were cultured at room temperature (18–25°C), while thermophiles (best growth at 60–70°C) and extreme or hyperthermophiles (growth at 80–110°C) were incubated in ovens at elevated temperatures (50°C and 80°C respectively).

Reduced sulfur-oxidizing bacteria were a particular focus of attention for several reasons: (1) Yellowstone National Park vents and geysers include representatives unmistakably rich in reduced sulfur, especially hydrogen sulfide (which is odorous) and elemental sulfur (which exhibits a halo of yellow, and sometimes crystalline precipitate, around orifices). The sulfur provides an energy source for chemolithotrophic bacteria to fix carbon dioxide as the principal building-block of tissue. (2) Sulfur-oxidizing bacteria are well represented in, or even dominate, marine hydrothermal vent systems with characteristics comparable to the vents of Yellowstone. (3) Many of the thermophilic and extremely thermophilic bacteria (i.e., growth at very high temperature) described from marine hydrothermal systems are sulfur oxidizers. (4) Certain metabolic characteristics, particularly carbon dioxide fixation in the dark, make possible an assessment of chemolithotrophic growth, including that of sulfur oxidizers, in the presence of other more common heterotrophic (organic matter-degrading) bacteria.

Chemolithotrophic activity (dark) and photosynthetic activity (light) were both assessed by an incubation method in which acid-volatile ^{14}C-bicarbonate was biologically converted into acid-stable organic-^{14}C (CO_2 fixation). All rate measurements were made in acid-washed 20-mL liquid scintillation vials using a temperature-controlled block, with ^{14}C-bicarbonate (ICN Corporation, Costa Mesa, California) added to 1 µCi/mL final activity. Dark fixation incubations extended for 9–12 hours, while photosynthesis measurements used 1.5–3 hour incubations in a light gradient (Back et al. 1991). Supplements and inhibitors were added at 1:100 or higher dilution to minimize inoculation artifacts. Incubation was terminated by addition of 2N H_2SO_4 to pH <2; capped vials were purged of unincorporated ^{14}C at the senior author's home institution in Milwaukee by shaking for 12–24 hours in a fume hood. Liquid scintillation cocktail (Hydrofluor; National Diagnostics, Manville, New Jersey) was added and samples counted in a Packard 1500 liquid scintillation counter (Packard Instruments, Meriden, Connecticut) for 20 minutes or 1% error, whichever came first. Zero time blanks were <200 DPM from additions of 2×10^7 DPM at inoculation. Rate calculations took into account the concentration of total CO_2 measured on site, with controls assayed in triplicate to quintuplicate depending on availability of sample and desired treatment matrix. Areal photosynthesis was modeled with the programs of Fee (1990).

Results and Discussion

Geochemical characteristics of hydrothermal fluids. Several products of hot water–rock interaction have been reliably enhanced in both marine and freshwater vents (Table 1). Comparing mid-Atlantic deep water and TAG hydrothermal vent fluids, Humphris and McCollom (1998) listed key geochemicals influenced by hydrothermal processes. Reliable increases have been documented for temperature, acidity, hydrogen sulfide, silicate, manganese, and iron (Table 1) in most marine vents, and Yellowstone Lake vents adhere to these same characteristics when compared with Yellowstone River inlet waters. On the removal side, marine systems completely remove magnesium and sulfate from their source waters, deep in the geothermal system, while this characteristic is muted in Yellowstone Lake vents (Table 1). One complicating factor is that the source concentrations of these components were small at Yellowstone, making such decreases difficult to demonstrate if they indeed occur. More significantly, it is apparent from many analyses that hydrothermal vent fluids at Yellowstone were diluted with lake water deeper in the conduits than we have been able to sample, at least in recent years. Comparison of current findings with much earlier data from Yellowstone Lake (Klump et al. 1988) suggests that vent geochemistry may have changed significantly over a decade. Because vent sites had not been marked until 2001, it is difficult to quantitatively compare among years, except on the broad scale of basin regions (e.g., Mary Bay, West Thumb) and observed extreme values. From the perspective of microbiology, however, geochemical processes were found to increase concentrations of reduced geochemicals supportive of chemosynthetic bacterial productivity in both marine and freshwater hydrothermal systems.

Dark carbon dioxide fixation—measurements of bacterial chemosynthesis. Extensive chemolithotrophic activity by bacteria in Yellowstone Lake was supported by utilization of geochemically reduced compounds and detected via dark $^{14}CO_2$ fixation in water, vent, and microbial mat slurry samples. In addition to outright chemosynthesis under favorable conditions, potential chemosynthesis was sought with the aid of incubation supplements, and microbial activity was verified through the use of specific metabolic inhibitors. In general there were three response patterns to the measurement matrix.

Active bacterial productivity using mineral-derived energy was demonstrated in many vent-orifice samples from the northern and north-central domains. The 1997 experimental design is exemplified by an active vent at Steamboat Point (Figure 2). Unamended control rates of dark CO_2 fixation were often 10–100 times higher than those of samples taken from the open lake and showed substantial inhibition by the prokaryotic protein synthesis inhibitor chloramphenicol (CAP). Methanol (MeOH) used to dissolve CAP had no effect. Addition of ammonium did not enhance chemosynthesis either by stimulating ammonia-oxidizing bacteria or by relieving possible nitrogen limitation of growth during the 9- to 12-hour incubations. Thiosulfate, a model reduced sulfur compound known to support growth of many sulfur-oxidizing bacteria, yielded a 60% stimulation of activity in this case (vent $[H_2S] = 34\ \mu M$) in the presence or absence of added ammonium. Stimulation also was eliminated by CAP, again indicating bacterial involvement. Collectively these data documented substantial bacterially mediated carbon dioxide fixation in habitats containing utilizable concentrations of

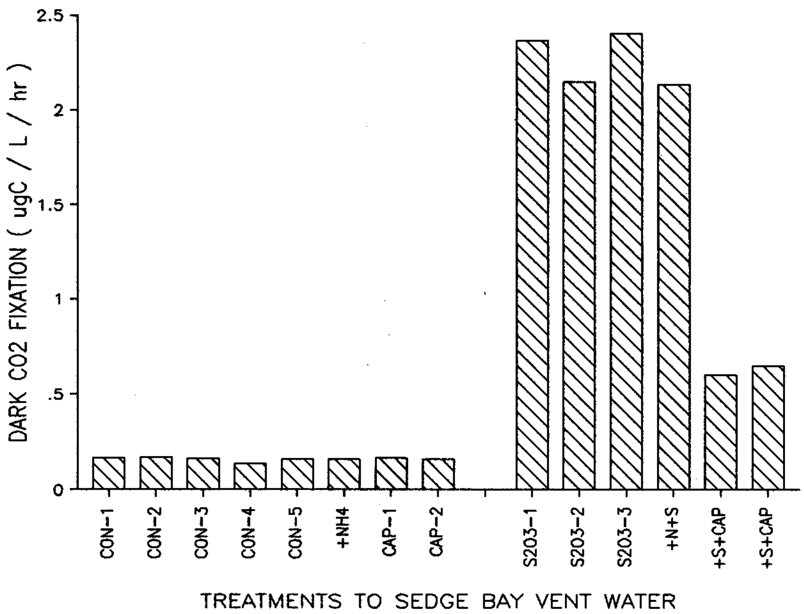

Figure 2. Response of 1998 Sedge Bay shallow-vent dark $^{14}CO_2$ fixation to added potential stimulants (e.g., 5 mM thiosulfate, S_2O_3= or S; 1 mM ammonium, NH_4+ or N; and a protein synthesis inhibitor (20 µg/mL chloramphenicol, CAP) alone or in combination (final concentration given). Individual replicates are shown.

reduced geochemicals.

Potential chemosynthesis was frequently encountered in the immediate vicinity of active vents and fumaroles, particularly where vigorous turbulent mixing of the water column was common (e.g., shallow nearshore areas) or where vent fluids were injected into confined volumes (e.g., narrow canyons). This response is well documented by a SCUBA-collected sample from a shallow (3 m deep) fissure in Sedge Bay, shimmering with warm water but readily exchangeable with overlying lake water (Figure 3). Controls and nitrogenous supplements yielded rates only 3–4 times higher than values in water taken from the open lake, but thiosulfate addition increased CO_2 fixation by over fifteenfold to levels competitive with photosynthesis. Thiosulfate stimulation was greatly reduced by CAP, as before, but the inhibitor had little effect on control activity. Often when dark fixation was low, the growth-oriented inhibitor CAP had little influence, but growth response to stimulation remained sensitive. Again ammonium addition was without effect. In these circumstances it was clear that when reduced geochemicals became available, bacterial populations were present and capable of immediate growth resumption. The spatial distribution of potential production most likely reflected the recent history and magnitude of reduced geochemical emanations.

The third type of finding was the absence of chemosynthetic activity (Figure 4), which is normal in non-geothermally influenced waters but provides an

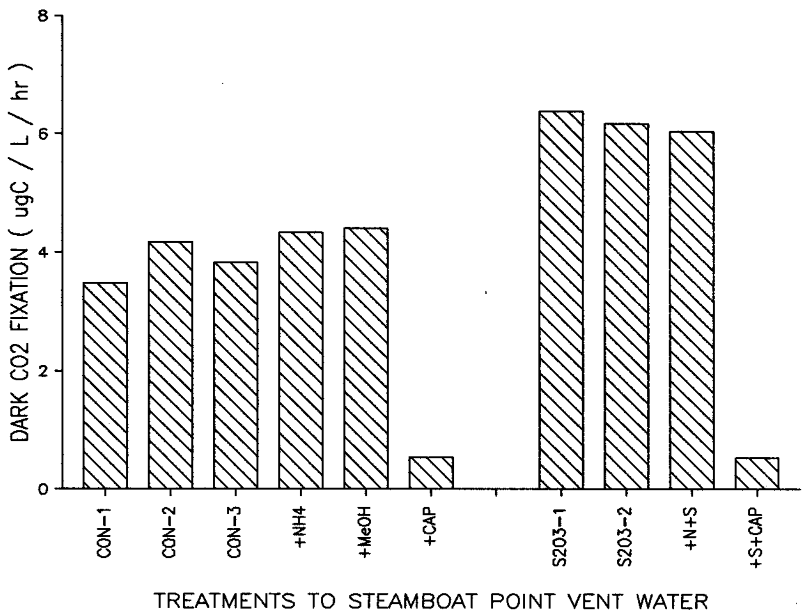

Figure 3. Response of 1998 Steamboat Point shallow-vent dark $^{14}CO_2$ fixation to added potential stimulants, as in Figure 2. Control for CAP addition was methanol (MeOH), the solvent. Due to limited sample availability, all samples did not receive all treatments.

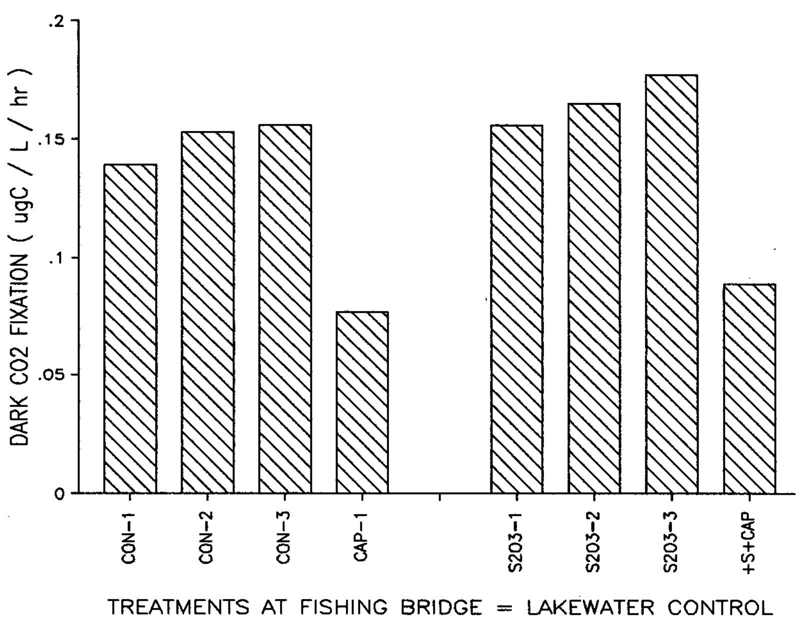

Figure 4. Response of 1998 surface water of the Yellowstone River outflow at Fishing Bridge dark $^{14}CO_2$ fixation to added potential stimulants, as in Figure 2.

important control in Yellowstone Lake. In this example, using the Yellowstone River outflow during 1997, unamended controls showed very low rates of dark CO_2 fixation (note scale expansion relative to Figures 2 and 3). Furthermore, addition of thiosulfate was not stimulatory and CAP exerted only moderate inhibition. While the absolute rates vary from extreme lows in the Southeast Arm to slightly higher values in the surface waters of the northern basin, the characteristics of non-stimulation by reduced sulfur and weak CAP effect are consistently demonstrable.

With the advent of large-volume ROV sampling (approximately 1 liter per sample) in 1997 came opportunities to measure bacterial productivity rates as well as aqueous chemistry on vent samples. Previously, only samples collected by divers or in the proximity of vents (with manual water samplers) could be tested for chemosynthesis processes to complement enrichment, isolation, and pure culture work. The 200 mL or more required for worthwhile rate measurement effort was simply too dear given the great value of interannual chemical analysis comparisons. Of the hundred samples from vents, fumaroles, water column profiles, and other lake sites, the vast majority fit one of the three above response styles. We now apply these results to understanding biogeochemical interaction of microorganisms and reduced compound emanations in specific vent fields and overlying waters.

Photosynthesis—the basis for comparison. In lakes, primary production (i.e., CO_2 fixation into organic matter) is usually carried out by photosynthetic organisms (algae, rooted plants) using light energy, in contrast to chemosynthetic CO_2 fixation described above and below. To place the bacterial contribution in perspective, a survey of photosynthesis was undertaken each year. A vertical profile of CO_2 fixation vs. irradiance was obtained with a photosynthetron (Lewis and Smith 1983) and areal productivity (mgC/m^2/day) calculated using the programs of Fee (1990). Both volumetric potential (µgC/L/hour) and most probable areal rates are relevant for comparison. Annual surveys exemplified by 1996 results provided representative photosynthesis rate ranges (Figure 5) for the main regions of Yellowstone Lake. In this approach, the light dependence of photosynthesis was measured in a light gradient, and the results used in conjunction with light penetration profiles to calculate whole water column photosynthesis (mg/m^2/day). Also relevant for comparison with chemosynthesis was the maximum volumetric rate of photosynthesis (µgC/L/hour), approximated by data between 250–800 µmol photosynthetically active radiation (PAR; 400–700 nm) photons/m^2/sec (10–30% of full sunlight).

Lowest volumetric photosynthesis was always found in the Yellowstone River inlet at the tip of Southeast Arm, with similarly low rates in the open waters of Stevenson Island and Mary Bay (1–2 µgC/L/hr). Intermediate volumetric productivity was attained in enclosed basins of West Thumb and the central Southeast Arm (3–4 µgC/L/hr), while the highest rate was found in the Yellowstone River outlet (5 µgC/L/hr). Chemosynthesis was certainly on a par with photosynthesis in the above examples, demonstrating that chemical energy

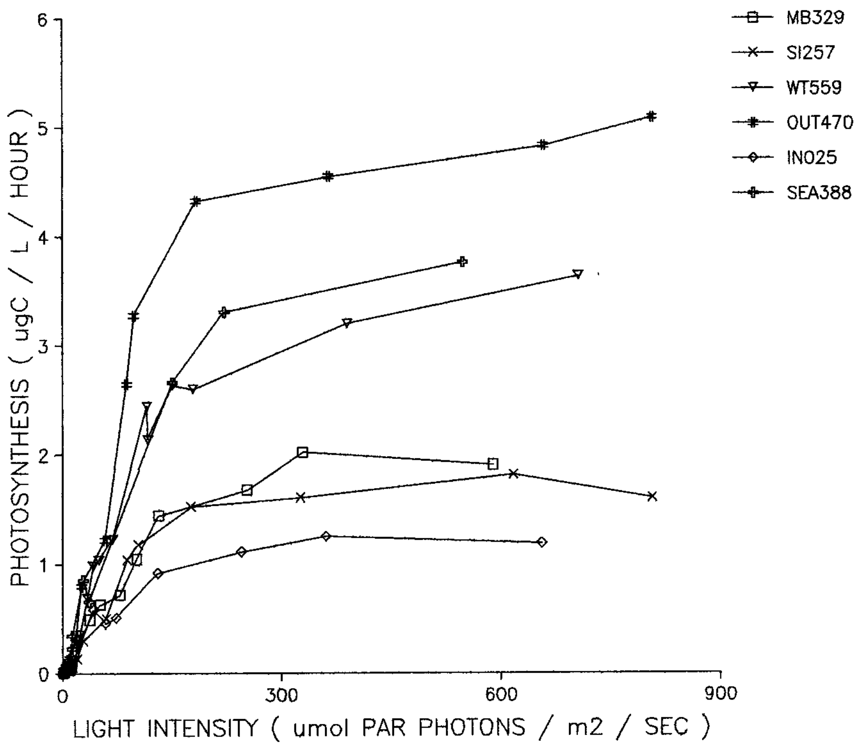

Figure 5. Light dependence of photosynthesis varied among locations in Yellowstone Lake. The three-digit number in the legend is the areal production (mgC/m2/day) calculated from these curves for 1996. MB, Mary Bay; SI, Stevenson Island; WT, West Thumb; OUT, Yellowstone River outlet at Fishing Bridge; IN, Yellowstone River inlet at Southeast Arm; SEA, Southeast Arm mid-basin.

could be as effective as light energy in promoting CO_2 assimilation into organic matter. Thus, active vents could attain sufficient production to support at least some degree of bacterial-based food web activity.

Areal production, integrated over the depth of the water column (for chemosynthesis) or over the depth of PAR light penetration (for photosynthesis), is a measure of ecosystem-level contribution. In the low-water year 1994, northern-basin chemosynthesis off Stevenson Island (3930 mgC/m^2/day) was significantly greater than photosynthesis (1620 mgC/m^2/day). Dark CO_2 fixation rates were only 2.2 µgC/L/hour but were uniform over a 75-m water column and the 24-hour day, while photosynthesis maxima were higher at 6–9 µgC/L/hour but decreased rapidly with depth (hence light) for the 14-hour light-day. Subsequent higher-water years demonstrated decreased areal photosynthesis and greatly reduced water column chemosynthesis. In the 1996 example (Figure 3), calculated areal production (mgC/m^2/day) by water column algae was highest in West Thumb (559) and Yellowstone River outflow (470) samples; intermediate in

Southeast Arm (388), Mary Bay (329), and Stevenson Island (257); and extremely low in the Yellowstone River inlet (25). Water column chemosynthesis was very low during high-water years, so areal chemosynthesis was dominated by near-vent production. At an average of 5 µgC/L/hour, vent haloes alone could account for over 100 mgC/m^2/day, a significant but limited contribution to total water column biomass production.

Biogeochemical domains of chemolithotrophy and a role for dissolved minerals. Reactions of rock and hot water at high hydrostatic pressure result in both passive geochemical leaching (e.g., chloride, silicate, carbonate) and active mineral transformation (e.g., reduction of carbon dioxide to methane, sulfate to sulfide, Fe[III] to Fe[II], Mn[IV] to Mn[II], often using hydrogen gas as reductant). In the areas of West Thumb and northern Yellowstone Lake, thermal features on shore appear to descend directly into the lake, and in fact underwater vents are abundant in those and other areas (Marocchi et al. 2001; Remsen et al., this volume). Biogeochemical domains (that is, characteristically coherent regions) appear to be important in both surface- and underwater venting systems.

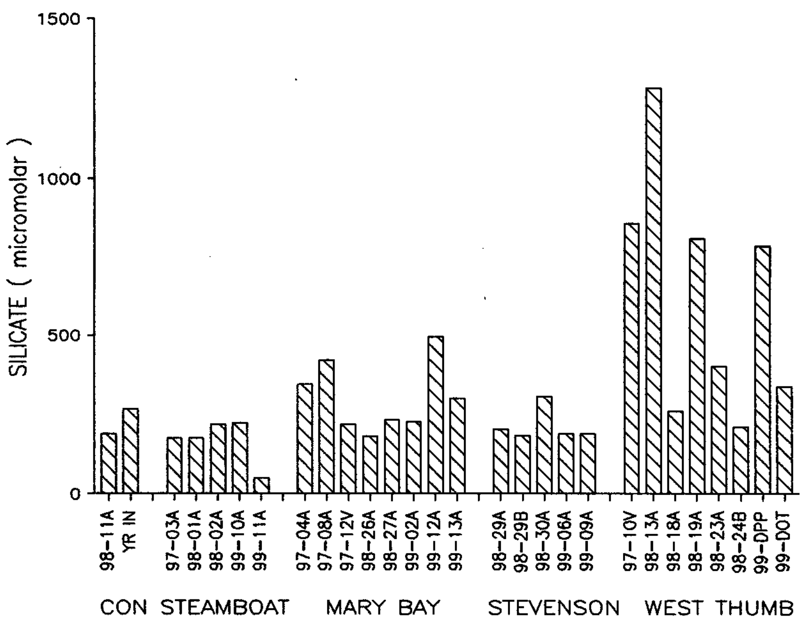

Figure 6. Domains of biogeochemistry were apparent at underwater hydrothermal vents in Yellowstone Lake, 1997–1999, as demonstrated by selected geochemical concentrations (Figures 6–10) and dark $^{14}CO_2$ fixation (Figure 11) in vent waters. Silicate showed strong enrichment in West Thumb vents. Left column, 98-11A, was a control bottom sample (35 m) taken with the ROV in a cold (10°C) inactive relic vent field in Mary Bay. YR is the Yellowstone River inlet control. From left to right, vent samples from Steamboat Point (5), Mary Bay (8), Stevenson Island (5), and West Thumb (8) are shown for each parameter. 1999 DPP (Pumice Point) and DOT (Otter vent) samples from the West Thumb area were collected by Jim Bruckner using SCUBA diving. Results are shown for all analyses, with low values appearing as blank. Missing samples (CH_4 only) have no identification label.

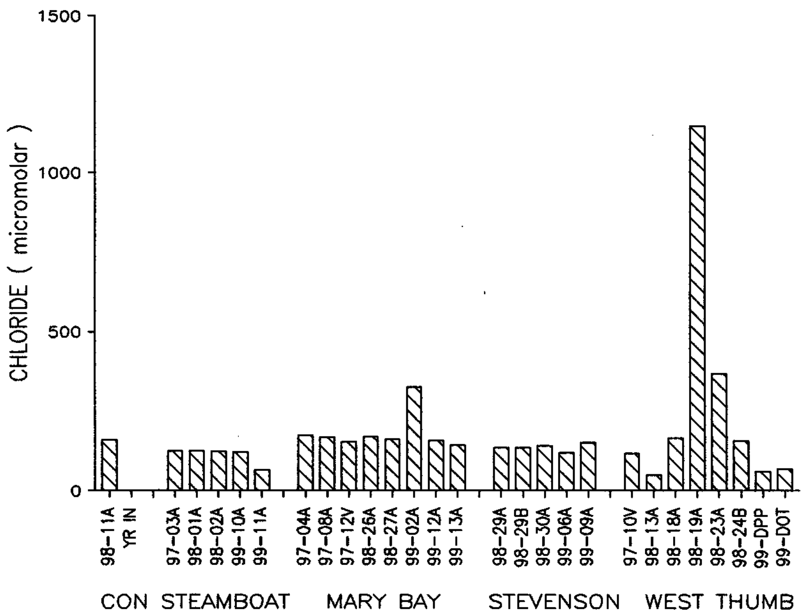

Figure 7. Chloride enrichment was less frequent in 1997–1999, but occurred in West Thumb vent waters.

Both silicate (Figure 6) and chloride (Figure 7) in hydrothermal vent fluids from West Thumb were frequently enhanced over lake water mean values of about 200 µM and 100 µM, respectively. In these and subsequent figures, vent 98-11A (far left) is a sampling control taken by the ROV sipper system very near the bottom in a deep but inactive relic vent field in Mary Bay, and represents one type of lake water control value. The Yellowstone River inlet is another important control sample. Though not all vents in West Thumb displayed elevated SiO_2 and Cl^-, only vents in this area reliably did so during 1997–1998 sampling efforts. Only slight increases in SiO_2 (less than twofold) were seen in 1997 Mary Bay and one 1998 Stevenson Island vent. The fact that only one area demonstrates high solute levels, yet all areas contain vents reaching extreme temperatures (up to 120°C), suggests that very different source reservoirs or vent conduit systems exist in the western vs. northern parts of the lake.

Three other geochemical indicators of water–rock interaction obeyed different domain specificity. Total CO_2 (lake water mean 0.6 mM) was variably but reliably enriched in all domains (Figure 8) with the most extreme values all in the Mary Bay region. Collection and handling of these samples was very important in obtaining accurate results because of degassing. Many of the vent samples formed visible bubbles with time in bottles on deck even though they were initially as warm or warmer than surface waters. For sensitive samples, however, we collected sub-samples in rubber-free syringes minutes after the submarine was out of the water. ΣCO_2 was found to decrease with a half-life of about 20 min-

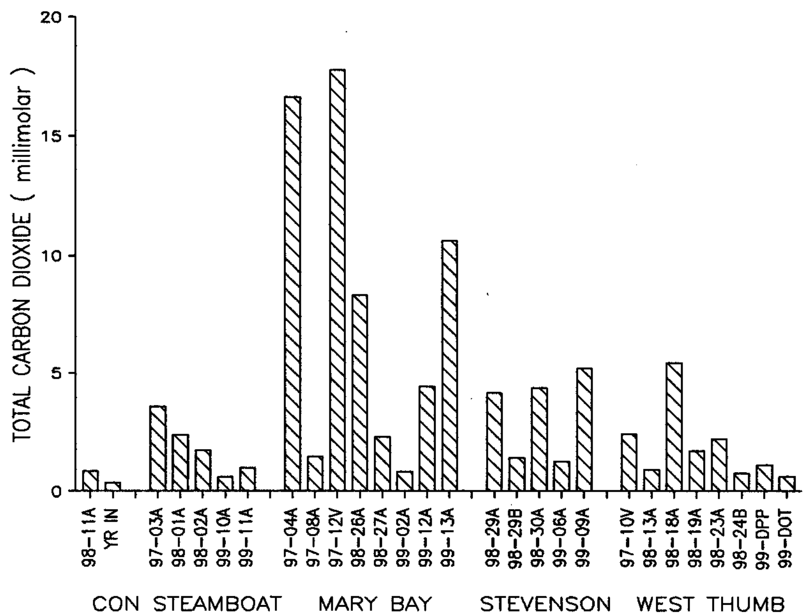

Figure 8. Total CO_2 enrichment was widespread and strong in many deeper vents regard - less of location.

utes in a beaker, but persisted undiminished for 4 to 6 hours in capped syringes (data not shown). All reported measurements of vent water ΣCO_2 were analyzed directly in capped syringes and represent the best (i.e., slightly less than to equal) estimate of *in situ* ΣCO_2. This has a strong bearing on calculations of chemosynthetic dark CO_2 fixation rates described below.

In contrast to ΣCO_2, both methane (lake water mean <1 µM; Figure 9) and hydrogen sulfide (lake water mean <0.5 µM; Figure 10) were well represented in Mary Bay and Stevenson Island vents, while they were rarely detected in West Thumb. Sulfide was also regularly found off Steamboat Point, though at a lower concentration (Figure 10). Thus, the northern and north-central domains were high in carbonate and reduced compounds, whereas the western domain did not stand out. These three components share one characteristic that differentiates them from chloride and silicate: they can exist and be transported in the gas phase. At acid pH all three are significantly or dominantly volatile, and may be distilled from reservoir fluids into a chloride- and silicate-free steam. By this mechanism the domains to the north could have origins in the same reservoir as the West Thumb vents, yet display vastly different geochemical features.

There is a strong association between the domains of reduced inorganic compound emanation and those of bacterial geochemical utilization, as exemplified by chemosynthesis measurements (Figure 11). Both extreme northern regions of the lake (Steamboat Point and Mary Bay) persistently had dark CO_2 fixation rates far above those of open lake water (approximately 0.05 µgC/L/hr) and often

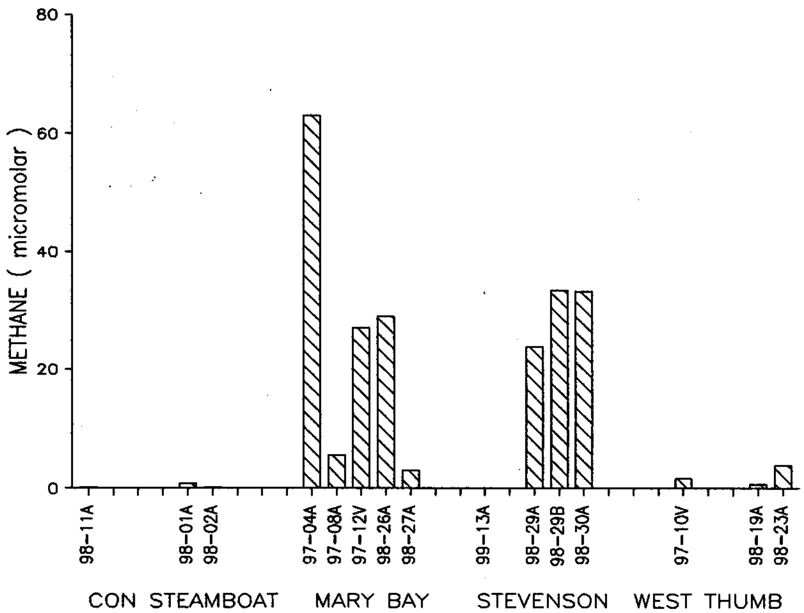

Figure 9. Methane occurred predominantly in Mary Bay and east of Stevenson Island. Analytical difficulty for this parameter in the field is apparent in missing values.

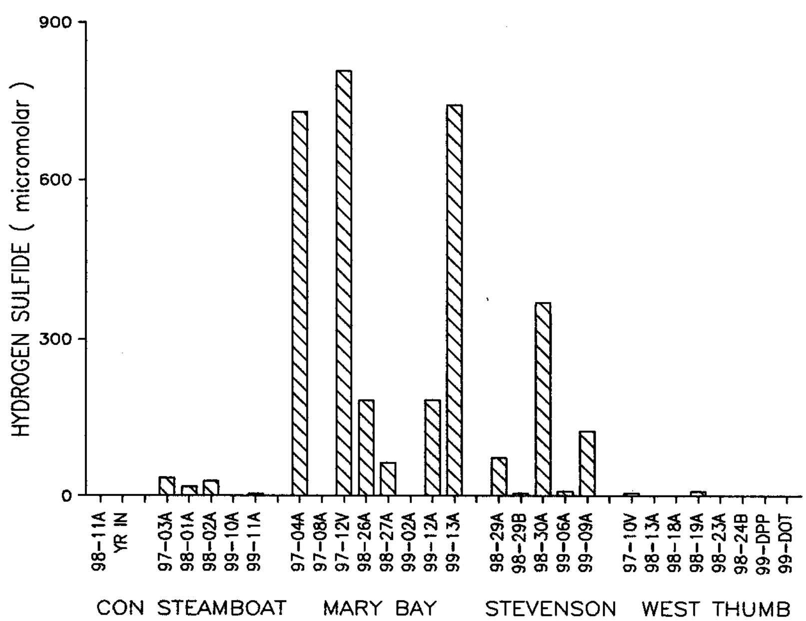

Figure 10. Hydrogen sulfide was frequently enriched in Mary Bay and east of Stevenson Island but was never of consequence in West Thumb.

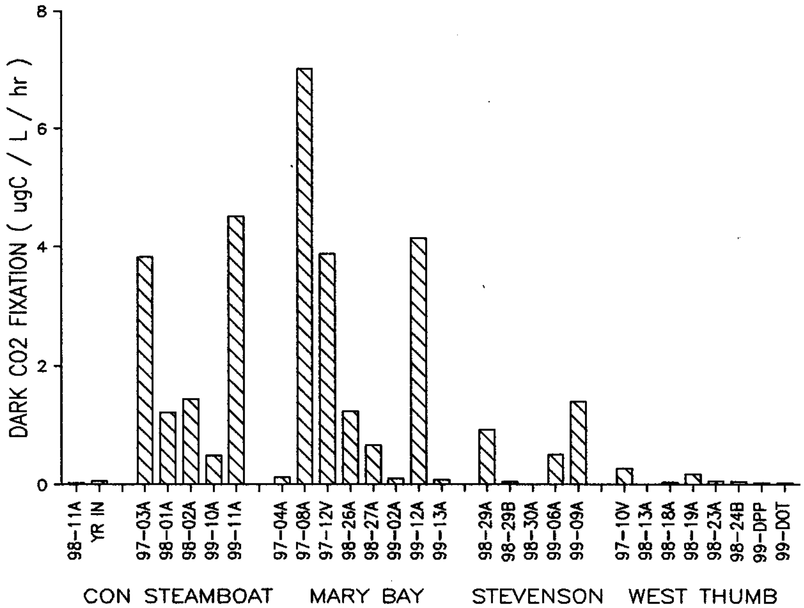

Figure 11. Bacterial chemosynthetic dark $^{14}CO_2$ fixation was common in all northern basin domains, but nearly absent in West Thumb.

exceeding photosynthesis at the surface (approximately 3 µgC/L/hr). Because CO_2-fixing bacteria require one or more reduced mineral-derived substances (e.g., H_2S, Fe[II], etc.) for growth and subsequently remove the nutrient, it is not necessary that high sulfide and high chemosynthetic rates be well correlated at a point in space and time. Hence, high levels of sulfide may presage bacterial vigor, while lower levels may be the result of consumption. In fact, in domains where H_2S was reliably present there tended to be an inverse relationship between standing concentration and bacterial productivity. However, where H_2S was rarely found, as in West Thumb, chemosynthesis was rarely found.

Temperature and microbial productivity in hydrothermal vent waters. Hydrothermal vent systems press the limits of life both through corrosive or otherwise toxic aqueous and gas phase composition, and through imposition of high temperatures. In marine habitats, sulfide and reduced iron often reach concentrations of several millimolar, with additional metals (zinc, copper, cadmium, etc.) often having concentrations in the tenths of millimolar or higher—levels rapidly fatal to most organisms of any kingdom. Toxicity of the chemical solutions is further exacerbated by vent fluid temperatures as high as 350°C in deeper, high-hydrostatic-pressure (>200 atmospheres) locations. Among the more common organisms known to humankind, thermally induced death occurs at temperatures of 42–45°C. This is a distinguishing characteristic of the mesophiles (mid-temperature-loving organisms), including virtually all plants, animals, fungi, and the overwhelming proportion of bacteria. While some organisms can survive higher temperatures, especially for short periods, the ability to thrive and grow at elevated temperatures belongs exclusively to a limited group of prokaryotic (without true organelles) bacteria and archaebacteria. These organisms, the thermophiles (heat-loving; 45–70°C) and extreme- or hyperthermophiles (70–113°C to date) are the sole inhabitants of hot, chemically inhospitable hydrothermal environments that may reflect conditions more widely distributed on early Earth or other planets (e.g., the Martian polar cap) and moons (e.g., ice-covered Europa, a moon of Jupiter). Even present-day extremophiles are restricted to the periphery of marine hydrothermal vent conduits and seeps where superheated, geochemical-laden fluids are cooled and diluted with cold ocean-bottom waters. From this perspective, Yellowstone Lake vents provide an ideal study site because the shallow depths (<150 m), resultant low hydrostatic pressure (<15 atmospheres), and in-transit mixing with lake water keep maximum vent temperatures in the vicinity of the limit currently known for growth.

Two approaches to studies of thermophily in Yellowstone Lake microbial ecology both make use of elevated temperature incubations to exclude common mesophilic bacteria for elucidation of extremophile activity. Growth, isolation, characterization, and molecular analysis of populations and strains have been a principal focus. Using growth at 50°C for thermophiles and 80°C for hyperthermophiles, enrichments and isolates for three major groups of chemolithotrophic bacteria have been successful. A thermophilic sulfate reducer has been characterized (Henry et al. 1994) and thermophilic methane- and sulfur-oxidizing bacteria have been obtained. Recently, a sulfur-oxidizing bacterium capable of growth at 80°C has also been grown. The laboratory organisms and publicly available molecular genetic database have been used as the basis for molecular probing of cultures and populations.

Presence of appropriate species of bacteria in a viable (living) state is necessary but not sufficient for expression of chemosynthetic productivity. Physical and geochemical conditions must also be supportive of growth; when they are not, bacteria may enter dormant phases that remain culturable but are actually inactive. It is partly through this mechanism that populations disperse to take advantage of either sporadic or newly established habitats (e.g., intermittent venting, opening of new geothermal features). As a first step toward corroborating molecular and culture investigations, measurements of chemosynthetic dark CO_2 fixation were sometimes paired: one at the temperature of receiving waters (4–25°C) and one at 50°C. At the elevated temperature, mesophilic bacteria are excluded, while both thermophiles and hyperthermophiles retain positive (though perhaps suboptimal in the latter case) activity in excess of their growth in bottom-water conditions.

Stimulation of chemosynthesis by 1.6–3 times during 50°C incubation was observed for three of the four vent samples tested in 1999 (Figure 12), and the fourth retained 67% of control (bottom-temperature) activity in northern and north-central basin samples. Under the same conditions, replicates of near-zero activity at 50°C were obtained at West Thumb and Southeast Arm (data not shown). Water samples sipped simultaneously from 0.5 m above the vent orifice

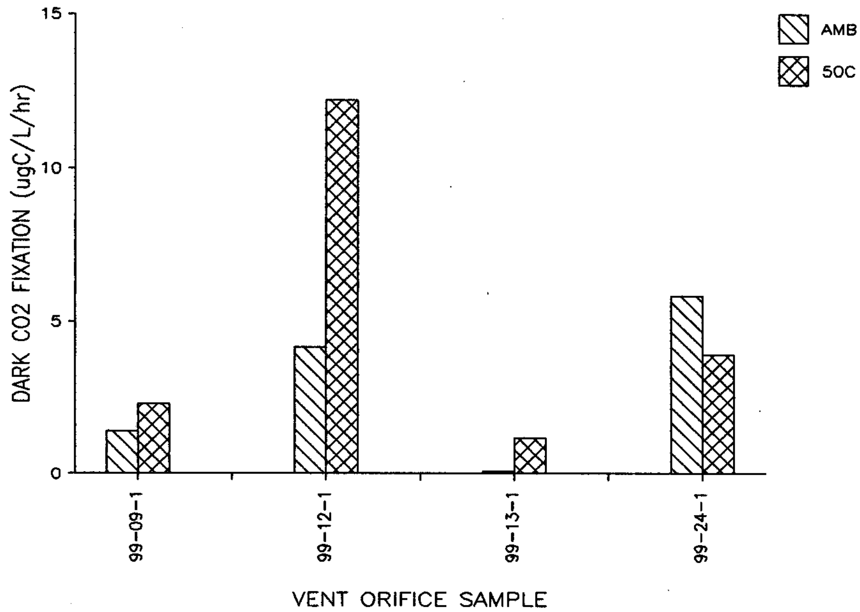

Figure 12. Elevated temperature supported or stimulated thermophilic bacterial dark $^{14}CO_2$ fixation in water samples collected within the hydrothermal vent orifice in Yellowstone Lake during 1999 sampling. Location of vents: 99-09, Stevenson Island (110 m); 99-12 and 99-13, Mary Bay Canyon (53 m); and 99-24, Pelican Roost (approximately 20 m; southeast of Mary Bay). Replicate samples (standard deviation <5%) were incubated in a temperature-controlled block at receiving water temperature (<10°C) and in an oven at 50°C.

displayed opposite behavior: more than 80% of control activity was knocked out by high-temperature incubation (Figure 13). Though measurements are few in number as yet, the method was unequivocal in selection against mesophilic bacteria. The results were consistent with growth of thermophilic bacteria within the vent conduits and their transport and expulsion into receiving waters of Yellowstone Lake. Even close to the orifice, population composition was adapted to the use of reduced mineral-derived substrates under mesophilic circumstances, leaving enrichable thermophile populations but at low proportion to total chemosynthetic bacteria. Thus, it is likely that very favorable habitats for detailed study of *in situ* living extremophile communities are present in the northern part of Yellowstone Lake. Ease of access relative to deep sea vents and a closer approximation to optimum growth conditions are significant factors when considering studies for early evolution and/or exobiological applications.

Microbial mats as persistent sources of chemolithotrophic activity. Though somewhat less tractable to quantitative analysis than vent water samples, visual evidence of microbial mats surrounding vents and fumaroles has been both ubiquitous (Marocchi et al. 2001; Remsen et al., this volume) and persistent from

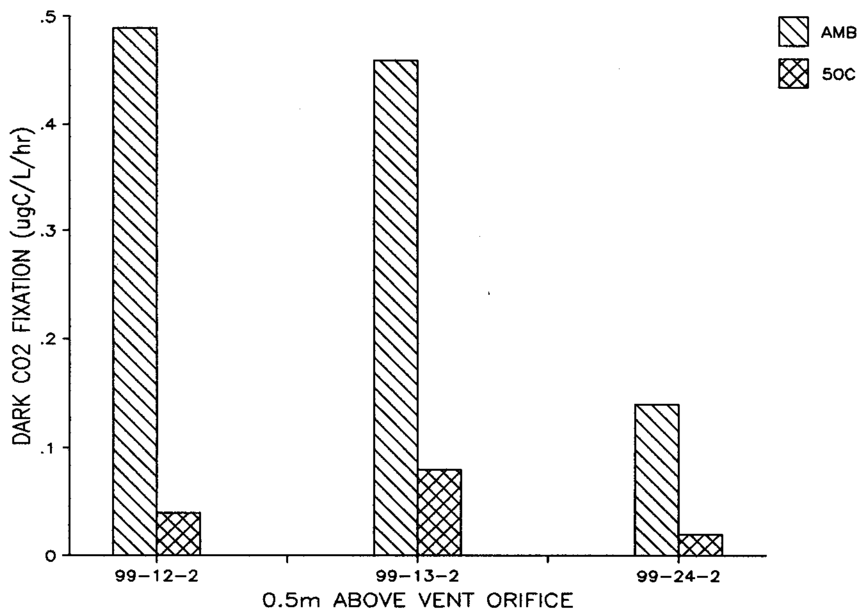

Figure 13. Elevated temperature greatly decreased bacterial dark $^{14}CO_2$ fixation in water samples collected at the top of the ROV arm, 0.5 m above the vent. Samples were incu - bated in parallel with vent orifice samples in Figure 12.

year to year. Microbial mats may be found on the sediment surface, on rock ledges overhanging vents, encrusting rooted plants in shallower water, or wherever a solid surface and dissolved mineral-laden waters come together. The very presence of entwined filaments of geochemical-oxidizing bacteria was often a clue to nearby vents and directed sampling efforts, particularly in the deeper canyons of Stevenson Island and Mary Bay. Because of their growth habit, mats could not be readily sampled with the ROV, but in 1994 SCUBA divers Lori Buccholz and Joel Kostka collected mat material in sterile Whirl-Pak bags from under an overhang of a Sedge Bay vent in late July. The mats were mildly homogenized to facilitate replicate sampling, and dark $^{14}CO_2$ uptake was measured in the presence of a variety of stimulants, primarily inorganic biomass nutrients (nitrogen, N as nitrate; and phosphorus, P as phosphate) and substrates of chemosynthesis (sulfur as thiosulfate, $S_2O_3^{=}$; nitrogen as ammonium, NH_4^+). As with some water samples, thiosulfate strongly stimulated chemosynthesis, while biomass nutrients or ammonium had no or only a minor effect on dark CO_2 fixation respectively (Figure 14). Although visible biomass was present in the samples, the rates of dark CO_2 fixation were also tenfold higher than most unamended vent water samples and were almost doubled by addition of a reduced sulfur compound, thiosulfate.

Summary: Photosynthesis and Chemosynthesis in Yellowstone Lake

The biogeochemical setting of Yellowstone Lake with its several areas of pro-

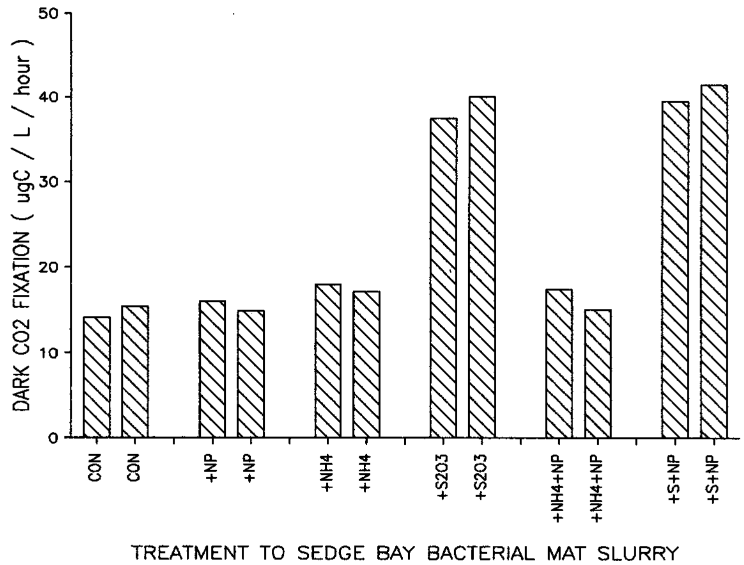

Figure 14. Vigorously chemosynthetic Sedge Bay bacterial mat slurries were stimulated further by thiosulfate addition. Supplements with inorganic growth nutrients nitrate + phosphate (+NP), ammonium (+NH_4), and combinations had little further effect.

nounced and persistent underwater hydrothermal venting provides an ideal setting for growth of mineral-oxidizing bacteria. They include representatives, many thermophilic, of the hydrogen-, reduced sulfur-, iron-, manganese-, and methane-oxidizing bacteria. Nitrifiers (ammonia oxidizers) may also be active, though few vents have been found to contain substantial concentrations of NH_4^+ in recent years. All but the methane-oxidizing bacteria assimilate carbon dioxide as the sole source of carbon for tissue. Using this assay for collective chemosynthetic activity, it was demonstrated that (1) both geochemical emanations and chemosynthetic bacterial activity were not ubiquitously distributed among Yellowstone Lake hydrothermal vents, but rather were focused in distinct regions; (2) a portion of bacteria in the vents themselves had thermophilic characteristics (enhanced or persistent production at 50°C); (3) bacteria growing in the immediate proximity of vents or in overlying waters often could be stimulated by addition of reduced sulfur compounds; and (4) slurries of white mat aggregates surrounding vents had very high rates of chemosynthetic production. Summarizing maximum rates of productivity for five years of sampling (Table 3), it was apparent that in most years vent water samples could attain rates of primary productivity (i.e., carbon dioxide assimilation into biomass) similar to that of surface photosynthesis by algae. Although access to enough vent samples for analysis of biological parameters was limited until 1997 when the syringe sampler was installed, the results still suggest that geochemical energy was sufficient to promote active, if sometimes localized, growth of bacterial populations.

Table 3. Summary of maximum rates of photo- and chemosynthesis in Yellowstone Lake, 1994–1998.

Parameter	Units	1994 Mid-July	1995 Early June	1996 Late July	1997 Mid-July	1998 Mid-July
Maximum surface photosynthesis	μgC/L/hr	6.9 (n = 1)	3.7 (n = 6)	4.8 (n = 9)	8.9 (n = 4)	4.6 (n = 17)
Maximum vent chemosynthesis	μgC/L/hr	3.2 (n = 1)	9.1 (n = 4)	N.D.	7.0 (n = 5)	1.6 (n = 13)
Maximum surface chemosynthesis*	μgC/L/hr	2.3 (n = 3)	0.11 (n = 6)	0.23 (n = 7)	0.23 (n = 5)	0.09 (n = 8)
Open water thiosulfate stimulation	X Control	50	7	2	20	4
River outflow discharge†	1000 ft^3/sec	<2	>4	>4	>5	>4

* Includes dark CO_2 fixation by algae.
† Data from United States Geological Survey Website: Gauging Station 06186500 at the Yellowstone River outflow, Fishing Bridge.

Most intriguing was the short visit in 1994, one of the two lowest-water years in the last decade (1992 being the other). During 1994, the entire basin north of Stevenson Island smelled strongly of H_2S, the beach at Mary Bay was nearly too hot to walk on, and fumarole bubbles rising through the water column off Stevenson Island broke on the surface to leave a yellow-white ring of presumed elemental sulfur from oxidation of bubble-borne H_2S. In surface samples from Mary and Sedge bays and in vertical profile at open-water Stevenson Island, dark CO_2 fixation was ten or more times that of typical dark rates for surface samples, and demonstrated strong thiosulfate stimulation. Only one vent was sampled (Sedge Bay), but it showed that under permissive conditions, chemosynthetic activity in the water column could be stimulated through physical mixing of vent-derived geochemicals to levels similar to near-vent samples. In years of high outflow, vents still provided oases of productivity capable of supporting limited animal-consumer biomass, even in deep waters where they would otherwise be absent.

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The Bridge Bay Spires: Collection and Preparation of a Scientific Specimen and Museum Piece

Russell L. Cuhel, Carmen Aguilar, Charles C. Remsen, James S. Maki,
David Lovalvo, J. Val Klump, and Robert W. Paddock

Abstract

Remotely operated vehicle dives on a site of unusual depth-sounder features unveiled a field of stalagmite-like spires of possible hydrothermal origin near the Bridge Bay marina. Fragments collected from the base of several spires were composed of very low-density, porous material resembling siliceous sinter. A National Park Service dive team retrieved a 2.5-ft tall specimen in 1999, and plans for cutting and distribution were made. After a computerized axial tomography (CAT) scan revealed the interior structure, the spire was sectioned using a high-pressure water-jet saw. One half, showing both exterior and cross-sectional surfaces, was sent to the National Park Service personnel at Yellowstone National Park for display purposes. The remaining half was shared between scientists at the University of Wisconsin–Milwaukee's Center for Great Lakes Studies and the U.S. Geological Survey in Colorado. The paper documents a stepwise progression from discovery to elucidation of the spire's structure.

Introduction

Yellowstone National Park has served the public as a source of wonder, amazement, and education for more than 125 years, yet has far from exhausted its bounty of stunning scientific discoveries. While some may be of purely scientific interest, many are suitable and appropriate objects of public appreciation as well. Geological phenomena are particularly appealing in both the scientific and visitor arenas. Many such treasures lie discreetly hidden below the frequently tumultuous waters of Yellowstone Lake (Marocchi et al. 2001), and it is clear that numerous revealing features have yet to be discovered. During the last five years, an incidental observation by National Park Service (NPS) archeologists in 1996 has been systematically pursued to finally produce a specimen of probable hydrothermal origin that will provide awe and insight to scientists and visitors alike.

That Yellowstone Lake harbors intriguing hydrothermal features should come as little surprise to anyone. Walking on the West Thumb geyser basin boardwalk, for example, it is not difficult to imagine Fishing Cone as being only one of a complex of underwater bubbling pots and geysers. Likewise, smoking, malodorous beaches of Mary Bay only hint at the wealth of active vents under the surface, though vigorous bubblers are clearly visible only a few yards from shore. Nor are all of the interesting features active today; in fact, there is much to be learned from relic structures that shed light on past geological processes. However, harsh conditions of Yellowstone Lake geothermal regions have restricted access to only a few experienced and persistent groups of explorers. Active collaboration between NPS and a long-standing program of the University of Wisconsin-Milwaukee's Center for Great Lakes Studies (CGLS) and Marquette University (Milwaukee, Wisconsin) with remote operated vehicle (ROV) contractor Dave Lovalvo succeeded in bringing one of the lake's secret riches to light.

Discovery of the Spires

The story began with a team of NPS archeologists searching parks nationwide for relics of previous inhabitants. During a 1996 acoustic survey of Yellowstone Lake for submerged artifacts in nearshore areas, they ran across an unexpected series of shallow depth soundings in about 60 ft of water near the Bridge Bay marina. Alerted by these NPS scientists, the CGLS team went to the site to investigate. The Bridge Bay area had received little attention because of its apparent lack of active hydrothermal venting, but the plot from the Furuno® depth sounder (Figure 1; 10 August 1996) piqued our curiosity. A seemingly straight line of tall features jutted abruptly out of an otherwise featureless plain, much as some geysers of the Old Faithful area protrude from barren landscapes. The form was much more suggestive of accretional (building up) rather than erosional (wearing down) action, possibly during long-past geological activity. Using one of the last dive days of the season, Tony Remsen, Jim Maki, and Dave Lovalvo deployed the ROV from the NPS research vessel *Cutthroat.* Their first dive landed near enough to the structures for rapid visual investigation.

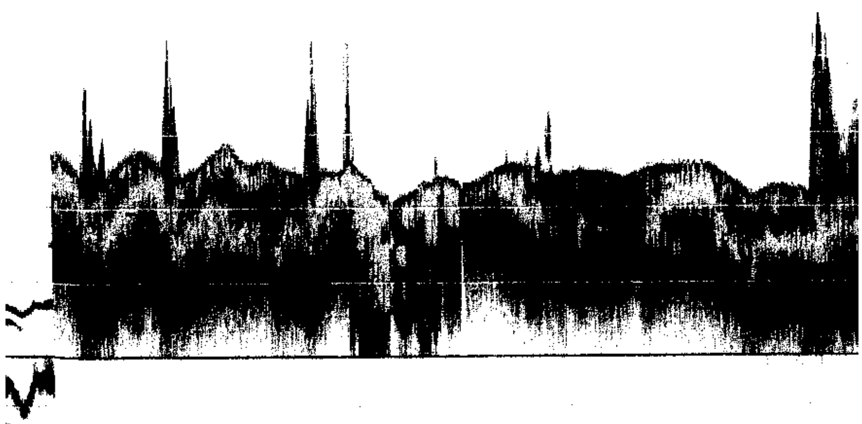

Figure 1. Bridge Bay spires are clearly visible on 1996 depth sounder charts from the R/V Cutthroat.

The visuals were stunning. Through the dim green "fog" of somewhat turbid nearshore water ghostly shapes emerged; up close, it suddenly became obvious that they were towering columns. Among the lot, graceful individual spires loomed like stalagmites (Figure 2), with clusters of spires resembling ancient

Figure 2. Backlit by green sunlight at depth, a solitary spire emerges from the turbidity at Bridge Bay in 1996. (Eastern Oceanics and CGLS)

castles interspersed among the string (Figure 3). Looming in the camera's lens, the structures varied from mere nubs to towers over 15 ft high, many covered with luxuriant growth. Well infused with natural sunlight at this depth (45–60 ft), large populations of algae covered the sides and tops. As we were to discover, a variety of animals, including colossal examples of freshwater sponges, also make the spire surfaces home (Marocchi et al. 2001). Common to the Yellowstone Lake geoecosystem, the organismal encrustation hides the true nature of the

Figure 3. Dual towers of a complex spire structure are encrusted with plant and animal growth. (Eastern Oceanics and CGLS)

underlying features. To understand what had been found, it was going to be necessary to take physical samples. The area also required some level of protection, as some evidence of damage (possibly from boat anchors, for example) was found during the initial video observation. A no-anchor zone was established by NPS, followed by negotiations to raise a piece of the spire field for scientific investigation.

Operating under a new two-year grant from the National Science Foundation (NSF) in 1998–1999, the CGLS team worked with NPS representatives to establish a procedure for obtaining and investigating a spire sample. Collecting even a small intact structure was well beyond the capabilities of the available ROV. Resource Management Coordinator Dan Reinhart agreed to arrange an expedition with Park Service divers to collect a specimen in the late summer of 1998. Due to scheduling constraints, the dive would have coincided with the last working day of the group, which would have endangered satisfactory preparation of the sample for transportation and analysis. The collection was postponed until the 1999 field season.

The spire fields and underwater vent work of the CGLS group on the NSF grant expanded to include involvement by the U.S. Geological Survey (USGS) and its associates. The USGS group, led by Drs. Lisa Morgan and W.C. "Pat" Shanks, had already done extensive mapping of Yellowstone Lake's magnetic properties. Further inspired by the Bridge Bay structures, they mounted a detailed survey of bottom topography during the summer of 1999. The first transects, in the northern basin area including Mary and Sedge Bays, led to discovery of many more, significantly larger, and extensive spire fields reaching to 100 ft tall (Elliot 2000). These observations all the more enthused the group about collecting a sample for study. The park likewise wished to obtain a display specimen for one of the visitor center's lake exhibits.

Collection of a Spire Specimen

Late in the summer of 1999 these wishes were fulfilled. On a somewhat dreary and overcast day, Dan Reinhart and Park Service divers Wes Miles (dive captain), Rick Mossman, and Gary Nelson boarded a landing-craft-like vessel captained by Dave Hall and headed out with the *R/V Cutthroat* to the Bridge Bay site. Observers from the CGLS team and USGS were also aboard both vessels. Once the features were located by sonar, the divers donned their cold-water gear (Figure 4), slid delicately off the bow into the water, checked their underwater cameras, and descended into the murky deep. From above, we could follow their progress by the trail of bubbles. Twice they surfaced, once with bags of water collected next to the base of a spire, and once bringing small pieces of "spire rubble" from scraps possibly damaged by previous anchoring. The spongy, porous, fragile fragments aroused substantial excitement: these were not at all like the hard pipes we had so often collected with the submersible! Clearly different mechanisms had been involved in the creation of these spires.

Somewhat more disappointing words then came from the divers: the small intact spire they wanted to collect was firmly rooted in the muck and couldn't be

Figure 4. NPS divers (L–R) Rick Mossman, Gary Nelson, and Wes Miles discuss sampling plans at the Bridge Bay site. (Russell Cuhel)

budged. One more try, please! Rob Paddock quickly fashioned a rope sling that would provide support for the probably very delicate sample—if it could be freed from its ancient home. After a seeming eternity, the large air bubbles at the surface were pushed apart by first a gloved hand and then a rubber-encased head, with thumbs up. The divers and boat crew struggled to lift the catch of the day out of the water and into a bubble-wrap-lined cooler (Figure 5). Much like pulling a tooth, the divers had rocked the 2.5-ft mini-spire until it broke loose

Figure 5. In a cooler on board, the intact 2.5-ft specimen exhibits a white zone of attach - ment to an adjacent structure near the base. (Russell Cuhel)

from confinement. The site of adjoinment to other structures, well below the sediment–water line, was evident as an exceptionally white spongy area on one side (Figure 5). What a find! The divers had a right to gloat over their day's work. Everyone present, including scientists from CGLS, Marquette University, USGS, and NPS, were anxious to examine the collection, but a rocking boat was certainly not the place to do it!

The spire was unwrapped on a desk at the Lake ranger station. Maki and Carmen Aguilar picked at the nooks and crannies for leeches, worms, sponges, and samples for bacterial analysis. Shanks, Morgan, and J. Val Klump prodded chips and fragments, looking at the intriguing layered structure of the apparently siliceous (glass-like) form. All marveled at the complicated swirls of mineral deposition visible on the exterior. What mysteries would be solved, or would arise, from examining the interior? Were secrets of the origin of spires and some history of Yellowstone Lake lying only millimeters away in the center? Once again, patience was required. Even during the short evening celebration, chips dried out to amazing lightness and could be crumbled easily between the fingers. It was evident that special precautions would be necessary to ensure that everyone received an uncompromised sample for their specific uses.

The spire was obviously much stronger when saturated with water, so for transport by truck to Milwaukee the intact specimen was heavily encased in bubble wrap and soaked with Bridge Bay bottom water. Upon return to CGLS, there was discouraging news from NSF: the renewal proposal for work in Yellowstone Lake had not been funded. While this did not dampen the enthusiasm for working up the year's collections, it did require a dedicated effort to secure support for further research. During 2000, the spire waited in a walk-in refrigerator while proposal-writing took precedence. At last we obtained three more years' worth of support through NSF's Life in Extreme Environments program. Also during 2000, Morgan and Shanks garnered funding from USGS and NPS to continue their high-resolution mapping of the lake bottom and magnetic anomalies. During the summer they surveyed the area between West Thumb and Bridge Bay, as well as the deep canyons east of Stevenson Island. The impetus was still strong for analysis of the spire, but how should the very fragile piece be handled? It was still completely unknown what the interior structure might be.

Preparatory Investigations

Is there a doctor in the house? By chance, Jim Maki's wife, Kay Eileen, is a doctor with St. Luke's Hospital in Racine, Wisconsin, and they came up with the idea of running a non-destructive CAT scan (computerized axial tomography; a method using X-rays to analyze density) on "our baby." The anxious "parents"—Maki, Remsen, and Klump—waited in the control room as the intact specimen was probed at 5-mm intervals. Almost 150 images were obtained, providing a detailed picture of the interior-density structure upon which we would base our sectioning. One such view, taken just above the sediment–water interface portion, is shown in Figure 6. In this rendering, dense areas are darker, while soft, porous material is lighter. The location of the section is shown as a line about

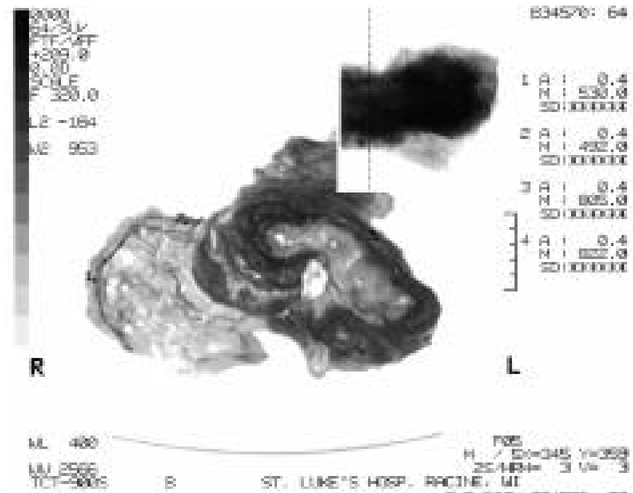

Figure 6. An X-ray cross-section of the spire at about one-third of the length from the base (vertical line on inset) reveals spongy, low-density (lighter shades) sinter in the bulb to the left side. The adjoining main spire section shows rings of higher-density material (darker shades) surrounding sinter with possible pores or conduits (white). (St. Luke's Hospital, Racine, Wisconsin)

one-quarter of the way up from the base (upper right). In the main image, the left-hand, lighter bulb is the white area in Figure 5 above, and extends to only about one-third of the height of the main spire component. The exposed edge of this section was very low-density, exceptionally white sinter with thin layers of hard, white crust meandering throughout. This portion appears almost to exude off the side of the main spire to the right. The main segment had a substantially denser external structure (dark oval), with several nearly white circular features that might have indicated vertical conduits within the column. These possible tubes did not continue to the point of the spire; rather, they became smaller and finally vanished about half-way from the bottom.

Collectively, the images provided a pre-cutting, cross-sectional map of the interior, and we opted to make four cuts to provide (1) one-half of the spire with cross-section for NPS to display; (2) one-quarter for the U.S. Geological Survey for their mineralogical analyses; and (3) one-quarter for the CGLS research team. The question now was, how? It was indisputable that the material was extremely fragile. Several concerns included the use of cutting oils, binding of the spire while moving across a cutting table, and possible fracturing of the material from the stress of cutting. Because it appeared to be primarily composed of silica (glass-like material), we consulted George Jacobson, a glass artist at Les'Glass in New Berlin, Wisconsin. Jacobson had just produced a fabulous etched rendition of a deep-sea hydrothermal vent scene on glass shower doors for us, and he was world-renowned for his leaded glass panels and other forms of plate glass work. Given the pictures of the specimen and the goals we had set, he instantly recommended Scott Cole, customer service representative of a water-jet saw facility at KLH Industries in Germantown, Wisconsin.

During our initial visit, Scott described the advantages of the water-jet saw for our application. It consists of a fine-orifice nozzle (3/64-in) through which a mixture of high-pressure water (55,000 lbs per in^2) and finely ground garnet is directed at the subject material from close range. Powerful enough to do filigree work in stainless steel while leaving satin-smooth edges, the instrument has several major benefits. First, there is no blade to bind on the work. The water jet cannot snag on regions of suddenly changing composition. Second, the nozzle is moved over the work, rather than pushing the work through the cutting edge. Third, the composition of the cutting material (water) and the abrasive (garnet) are chemically pure compared with that of machine cutting oils, and can be readily analyzed. The water is not recirculated, so the material is not in contact with waste from previous jobs. Fourth, the material need not rest on a hard surface. The tool cuts into a large water bath with wood slats across it. The work may be placed on the wood, on foam or any softer material, or on a bed of tissue: the saw will cut through that as well. A disadvantage for us is that in thick material, the physical broadening of the stream with distance means some loss of material at the bottom of the cut. Watching a current job with stainless steel, we were convinced that a test with some of the larger fragments was in order.

The first test piece was a nodule about 3 inches thick. Although it was somewhat more dense than the spire itself, the hard mineral component seemed to have the greatest degree of difficulty. This kind of material was apparently well represented around the outer crust of the spire, based on the acoustic scans. Jet saw technician Brian Bagget helped us nestle the fragment into a foam bedding on the cutting pond, after which we discussed set-up. Normally the jet saw is fully automated. A design is read into a computer aided design (CAD) file in the computer, registration points are identified on the work, the height above surface is set, and the program runs the nozzle through the x–y coordinates of the design much like a plotter on paper. For our job, the cut itself was to be linear, and it was the height above base, to follow the contours of the spire surface, that had to be varied. With more than nine years of jet saw operational experience, Bagget felt that manual control of the z-axis (height of the nozzle) during a constant-rate, straight-line run would work best. He would be able to keep the nozzle close to the surface, minimizing stream broadening, without having to make a large number of thickness measurements with subsequent programming. His effort with the fragment proved his expertise. A very flat cross-section was obtained that preserved both the detail of interior pits and pockets, and maintained intact areas near the upper edge where fractures left thin brittle plates of mineral. A second piece of smaller size but representing the silica sinter (light, porous material) also cut very cleanly and without any “shivering” that might have obliterated delicate interior features. The demonstration was convincing that this was the method of choice. An appointment for an estimated three-hour session with the actual spire was made, and we took samples of the water and the garnet abrasive for analysis.

Sectioning of the Spire for Science and the Public

To expose the interior of the sample to best advantage while retaining an undisturbed external segment for each sample, the plan was to cut across the rough bottom, or "root," to provide a flat base and cross-sectional view. Then the low-density silica "bulb" on the side would be removed. A subsequent longitudinal section would provide a full-length half-spire for the NPS museum piece, and lengthwise cutting of the remaining half would give USGS and the Milwaukee team each a representative section for analysis. Cole helped set up the spire on the cutting pond for bottom removal (Figure 7). Using a straight-line progression,

Figure 7. KLH representative Scott Cole (right) discusses set-up of the water-jet saw with the author prior to sectioning of the main specimen. The light–dark transition was the mud-line in situ. (Carmen Aguilar)

Bagget kept the nozzle as close as possible to the work, which was especially important at the fragile trailing edges of the cuts (Figure 8). The best support was thin plywood with a sheet of light foam packing material under the spire because the jet cut through the support with minimum backsplash.

Anxious as we were, the first cut across the base turned out beautifully. Figure 9 shows the fidelity of the CAT scan (Figure 6) to actual composition, with a very low-density silica mass (the "bulb" to the left) and the harder, apparently conduit-like structure to the right. The dark areas surrounding the orifices resemble iron sulfide precipitates, though analysis is currently in progress. The sample was rotated 90° and the low-density bulb was cut off parallel to the long axis of the specimen. Using the large flat edge for stabilization, a lengthwise axial cut was started up the center of the main spire. Slight expansion of the jet stream made a thin but decidedly V-shaped channel (Figure 10), but material loss was mostly confined to the softer silica material rather than the conduit segment of greatest interest. Bagget carefully maneuvered the nozzle close to the specimen all along

Figure 8. The water-jet saw finishes a transverse section across the bottom of the spire with the nozzle held close to the surface of the object. (Russell Cuhel)

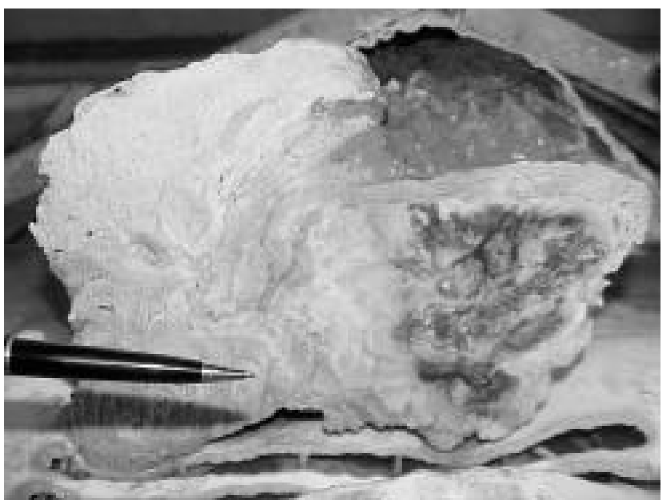

Figure 9. Cross-section of the spire viewed from the bottom reveals the porous sinter on the left and the harder main spire with dark precipitates to the right. Pen segment is 3 inches long. (Russell Cuhel)

the path (Figure 11). The water-jet saw was especially valuable at the very tip of the spire where the delicate silica was most susceptible to disintegration (Figure 12). Moving this piece through a conventional saw blade would have been a great risk to the integrity of the fine structure near the tip.

Excitement and suspense replaced anxiety as the two pieces were carefully pulled apart. Was this form the result of accretion by seepage of geothermally enriched water? Was it a product of vigorous venting through an orifice? Or was

Figure 10. Early during the axial cut along the length of the spire, stream spreading is evi - dent for the very thick base. (Russell Cuhel)

Figure 11. Technician Brian Bagget works the height adjustment to keep the nozzle as close to the specimen as possible. (Russell Cuhel)

it simply mounded into shape from adjacent sediment? The first view of the interior revealed a definitive conduit-like feature extending from the base to about one-third of the way to the tip. A thin shell of hardened material surrounded a pipe plugged with granular reddish-brown material, perfectly preserved in the sectioning. A close-up of the base region (Figure 13) shows the conduit and its contents clearly, but the feature disappeared half-way up the length of the tower. Surrounding the pipe, and accounting for most of the upper half of the spire, was more of the lower-density silica-like material. There were bands of dark precip-

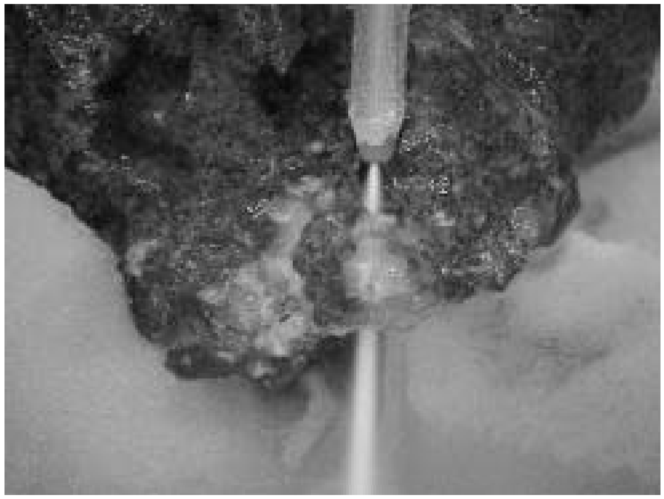

Figure 12. No sample disintegration occurred even as the cut approached the thin, deli - cate tip of the main spire segment. (Russell Cuhel)

Figure 13. A close-up of the presumed conduit at the base (left) of the spire shows the thin enclosure filled with heterogeneous material. (Russell Cuhel)

itate throughout the porous component, including two apparent “shells” at different distances from the exposed exterior surface. No single mechanism appeared to explain the structure; rather, it appeared as if a combination of geochemical and geophysical forces worked to shape the object. The intrigue further enhanced the value of the museum piece for NPS. In cross-section this half elegantly displays the interior structure of the spire, and, when rotated 180°, the original view of an undisturbed specimen as seen in Yellowstone Lake is retained.

The final cut would provide the material for scientific research at the U.S. Geological Survey and for the Milwaukee team. The “less beautiful” of the two halves was supported over the cutting pond and the idle nozzle run along the center of the conduit to the tip, with alignment perfected by Bagget. Starting at the base, cutting this thinner section resulted in much lower loss of material on the downstream edge of the work (Figure 14), and each now-quarter spire contained components of all of the visually apparent features for detailed investigation.

Figure 14. For the thinner half-section, stream broadening was much less pronounced during cutting even near the base. (Russell Cuhel)

Again the tool proved valuable, as the “blade” separated two sections in the very thin and fragile spire tip area.

Final Disposition of the Sections

An exploded view of the product is shown in Figure 15. A line from the sediment–water interface can be seen clearly on the forward sections. New homes of the pieces are (clockwise from center) Yellowstone National Park, Milwaukee research team, USGS, and Milwaukee team. Of the two research quarters, the one containing both the conduit and the adjoining section of silica bulb was sent to USGS scientists while the smaller quarter and disjoined bulb fragment were retained in Milwaukee. Among the many analyses underway are high-resolution electron microscopy with elemental analysis, radio- and stable isotopic age determination and geochemical formation studies, mineralogical examination, and others. Results of the combined efforts will resolve some of the mysteries surrounding the formation of the spires, as tentatively described in a *Science* “News Focus” article of mid-2001 (Krajick 2001).

Resource Considerations

Detailed scientific analysis is not necessary to recognize that the Bridge Bay

Figure 15. Spire segments arranged in exploded view as they existed in the field, emphasizing the contrast between exterior (forward, right) and interior (rear) composition. (Russell Cuhel)

spires are both awesome and delicate. Only recently discovered, though probably thousands of years old (research in progress), it is now clear that there must be a balance struck between protection of the resource and access for public viewing. In the words of Yellowstone Center for Resources Director John Varley: "It would be the most spectacular part of the park, if you could see it" (Krajick 2001). In the lake, the spectacular views (Figure 2 and Marocchi et al. 2001) are shallow enough for sunlight to penetrate, but are accessible only by SCUBA diving. Even so, just the seemingly rugged exterior is visible, and it will be only through the park's display that visitors can glean the complexity of the spires' long history. With the hundreds of much larger spires later discovered by USGS in the northern end of the lake (Elliott 2000), there exist several opportunities to develop a "spire preserve." A remaining challenge will be to provide viewing possibilities without the requirement of diving, thus increasing the breadth of public access while simultaneously protecting the features from accidental or intentional vandalism. This challenge extends beyond the spires to numerous and diverse hydrothermal geoecosystems throughout the lake (Marocchi et al. 2001; Remsen et al., this volume). For example, NPS divers or ROVs might collect a video survey of spire fields which would be played at a visitor center from CD-ROM or endless-loop video. Many other scenarios may be envisioned. For certain, the events depicted in this presentation have elevated the Bridge Bay spires from "mounds of rubble" to geological features containing some of the keys to understanding Yellowstone Lake's past. Research in progress by all involved agencies will serve to augment the already great contribution of Yellowstone Lake to awareness of Earth's geoecosystem functions.

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Natural Variability in Annual Maximum Water Level and Outflow of Yellowstone Lake

Phillip E. Farnes

Abstract

The water level in Yellowstone Lake varies each year in response to differences in the winter's snowpack accumulation, spring precipitation, and air temperatures. Restriction at the outlet of Yellowstone Lake retards the outflow, and water backs up in the lake during periods of high inflows. The U.S. Geological Survey started publishing Yellowstone Lake elevations in 1922 and outflows in 1926. The gage for observing the lake's elevation was originally located at the Lake Hotel dock. It was moved 1,500 feet southwest to the National Park Service dock on 17 June 1940. On 1 October 1966, the gage was moved to Bridge Bay marina, where it is currently located. The U.S. Geological Survey stopped publishing gage heights of Yellowstone Lake in 1986, but the Bridge Bay ranger staff and boating concessionaire employees have continued to make periodic water level observations. Since the early 1950s, the dates of Yellowstone Lake's freeze-up and melt-out have been obtained from ranger, resource, and marina caretaker staff. Since 1926, the highest water level recorded was 7.72 ft on the Bridge Bay staff gage in 1997. The lowest annual maximum was 2.40 ft in 1934. The 1971–2000 average annual maximum water surface elevation on the staff gage is 5.46 ft. During winter months, readings are limited, but water levels that have been recorded are usually near or below zero on the staff gage. A summary of annual maximum gage readings and outflow and dates observed from 1926 through 2001 is presented. Freeze-up and melt-out dates are available for most years since 1951. Impacts of the 1988 fires on Yellowstone Lake water surface elevations are discussed, as are methods of forecasting upcoming elevations from snow survey and precipitation data. Recommendations for future observations are presented.

Introduction

The water level in Yellowstone Lake varies in response to the winter's accumulation of snowpack within the drainage, amount of spring precipitation, and temperatures during snowmelt. The restricted outlet causes water to back up in the lake during periods of high inflow. Water surface elevations and outflow have been observed since 1922 by various entities. Observers have recorded freeze-up and melt-out dates for most years since 1951. The water level in Yellowstone Lake affects water temperatures in the Yellowstone River, spawning dates of cutthroat trout, success of spawning runs, the fishing success of bears, boating through the Bridge Bay channel, nesting success of white pelicans on Molly Islands, streamflow over the Upper and Lower Falls, downstream flows in the

Yellowstone River, shoreline erosion, and many other resources in the area. The fires of 1988 had some influence on Yellowstone Lake elevations and outflows.

Study Area

Yellowstone Lake is located in the southeastern part of Yellowstone National Park and covers an area about 136 mi^2 (352 km^2) depending on the level of water in the lake. There is no artificial regulation of lake levels. The 1,006-mi^2 (2,606-km^2) drainage area is the headwaters of the Yellowstone River, a tributary of the Missouri River. The highest point in the watershed is 12,156 ft (3,705 m) at Younts Peak in the southernmost part of the Yellowstone River headwaters. The U.S. Geological Survey (USGS) established a stream gage at the outlet of Yellowstone Lake in 1922, but only gage heights were recorded through the 1925 water-year. Outflow was measured starting in the 1926 water-year, and these data continue to be recorded and published by USGS. Elevation at the stream gage location about 450 ft (137 m) downstream from Fishing Bridge is approximately 7,730 ft (2,356 m). A separate gage for lake level observations was established at the Lake Hotel boat dock on 7 October 1921. On 17 June 1940, the lake elevation gage was moved 1,500 ft (457 m) southwest to the National Park Service (NPS) boat dock. On 1 October 1966, the gage was moved approximately 2 mi (3.2 km) southwest to the Bridge Bay marina docks. This location is about 3.7 mi (6 km) from the outlet. The datum of these gages was 7,729.51 feet from 1926–1932 and has been 7,729.45 feet since. In 1986, USGS stopped publishing the records. Gage readings have been observed since then by staff from the Bridge Bay ranger station, Yellowstone National Park resource division, and Bridge Bay marina boating concessionaire. Restriction near the outlet causes the water level in Yellowstone Lake to rise when the inflow exceeds the outflow during spring runoff. The 1961–1990 average annual precipitation for the drainage was 38.2 in (971 mm) (Farnes et al., in press) that produced an average 1961-1990 annual water-year outflow of 966,000 acre-ft (1,192 $m^3 \times 10^6$). Since 1926, this annual outflow has varied from 494,000 acre-ft (609 $m^3 \times 10^6$) in 1934 to 1,631,000 acre-ft (2,012 $m^3 \times 10^6$) in 1997. About 59% of the annual outflow occurred during the period of April through July. During the Yellowstone fires of 1988, 21% of the watershed had canopy burn. Increase in annual outflow as result of the fires was estimated to be about 3.2% (Farnes et al., in press).

Methods

Data have been obtained from USGS Water Supply Papers, the Natural Resources and Conservation Service (NRCS) database in Portland, Oregon, Yellowstone National Park archives, and from the park's resource management, ranger, and concessionaire staff. Missing records in 1983 (outflow), 1987 and 1988 (both elevation and outflow), and 1989 (elevation) have been estimated using the relationship between outflow and Yellowstone Lake elevations, outflow and downstream flows at the Corwin Springs gage, and outflow and snowpack and precipitation. In some years, the maximum outflow or staff gage readings extends for more than one day. Dates shown in Table 1 are for the latest day.

Levels from a known benchmark to the staff gage at Bridge Bay marina have probably not been run since the USGS discontinued observations in 1986. The

Table 1. Dates of freeze-up, ice-off (melt-out), maximum daily outflow, and maximum lake elevation for Yellowstone Lake, 1926–2001. Volume of maximum daily outflow is given in cubic feet per second (cfs). Annual maximum elevation given in feet, as measured on Bridge Bay staff gage.

Water-year	Date of freeze-up	Date of ice-off	Maximum daily outflow, cfs (date)	Maximum lake elevation, ft (date)
1926			3,200 (Jun 14)	3.67 (Jun 15)
1927			7,420 (Jul 01)	6.12 (Jun 30)
1928			5,680 (Jun 10)	5.25 (May 31)
1929			3,700 (Jul 05)	4.00 (Jul 02)
1930			3,780 (Jun 26)	3.95 (Jun 25)
1931			2,480 (Jun 19)	3.20 (Jun 19)
1932			5,570 (Jul 05)	5.00 (Jul 05)
1933			4,520 (Jun 30)	4.42 (Jun 30)
1934			1,740 (Jun 22)	2.40 (Jun 16)
1935			4,360 (Jul 09)	4.40 (Jul 06)
1936			4,690 (Jun 19)	4.53 (Jun 19)
1937			3,590 (Jul 01)	3.84 (Jun 28)
1938			5,950 (Jul 02)	5.32 (Jul 03)
1939			3,230 (Jul 09)	3.68 (Jul 09)
1940			3,590 (Jun 23)	4.04 (Jun 21)
1941			2,750 (Jun 28)	3.48 (Jun 27)
1942			3,890 (Jul 13)	4.41 (Jul 09)
1943			6,900 (Jul 10)	6.26 (Jul 10)
1944			3,450 (Jul 10)	4.03 (Jul 10)
1945			3,940 (Jul 17)	4.48 (Jul 20)
1946			3,700 (Jun 24)	4.20 (Jun 19)
1947			4,490 (Jul 11)	4.78 (Jul 14)
1948			5,580 (Jun 19)	5.45 (Jun 20)
1949			5,260 (Jun 23)	5.15 (Jun 23)
1950			6,120 (Jul 11)	5.76 (Jul 12)
1951		May 18	5,090 (Jul 10)	5.18 (Jul 11)
1952	Dec 26	May 16	5,340 (Jun 15)	5.25 (Jun 16)
1953	Dec 25	May 20	4,240 (Jul 06)	4.58 (Jul 07)
1954	Jan 11	May 18	5,580 (Jul 05)	5.52 (Jul 02)
1955		May 27	4,090 (Jun 30)	4.66 (Jul 01)
1956	Dec 14	May 25	7,570 (Jun 21)	6.54 (Jun 18)
1957	Dec 23	May 29	5,270 (Jul 04)	5.32 (Jul 04)
1958	Dec 31	May 21	3,500 (Jun 13)	4.24 (Jun 24)
1959		May 27	5,590 (Jun 28)	5.47 (Jun 30)
1960	Dec 18	May 22	3,210 (Jun 21)	4.05 (Jun 22)
1961	Dec 11	May 27	3,690 (Jun 20)	4.43 (Jun 22)
1962	Dec 10	May 21	5,780 (Jul 02)	5.73 (Jul 01)
1963	Jan 12	May 30	5,230 (Jun 25)	5.50 (Jun 26)
1964	Jan 08	May 29	6,420 (Jul 09)	6.06 (Jul 09)

continued

Table 1 (continued)

Water-year	Date of freeze-up	Date of ice-off	Maximum daily outflow, cfs (date)	Maximum lake elevation, ft (date)
1965		May 28	6,820 (Jul 11)	6.47 (Jul 11)
1966	Jan 16	May 21	3,570 (Jun 24)	4.64 (Jun 25)
1967		May 31	6,590 (Jul 09)	6.28 (Jul 06)
1968	Dec 15	Jun 02	4,600 (Jun 30)	5.28 (Jun 30)
1969	Dec 21	May 17	4,500 (Jun 08)	5.24 (Jun 29)
1970	Dec 28	Jun 04	6,460 (Jun 30)	6.33 (Jun 30)
1971	Dec 14	May 31	8,140 (Jun 29)	7.06 (Jun 30)
1972	Dec 28	Jun 02	6,880 (Jun 24)	6.38 (Jun 24)
1973	Dec 10	May 27	3,460 (Jul 01)	4.37 (Jul 01)
1974	Dec 24	May 27	9,120 (Jun 30)	7.34 (Jun 30)
1975	Jan 01	Jun 07	6,360 (Jul 14)	6.06 (Jul 15)
1976		May 21	5,380 (Jul 12)	5.68 (Jul 07)
1977		May 13	2,130 (Jun 20)	3.45 (Jun 22)
1978	Dec 21	May 17	5,400 (Jul 12)	5.74 (Jul 12)
1979	Dec 28	May 27	3,710 (Jul 02)	4.78 (Jul 02)
1980	Dec 29	May 10	3,770 (Jul 06)	4.78 (Jul 09)
1981	Jan 12	May 19	4,250 (Jun 28)	5.09 (Jun 29)
1982	Jan 07	May 26	7,670 (Jul 12)	7.00 (Jul 09)
1983	Dec 15	May 30	4,700 (Jul 11)	5.40 (Jul 11)
1984	Dec 22	May 31	5,080 (Jul 08)	5.74 (Jul 10)
1985	Dec 06	May 21	3,470 (Jun 19)	4.66 (Jun 25)
1986	Dec 11	Jun 04	7,360 (Jun 20)	7.01 (Jun 19)
1987	Dec 16	May 08	2,000 (Jun 16)	3.55 (Jun 16)
1988	Dec 24	May 19	2,150 (Jun 21)	3.70 (Jun 21)
1989	Dec 18	May 18	4,470 (Jun 22)	5.20 (Jun 22)
1990	Dec 30	May 20	4,290 (Jul 03)	4.95 (Jul 05)
1991	Dec 21	Jun 01	5,670 (Jun 22)	5.74 (Jun 22)
1992	Dec 17	May 08	2,780 (Jun 30)	3.94 (Jul 01)
1993	Jan 04	May 28	4,700 (Jun 23)	5.04 (Jun 24)
1994	Dec 27	May 16	3,000 (Jun 10)	3.92 (Jun 12)
1995	Dec 25	Jun 03	5,730 (Jul 13)	5.70 (Jul 13)
1996	Dec 01	Jun 03	8,730 (Jun 28)	7.08 (Jun 24)
1997	Dec 19	May 20	9,930 (Jun 19)	7.72 (Jun 22)
1998	Dec 26	May 15	4,750 (Jul 08)	5.20 (Jul 11)
1999	Jan 26	May 29	6,720 (Jun 27)	6.44 (Jun 29)
2000	Dec 28	May 06	4,250 (Jun 14)	4.94 (Jun 08)
2001	Dec 27	May 15	2,520 (Jun 14)	3.56 (Jun 16)
average, 1971-2000	Dec 24	May 23	5,200 (Jun 29)	5.46 (Jun 29)

staff gage was replaced at the same elevation and location on 25 September 1998 because ice had destroyed some numbers on the lower portion of the gage. Double-mass analysis was used to compare annual maximum outflow with the highest water levels of Yellowstone Lake and the maximum annual outflow with the annual weighted snow and precipitation values for period of record.

Results

Data for Yellowstone Lake freeze-up, melt-out, maximum annual outflow, and maximum water level are shown in Table 1 for water-years 1926 through 2001. The water-year starts on October 1 and goes through September 30. Some data were estimated, as noted above. Double-mass analysis comparisons between maximum daily outflow and staff gage readings of water surface do not show any significant breaks for the period of record. However, there are some differences associated with each individual staff gage location. Analysis using double-mass regression suggests that the annual maximum lake level since the 1988 fires may have been reduced slightly even though the total inflow volume increased. This was due to increased melt rates in the fire-generated openings in the forest canopy, which spreads the snow melt over a longer period due to the increase in percentage of open stands (McCaughey and Farnes 2001). Freeze-up and melt-out dates are functions of air temperatures and early-winter water levels in Yellowstone Lake. However, no detailed analysis has been performed to develop a relationship. Assuming low-water levels near zero on the staff gage around the time of ice-off, the spring rise in the lake water level over the past 75 years has varied from about 2.5 ft (0.7 m) to 7.75 ft (2.4 m), with an average annual rise of about 5.5 ft (1.7 m). The maximum elevations of the water surface in Yellowstone Lake and the maximum outflow from Yellowstone Lake are well correlated (R^2 = 0.927) for the entire period of record (1926–2001) for the staff gage at three locations. Separating the correlations for period of record at each gage location improves the R^2 to 0.989, 0.971, and 0.970 for the three locations.

Summary

Both the outflow and maximum water surface elevation of Yellowstone Lake for each year are functions of the winter's snow accumulation and spring precipitation inputs, and vary significantly from year to year. Yellowstone Lake's water levels and outflows have a direct effect on many of the resources in the vicinity of the lake or downstream. Water temperatures are suppressed in heavier-snowpack years as meltwater draining out of the snowpack is near 32°F (0°C). These suppressed stream and lake temperatures delay emergence of salmon flies and spawning of cutthroat trout. Success of spawning runs has been related to runoff and can influence recruitment of cutthroat trout (Farnes and Buckley 1964). Streamflows during spawning runs affect success of bears feeding on migrating and spawning cutthroat trout (Dan Reinhart, personal communication). High and low lake levels affect tour boating and boat rental operations by the Bridge Bay concessionaire (Hal Minugh, personal communication). Nesting success of white pelicans has been greatly diminished during years with high water levels because the Molly Islands are almost completely covered with water then (Terry McEneaney, personal communication). Shoreline erosion can be accelerated in high-runoff years particularly if accompanied by wind during times of the highest water levels. Downstream water users have been affected by low-water years (e.g., by shortages of in-stream flows and irrigation water supplies).

Recommendations

Since the elevations of the water surface in Yellowstone Lake affects many resources, it would be desirable to have the Montana office of the USGS Water Resources Division resume responsibilities for Yellowstone Lake level observations at the Bridge Bay gage and make these data available to the public in a manner similar to that of the outflow observations. This would provide a level of accuracy comparable with that of earlier records.

Have the Montana office of NRCS develop procedures to forecast upcoming elevations of Yellowstone Lake at the Bridge Bay gage using snow–water equivalent, soil moisture under the snowpack, and spring precipitation and make this information available on their Web page in a format similar to that of other water supply forecasts. This would provide warning of low or high water levels that could affect resources associated with lake elevation. It would also permit researchers advance time to arrange for collection of any related data that might be pertinent to their study.

Suggest that researchers consider the impacts of natural variability in inflow, lake levels, and outflow when researching phenomena associated with Yellowstone Lake.

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Rich in Resources, Short on Cash: How Philanthropy Helps Yellowstone and Other National Parks

Kézha Hatier-Riess

Introduction

The purpose of the Yellowstone Lake Conference was to encourage awareness and application of wide-ranging, high-caliber scientific work on Yellowstone Lake. The lake basin is one of Yellowstone's greatest resources and is increasingly being recognized by the scientific and conservation world for its significance. Because the full implications of the changing geology and ecology of the lake area are still unknown, the opportunities for research and discovery are many. Unfortunately, federal funding for science-related projects in national parks is insufficient to meet the growing needs of research. If studies on the relationships between the regional landscape and its resident species are delayed in Yellowstone and other national parks until federal funding is available, irreplaceable resources and information could be lost forever.

Due to a lack of human development, as well as limits on recreation, protected lands such as national parks are great laboratories for research. With the ceaseless growth of urban areas, these protected lands are becoming more important to our civilization. Yet high-quality research is often expensive and, though important, is usually not as high a priority for federal funding as are the reconstruction of roads, the reroofing of leaky buildings, or the repair of hazardous structures. Furthermore, an important part of research is the use of the results. Even if a research project is federally funded, there is often limited or no funding available to disseminate the valuable information that is discovered.

Increasingly, philanthropy is being used to help the National Park Service (NPS) protect ecosystems, improve education, fund research projects, and inform the public about the results of the significant scientific work that is happening in Yellowstone and other national parks.

The History and Current Role of Philanthropy in Protecting National Parks

The national park idea was started in the United States and has since spread throughout the world to help protect in perpetuity some of our earth's most precious lands. The donating of private money to public causes is also primarily an American phenomenon. Philanthropy played an important role in helping to establish and protect national parks and in creating the NPS. Before the NPS was established in 1916 and Congress appropriated funds each year to run parks—and later, when land acquisition needs to expand the national park system exceeded available federal appropriations—private donations were responsible for substantial additions and funding to parks.

Barry Mackintosh, a former NPS historian, lists a number of examples of the earliest philanthropic efforts in national parks in his paper "Philanthropy and the National Parks" (Mackintosh 1998). The following paragraph highlights some examples from his paper, which is an excellent summary of the role of philanthropy in national parks.

Among the earliest large donations were a 1907 land donation from Mr. and Mrs. William Kent, which allowed for the creation of Muir Woods National Monument. Another land donation came in 1916 from a group of private donors for what is now Acadia National Park. Before Stephen T. Mather became the first director of the NPS, he too gave a substantial amount of his own money for the protection and administration of national parks, including funds to buy more land for Yosemite National Park and money to publish the *National Parks Portfolio.* This portfolio was distributed to 250,000 people and was helpful in drumming up support to convince Congress to create the NPS on 25 August 1916. In the early 1900s, the Rockefellers donated a significant amount of money and land for national parks, including millions of dollars to buy land for Acadia, Grand Teton, Great Smoky Mountains, Virgin Islands, and Yosemite National Parks, among others. Since the 1940s, the Mellon family has given millions of dollars to acquire lands for the public, including for Gettysburg National Military Park and Shenandoah National Park, as well as to preserve existing parklands at Redwood and Rocky Mountain National Parks. More recently, in the 1980s individuals, foundations, and other non-profit entities donated $350 million to refurbish the Statue of Liberty and restore Ellis Island's Great Hall. The latest substantial act of philanthropy in the United States was from the Haas family, who donated $16 million to transform Crissy Field in Golden Gate National Recreation Area from a dirt wasteland into a beautiful waterfront park.

Mackintosh's paper ends with a discussion of how Congress recognized the importance of philanthropy in the protection of parks and established the National Park Foundation in 1967, which was launched, appropriately, with a $1 million donation from Laurance Rockefeller. The National Park Foundation raised more than $35 million in 2000 for the benefit of all national parks. Since the creation of the National Park Foundation, more than 20 other non-profit groups that raise money for national parks, called "friends groups," have been established to help individual parks. Yellowstone's friends group is called the Yellowstone Park Foundation.

The Current Role of Philanthropy in Protecting Yellowstone

The Yellowstone Park Foundation and other friends groups do not replace congressional funding for national parks, but enhance it. The purpose of friends groups is to help the NPS achieve a margin of excellence by funding programs that do not directly affect visitor and staff safety, but that enhance the experiences of visitors in parks and the protection of natural and cultural resources in ways that are beyond the financial capacity of the NPS.

In 2001, Yellowstone received $25,122,000 in direct federal appropriations, $5,656,000 in user entrance and special use fees, and $714,000 in concession fees—a total of $31,492,000 to run the park. This equates to approximately $10 spent on each visitor to Yellowstone to fund interpretive talks, ensure visitor safety, provide adequate staffing to meet visitor needs, clean campgrounds, and create educational exhibits—just part of the unseen work that is done for the benefit of each visitor.

Assuming an annual visitation to Yellowstone of about 3,000,000, the abovementioned work is done by a full-time staff of approximately 556 people—which means that each full-time employee is responsible for approximately 6,000 visitors per year. The level of federal funding has prevented the park from filling 15% of its permanent positions and has led to a number of operations being reduced or cut, including exotic species control, monitoring park resources, ranger patrols, and interpretive programs. Yet, all of these cut programs are essential to the long-term protection of Yellowstone's resources and to visitor fulfillment.

Though Yellowstone was not the recipient of many of these large, early donations mentioned earlier as part of Mackintosh's paper, philanthropy is now playing an increasingly important role in the conservation of and research on the world's first national park.

Much of the philanthropy that has taken place in Yellowstone has been done quietly. Therefore few people know if a research, interpretive, or wildlife restoration project has been funded with private money. But millions of private dollars have been designated for Yellowstone's benefit in recent years.

Recent philanthropic contributions to Yellowstone include close to $1,000,000 contributed by American Gramaphone and its owner, Chip Davis, to help restore the park after the 1988 wildfires. This large gift was used for trail rehabilitation projects and educating the public about the role of fire in Yellowstone's ecosystem through funding a supplement to the park newspaper. Later, American Gramaphone funded the "top ten issues" supplement to the park newspaper. The Yellowstone Association has contributed more than $6.5 million since 1933 to provide educational programs, exhibits, and publications for park visitors. The Association also runs the Yellowstone Institute, which offers a variety of courses that teach people about the ecological processes of Yellowstone. Moose Charities has long been a supporter of Yellowstone by funding the park's Youth Conservation Corps program each year for 12 years. Their donations have totaled more than $1,500,000 since 1989.

In 1996, Conoco donated $200,000 in seed money to start the Yellowstone Park Foundation. Since then the company has donated more than $2.2 million, including $2 million for a new visitor education center at Old Faithful for which the Foundation, in cooperation with NPS, is currently raising money. This new visitor education center will have a large theater and classrooms and will be an important hub for education and research on Yellowstone's geyser basins. Unilever launched the Old Faithful Visitor Education Center campaign by donating $1.25 million for the cause. They also have donated a considerable amount of recycled material for boardwalks throughout Yellowstone, including for the boardwalk that circles Old Faithful.

Defenders of Wildlife has made a considerable difference in the protection of Yellowstone's wolves and grizzly bears by providing money to ranchers for livestock lost to these predators. National Parks Conservation Association (NPCA) advocates for the protection of Yellowstone and other national parks and has recently worked with park staff to create a business plan that NPCA plans to use to encourage more financial support of national parks from Congress.

Canon, USA, and the Turner Foundation have both contributed large donations for research and education in Yellowstone. For example, starting in 1997 Canon donated a total of $300,000 over three years to fund conservation research on grizzly bears and amphibians, and for native plant and native fish restoration. The Turner Foundation has been a long-time supporter of Yellowstone, including supporting wolf restoration and research on the army cutworm moths that are one of the favorite and most important fall food sources for grizzly bears.

Why National Parks Should Not Simply Make Do with the Federal Funds that Congress Appropriates

Though the world has changed profoundly since Yellowstone was created in 1872, the role of national parks has evolved with the needs of our country and now provides benefits of fundamental importance to virtually every community in America. The future would be bleak without national parks. The programs they provide include everything from campfire talks in Yellowstone about wildlife, to discussions of the history of early civilizations at Aztec Ruins National Monument in New Mexico, to learning about civil rights at Frederick Douglass National Historic Site in Washington, D.C.—yet all of these NPS units are struggling for viability.

In December 1999, the director of the NPS asked the National Park System Advisory Board to "develop a report that should focus broadly on the purposes and prospects for the National Park System for the next 25 years." An excerpt from the resulting 2001 report, titled *Rethinking the National Parks for the 21st Century*, states the following:

> Private citizen involvement with national parks has a long history. In recent years the number of volunteer 'friends' groups supporting individual parks has grown significantly. These groups provide tens of millions of dollars each year to support individual park operations and enrich the quality of public service offerings. The work of the friends groups is extremely valuable to the Park Service…National parks will always be dependent on federal appropriations for their primary support. However, the opportunity to provide additional private resources for the parks should be encouraged. The added value expressed through private funding is a measure of the importance placed on this revered American institution (National Park System Advisory Board 2001: 29, 30).

Conclusion

Barry Mackintosh writes:

> Philanthropy is more than a source of land and money for the parks. It is a means of building and strengthening bonds between parks and their advocates.

> While all taxpayers contribute to the parks, those who make additional voluntary contributions will have a special interest in the park's welfare. The parks and the National Park Service benefit from their devotion as well as their dollars.

As our daily environment is filling with strip malls, as we watch our farmlands being replaced by parking lots, and as our world becomes more technologically and politically complicated, national parks are an increasingly important source of connecting with our roots and of peace and refuge. Their role as a laboratory and an infinite source of learning and wonder is only strengthened. Yet as parks become more essential to our world's balance, the economic and physical demands on them become greater. Without what Mackintosh mentions as the private sector's devotion to enhancing federal funding, access to national parks may have to be restricted and education programs cut even further. We may lose vital elements of the very places of solitude and wonder that we seek.

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Archeology Around Yellowstone Lake

Ann M. Johnson

In this paper, I will be looking at Yellowstone Lake during the Precontact period—that time in the past before written records—and I will summarize our current thinking about who was here and when, what their activities and subsistence practices were, and how these activities varied across the seasons. These questions are, of course, interrelated. Presentations in this symposium cover a grand diversity of topics relating in one way or another to Yellowstone Lake. Through archeology, we can learn about the people of many cultures who visited and lived here at different times in the past, and compare their different adaptations to the changing environment. The unique contribution that archeology brings is that of time depth. In addition, archeological sites also contain bits of pollen, burned seeds, animal bones, and other residue remains from which it is possible to learn about the past environment, including its plants and animals.

Before discussing what we have learned about the past, I need to first describe the data from which my thoughts and impressions are derived (Figure 1). Yellowstone Lake has 100–110 miles of shoreline and seven islands. At the pres-

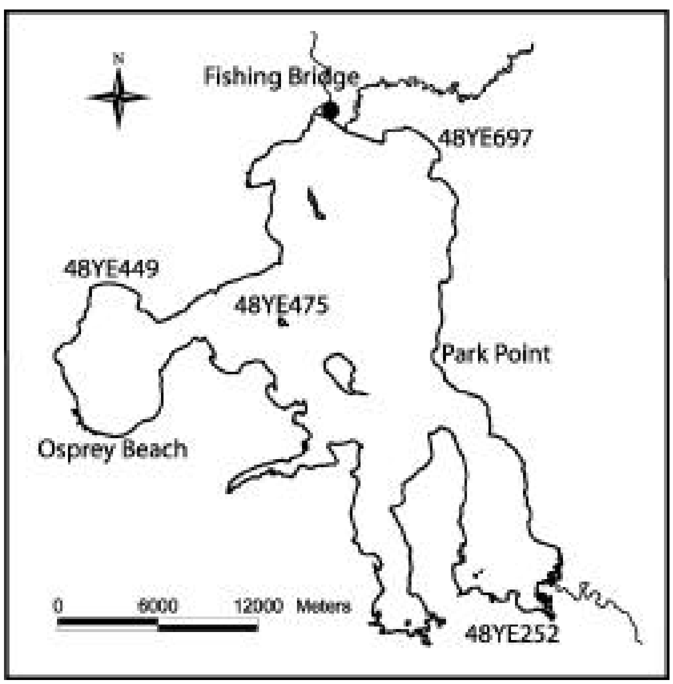

Figure 1. Archeological sites around Yellowstone Lake.

ent time, there is a good-quality archeological inventory for only about 10 miles of shoreline, with occasional reporting of sites along another 50 miles. These are primarily on the north and west sides of the lake. Additionally, there are archeological sites on six islands, but a reasonable inventory is available only for Dot and Peale islands. Most sites are known only from eroding cultural deposits or a few tools. It is ironic that our best information about prehistoric use of Yellowstone National Park comes from cultural deposits that are being destroyed by erosion.

Chronology

The most basic question is, When were people here? Figure 2 illustrates the frequency of radiocarbon dates for the entire park in 300-year increments, with the year AD 2000 on the left side. Dates in the text are in BP (years before present) starting at AD 2000. There are few dates for the oldest and the most recent human use of the park. We expect to find that all of the earliest peoples in Montana, Wyoming, and Idaho visited Yellowstone Lake. In fact, more of the points representing early (Paleoindian) use of the park are found around the lake than any other area. This is due to the greater erosion, and thus exposure of sites, in this area. But unfortunately, sites from 7,000 to 11,000 years ago are rarely identified, at least in part because they have been removed by natural erosion or are buried.

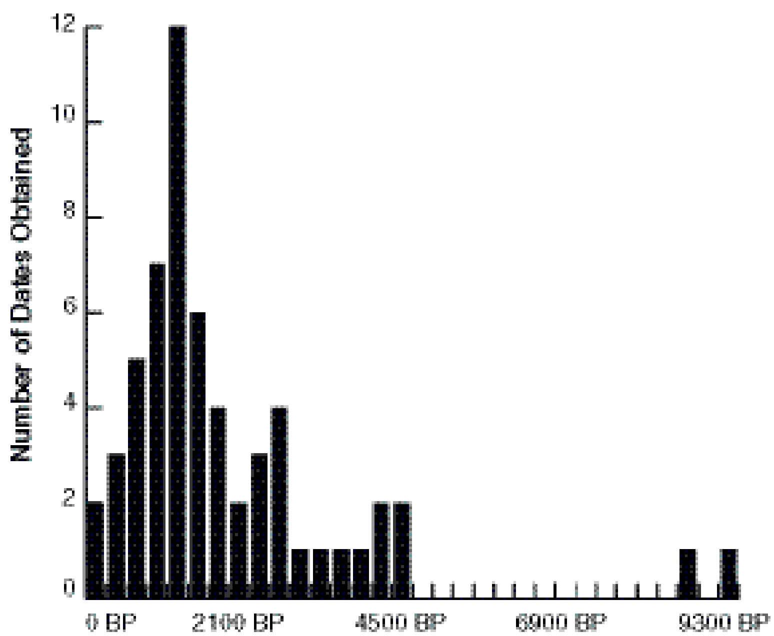

Figure 2. Frequency of radiocarbon dates for Yellowstone National Park in 300-year increments, beginning with AD 2000–1700 on the left.

The oldest recognized site in the park is the Osprey Beach site (48YE409), which represents occupation by the Cody Complex. It is called a complex because this "culture" is identifiable by more than one diagnostic artifact, including Scottsbluff and Eden points, and Cody knives (Figure 3). The radiocarbon date from the Osprey Beach site (48YE409) is represented in Figure 2 by the date on the far right of the chart at more than 9,000 years ago (Shortt 2001; see also Shortt, this volume). On the other end of the time scale, there are few dates (and sites) after 800–900 BP. The reasons for this are not clear, but the interior of the park may not have been as favorable for animals and humans due to the colder and snowier environmental conditions during the Little Ice Age (150-550 BP).

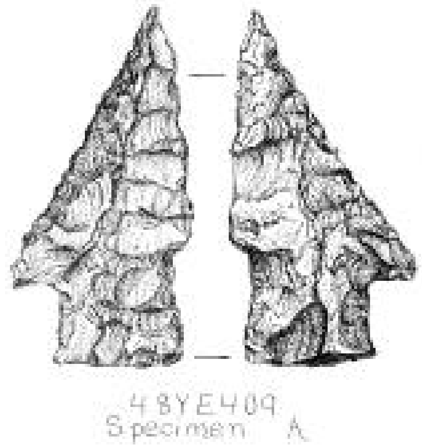

Figure 3. Cody knives from the Osprey Beach site.

The McKean Complex dates to about 3000 to 5500 BP and is well represented in sites around the lake. However, the most intensive use of the park dates from about 900 to 3000 BP (see the frequency peak in Figure 1); 78% of the dates fall within these time brackets. The Pelican Lake culture (Figure 4) is dated from 1800 to 3000 BP, and more sites in the park are identified as Pelican Lake culture than any other. The reasons for this period of intensive use are unknown, but this was also the time of the most intensive use of Glacier National Park. We speculate that environmental conditions must have been favorable during this time period. In recent years, there are more and complementary studies on the past environment, ranging from pollen, dendrochronology, and geomorphological age correlations with lake terraces. These all contain good information for the archeologist's interpretations.

Figure 4. Typical Pelican Lake projectile point.

Use of the Islands

Although there are archeological sites on six of the seven islands in Yellowstone Lake, the temporal parameters of this use are basically unknown. One reason for this is that the archeological resource has been severely affected by erosion and collecting. The islands were heavily used by the concessionaires, tourists, and park staff and their families during the 20th century and collection of Indian artifacts was a popular pastime.

One prehistoric campsite (48YE475) is contained within buried soil at Dot Island. Site 48YE475 has been severely damaged by erosion, but produced a radiocarbon date of 1500 ± 40 BP (Beta-157907). There is a bison bone deposit at the top of the buried soil that was previously identified as a paleontological site (Cannon 1996). The bone deposit was very compact, without taphonomic disturbance, and represented at least one animal. Because wave action has so severely eroded this deposit, it may never be possible to resolve whether this is a natural or cultural deposit of bison bone.

I am frequently asked, How did people get out to the islands? Did they walk out on the ice? That question presumes people were present in the winter. One wonders what resources people could find on the islands in the winter. Animals, of course, are able to cross on the ice and to swim back and forth to the lakeshore, but it is highly unlikely that people would swim out. This is not because of the distances, but because the cold water temperature could be expected to cause hypothermia. Various kinds of watercraft (canoes and rafts) might have been used.

As to why people went out there, the answer may be as simple as they were curious. We are unaware of any resources that would not have been available in greater quantities on the lakeshore.

Seasonality

As hinted at above, archeological sites have another aspect of time: seasonality, that is, the time of the year or season that the sites were occupied. Analysis of animal bones from archeological sites is the most common method of seasonal identification. However, few bones survive in the acidic soil around the lake, and other approaches, perhaps pollen analysis or identification of insects, will need to be used.

To date, we have not found any seasonal indicators for sites around the lake. This is not unusual because only four or five sites parkwide can be placed during a particular time of the year. Interestingly, these few sites all show early-spring to early-summer occupations. While it is premature to extrapolate from such a small data set to the lake area or to the entire park, it seems reasonable to suggest sites around the lake were used during the summer and into the fall. The archeological season-of-use data set will grow through time, and clearly illustrates the need for long-term research goals so that relevant data can be captured as they are identified.

If elk, deer, and bison stayed in the center of the park over the winter, then people would have been able to as well, because the limiting factor for human survival is availability of food resources. Winter travel would have been facilitated through the use of snowshoes. Today, some small groups of ungulates do not migrate out and those that successfully overwinter usually are found in thermally influenced areas. If bison and elk migrated to lower elevations for the winter prehistorically, with no political boundaries or developments to hinder their movement, we believe Precontact people would have followed. Typically, people time their movements around the landscape to match resource availability, such as fish spawning, the presence of camas and other edible bulbs, ripening fruit, and so on. Since Idaho obsidians are represented in tools found at sites on the lake, the seasonal movement model suggests that people wintered at lower elevations in Idaho and summered on the lake.

Site Types

Sites reflect the people and activities that created them, and can be interpreted by artifacts and other remains, such as hearths. Thus, archeologists classify sites into different types representing those activities.

Functionally, sites around the lake are dominated by base camps and sites where tools were manufactured or repaired. Base camps would be populated by extended family groups, young and old, men, women, and children. Most necessary living activities would take place there, and are represented by a wide variety of tools: projectile points, knives, scrapers, and perforators, and stone debris from their maintenance. Tools such as drills and perforators suggest manufacturing, possibly with leather and wood. Prehistoric pottery was first identified in the park at site 48YE449 and dates to about 500 BP. Base camps occupy favored locations around the lakeshore; these places were often used by many groups through time.

We do seem to find fewer end-scrapers than one might expect. If these are summer camps, the infrequency of these hide-working tools might suggest few hides were prepared in summer, when hair is thin and the hides would have to be carried to winter camp many miles distant.

There are few examples of kill sites in the park, in part due to the poor bone preservation in the generally acidic soil, but also because the topography does not lend itself to mass kills such as bison jumps. Instead, it is likely that one or more animals were taken by ambush at the tree–meadow juncture. It is possible that bison bone on the north shore of the lake (site 48YE697) represents a kill of an individual animal (Cannon et al. 1997). A problem with this interpretation is that the bison was basically not butchered, and the few flakes and tools found in association with the bones could have washed downslope from a campsite (48YE696). Also, lakeshore erosion removed an unknown amount of bone before the locality was documented.

We have little evidence for the types of shelters people may have used. No tipi rings (circles marked by the stones used to hold down the tipi cover) are known from around the lake, but due to the heavy ground cover they may be nearly impossible to identify. In the early historic period, conical timbered lodges (wickiups) were observed around Indian Pond (Norris 1880). In most cases, wickiups are temporary shelters for traveling groups (Kidwell 1974; Grinnell 1920).

Subsistence

As mentioned above, animal bone is rarely preserved in the acidic soil. Specialized analysis for blood residue left on tools provides clues about hunted animals. The standard suite of animals—rabbits, sheep, bison, canids—are present in the park from at least 9,000 years ago (Cannon et al. 1994; Shortt 2001). Grinding stones are usually assumed to represent plant processing, but a metate from site 48YE701 tested positive for deer antiserum and is interpreted as representing the processing of meat.

To date there is no evidence for prehistoric predation of fish around the lake, but relatively few excavations have been carried out and the fine screening of archeological sites necessary to recover such small bones has not been used. Because fish bone is small and fragile, there may be preservation and visibility problems. It is worth mentioning that flotation of hearth contents would recover fish bones if present, but the analyzed contents of seven such features have tested negative for fish.

Notched pebbles (net weights) are interpreted as evidence of weights used to hold fish nets in place. These can have either two or four notches, set opposite each other (in the case of two) or at 90 degrees from one another (in the case of four). Net weights have not been found around the lake, although some are known from the Yellowstone River close to Gardiner. Of course, specialized tools would not have been necessary to obtain or cook spawning cutthroat. While it may seem unusual to us, fish is one potential resource that many cultures do not define as food. The prehistoric use of fish is a matter of continuing investigation.

While there is some camas in the Lake horse pasture, this is marginal habitat and probably could not survive heavy collecting.

Stone, Tools, and Travel

Sites contain large amounts of fire-cracked rock, as well as debitage or flakes and shatter (broken flakes) that represent repair, manufacture and sharpening of tools. The fire- cracked rocks are derived from the local gravels, and are usually of the igneous varieties. These rocks would fracture in recognizable patterns after heating and cooling. Their presence represents hearth construction and stone boiling cooking of food.

The stone selected for tool production can be glossed as tool stone and includes a wide variety of different raw materials contained within the Absaroka glacial gravels as cobbles. The presence of tool-quality raw materials increased the attractiveness of the southern lakeshore and possibly increased the length of stay at these sites while tool kits were repaired and replenished. These gravels contain agates, petrified woods, quartzites, and volcanic tuffs: a grocery store for the flint knapper.

Volcanic tuff is similar in appearance to poor-grade obsidian and occurs as cobbles (both Huckleberry Tuff and Lava Creek Tuff). People were actively selecting these raw materials from which to manufacture tools. The tuff is typically black (or less often, red), opaque, and may have white crystalline inclusions. A geological source of this material is Park Point on the east lakeshore, but we don't understand the distribution nor do we know which parts of the geological exposure may have been used by people.

Questions about where people were before they came to the lake can in part be answered through the analysis of their tools: specifically, the sources of the stone. Archeological modeling suggests that people were familiar with resources in their home territory and would collect stone for new tools when near known geological exposures. Obsidian Cliff obsidian dominates tool assemblages throughout the park, although the percentages vary from area to area (Figure 5), so it is often the stone that occurs in smaller amounts that is more interesting.

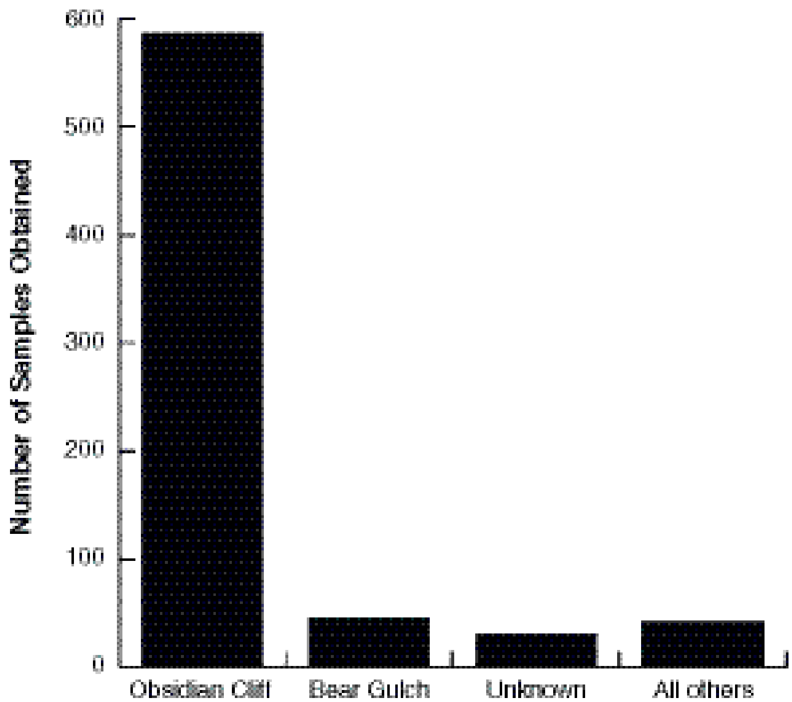

Figure 5. Obsidian sources in archeological artifacts in Yellowstone National Park.

We find evidence of contact or movement to and from Jackson Hole in the presence of tools manufactured from Teton Pass, Conant Creek, and Crescent H (south of Wilson, Wyoming) obsidians. These are limited, just as Obsidian Cliff obsidian is infrequently found in Jackson Hole. Packsaddle, Timber Butte, Malad, and Bear Gulch obsidians were imported into the park from Idaho. Bear Gulch was imported into the park in the highest amount and is second to Obsidian Cliff in popularity of use (Figure 5). Any analysis of a large sample of obsidian specimens results in some specimens with chemical fingerprints unlike any in the existing database, and we continue to seek samples of geological obsidians to add to the database.

As topography channeled early travel to a much greater degree than today, we are looking at mountain passes, river valleys, and lakeshores as transportation corridors. Through this line of inquiry we are investigating north–south prehistoric travel between Jackson Hole and Yellowstone, and between the park and Idaho, either over Jackson Pass, past Grassy Lake Reservoir, or down the Madison River valley. As people would obtain new obsidian for tools from sources along these routes, analysis of artifacts from Yellowstone Lake sites show where people had been. It is clear from tool and raw material analyses that people living on the southern lakeshore have very different territories (to the south into Jackson Hole and southwest into Idaho) from those around park headquarters, where there are greater relationships with the west and north.

Summary

Yellowstone Lake was important to people throughout prehistory because it is rich in plant, animal, and stone resources. The oldest sites in the park are known from around the lake. One of the reasons for this is the erosion that is exposing and destroying terrace deposits. On the positive side, because of this erosion, we have the opportunity to look "under the ground," to see cultural deposits that elsewhere in the park are deeply buried. At the present time, we interpret the archeological deposits around the lake as representing seasonal occupations where tool stone procurement, tool manufacture, and repair activities took place. As the basic outline of who used the park and lake area is understood, we can begin to ask better questions of our site data. Clearly, we are poised to make significant increases in our understanding and interpretations of the prehistoric human use of Yellowstone Lake.

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Climate, Tectonics or ...?: Speculations on the Recent Paleolimnology of Yellowstone Lake

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Abstract

The sediments of Yellowstone Lake may reveal the paleoecological history of this lake over the last few centuries. These sediments contain up to 60% biogenic silica derived from diatom frustules settling out from the overlying water. The sediment record reveals large variations in the diatom deposition over the last ~350 years. Some of these variations appear to correlate extremely well with independent climate records, particularly mean annual winter temperature and precipitation, derived from tree ring data extrapolations. A strong correlation occurs, for example, during an extended period of below-normal winter temperatures and above-normal precipitation seen during the late 1800s. Below-normal winter temperatures can significantly extend winter ice cover and shorten the ice-free, isothermal period during which the spring diatom bloom occurs. Rapid thermal stratification following prolonged ice cover may reduce annual diatom production and the subsequent silica deposition. Yet the forcing factors in this system may not be so straightforward. Sublacustrine hydrothermal springs found in the lake are a potential source of nutrients that may vary in strength and in time. These inputs may have the potential to alter the nutrient biogeochemistry of the lake. A pronounced chloride enrichment observed within the lake may be explained by input of a source of undiluted geothermal water equivalent to >0.06% of the riverine input. Calculations based upon silica removal indicate that such hydrothermal inputs would have to contribute up to ~10^7 moles of nitrogen annually, for example, in order to significantly shift the nutrient status of the lake. Observations to date, which are limited in space and time, do not appear to support such a flux for the whole lake. However, the existence of high-activity vents in past eras (as indicated by numerous relict features) or in unexplored regions of the lake cannot be ruled out.

Introduction

The integrity and value of the paleoecological history recorded in lake sediments is dependent upon a number of factors. For example, a good record contains: a relatively undisturbed sediment accumulation rate regime, a coherent and quantifiable sediment chronology, and minimal or quantifiable post-depositional alteration of biological or geochemical indicators as a consequence of diagenesis, mixing, migration, or other physical disturbances. The time scale of interest can range from years to millennia and is dependent upon the age of the lake and the existence of geochronological techniques to independently date various sediment horizons within the sediment column. Sediments within the depositional basins of Yellowstone Lake consist largely of a diatom ooze, up to 60% biogenic silica by weight, and have been examined in a number of studies for their potential in revealing the ecological history of this high-altitude system. Shero and Parker (1976) examined sediments from the South and Southeast arms of the lake and identified over 150 taxa of diatoms in cores with maximum ages estimated to be on the order of 1500 BP (years before the present). Many of these taxa were extremely rare, but the diversity of the flora indicates a potentially rich record of ecological changes and evolution over this period. In general, Shero and Parker (1976) observed a decrease in diatom abundance over the last 1500 years and hypothesized that lake productivity may have decreased over that period as a consequence of decreases in the annual nutrient supply, perhaps related to decreases in annual precipitation. More recently, Kilham et al. (1996) have provided an excellent review of the factors linking diatoms and climate change in the large lakes of the Yellowstone ecosystem.

The observations reported here are the result of work begun by our group some time ago (1983) in looking at the recent record (i.e., over the last 200 years) in these sediments, and in the sublacustrine hydrogeothermal activity within the Yellowstone Lake basin (Klump et al 1988).

Analytical Methods

Sediment cores were collected using a standard 7.5-cm-diameter Benthos gravity corer deployed from the U.S. Fish and Wildlife Service *R/V Cutthroat.* Intact cores in excess of 60 cm in length were retrieved. Upon returning to shore, cores were sectioned on a hydraulic extruder at 0.5- to 5-cm intervals. Sediment sections were placed in tared plastic 125-ml bottles, dried in an oven at 60˚C to a constant weight, and reweighed to determine the percent water content and porosity, assuming a dry sediment density of 2.3 g cm^{-3}. Sediments were pulverized in a mortar and pestle to a fine powder. Pb-210 activities were determined following a modification of the procedure of Robbins and Edgington (1975). An internal Po-208 standard was added to ~0.5 g of sediment to determine recovery efficiency, and the sediments were digested in 6N HCl at 95°C with sequential additions of 30% hydrogen peroxide. The solutions were cooled, filtered, pH-adjusted to 0.5 to 1.0, and amended with 100 mg of ascorbic acid. Po-210 and Po-208 were plated unto a polished copper disk in a boiling water bath and counted via low-level alpha spectrometry.

Pigments (chlorophyll and total carotenoids) were measured according to the spectrophotometric technique given by Strickland and Parsons (1972). Aliquots of whole, wet sediments were extracted in 90% acetone at approximately 30 ml per gram dry sediment for >20 hours in the dark, centrifuged, and the supernatant decanted into a 5-cm-path-length spectrophotometer cell. Values for carotenoids are reported as relative concentrations for time-series analysis and are roughly equivalent to ug g^{-1}dry sed. Daphnia winter-resting eggs or ephippia were counted in known wet-sediment aliquots under a dissecting microscope and are reported as number per gram dry sediment. Ephippia were easily recognized and counted, being the only large particles in these otherwise very fine-grained sediments. Biogenic silica was determined following the differential dissolution technique of DeMaster (1981) in which sediments are dissolved in a 85°C, 1% solution of Na_2CO_3. Sequential samples of the solution are analyzed for dissolved silica (Strickland and Parsons 1972) over a 5-hour period and the initial rapid rise in silica concentration taken as the dissolution of diatom frustules. Scanning electron microscopy micrographs made of both dissolved and untreated samples confirmed complete dissolution.

Results and Discussion

The cores examined here were collected from the deepest portion of the central basin of West Thumb in 1983 and 1985. The water depth here is ~310 feet and was, at the time, considered to be the deepest sounding in the lake. (Subsequently, more precise bathymetry with higher spatial resolution and remotely operated vehicle explorations of the bottom shifted the known deepest location to a small “canyon” southeast of Stevenson Island with soundings of nearly 400 feet.) Visually, the cores appeared to be relatively undisturbed, with a surface “flocculent layer” of a few millimeters. Below this surface floc, sediments were consolidated, highly porous (90% at 50 cm), fine-grained muds. X-radiographs revealed some apparent laminations, although not distinct or regular. In casual observations at the time of collection, benthic macroinvertebrate infauna were not observed and biogenic mixing is assumed to be minimal. The Pb-210 geochronology at this location for these cores (see Figure 1 for 1985) appears to bear this observation out. Excess Pb-210 (half-life 22.3 years) decreases exponentially from a value of ~23 pCi g^{-1} at the sediment–water interface to a supported value of <0.3 pCi g^{-1} at a depth of ~18 cm. Calculations from a curve fit of the excess Pb-210 data to the mass sediment accumulated with depth (g cm^{-2}) yield a net average mass sediment accumulation rate over this interval of ~22 mg cm^{-2} y^{-1} ($r^2 = 0.97$), or a linear sedimentation rate of ~0.16 cm y^{-1}. In general, Pb-210 dating may be extended to ~5 half-lives, or 100–120 BP. In this analysis we have extrapolated this rate to the length of core for chronological purposes, but add the caveat that dates prior to about 1870 are simple extrapolations and that these dates become increasingly sensitive to relatively small changes in sedimentation rate with increasing age. Indeed, one of the most interesting features in this core dates near the lower end for resolution by Pb-210 (1860–1900). This extrapolation, however, does fall within the range of sedimentation rates calculated by Shuey et al (1977) using paleomagnetic data of 0.100 to 0.213 cm y^{-1} (excluding the South Arm) for the period 1175 AD to present.

Diatom remains (intact frustules and fragments) make up the major portion of the sediment mass in the depositional basin of West Thumb. The biogenic silica content of these sediments reaches nearly 60% by weight at depth, but ranges from ~45% to 58% over the last 200 years (Figure 2). These changes in the biogenic silica content argue for significant changes in the production, burial, or

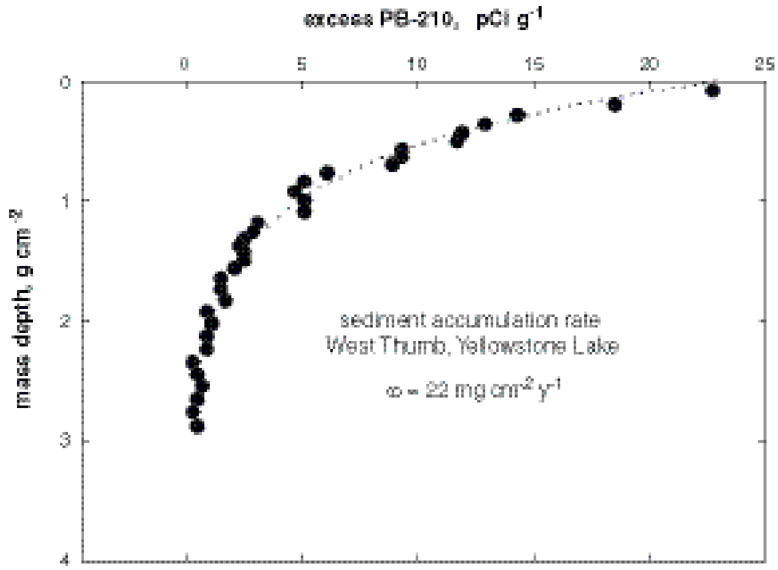

Figure 1. The Pb-210 geochronology for the West Thumb core (WT-85) shows a remarkably constant mass sedimentation rate averaging ~ 22 mg cm^{-2} y^{-1}.

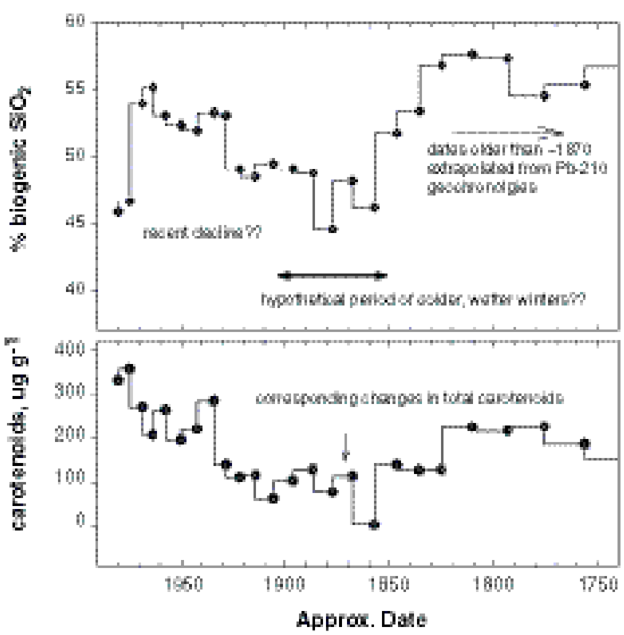

Figure 2. Percent biogenic silica (dry weight) and total carotenoids plotted as a function of time of deposition in WT-83. Both show significant drops in the late 1800s.

preservation of diatoms over time. Nothing within these cores indicates an alteration in the preservation of diatoms, although significant changes in speciation to species with more fragile, readily dissolved frustules is possible. Sedimentation rates, on the other hand, are remarkably constant. Our hypothesis is that the changes observed in the biogenic silica record are the result of changes in diatom production related to annual variations in whole lake productivity.

Of particular interest is the dramatic decrease in biogenic silica production (i.e., burial) in the late 1800s. At steady state, this decrease would translate to a drop in diatom production of 10–20%, depending on the reference period. The core used for this analysis was collected in 1983 and was sectioned at 1-cm intervals to a depth of 20 cm, 2-cm intervals to a depth of 30 cm, and then at 5-cm intervals to the bottom of the core. The lowest point in the biogenic silica stratigraphy (44.6%) occurs at 14–15 cm, an interval for which we place a date of ca. 1877. Quantification of simple algal pigments preserved in this record also shows a strong correlation with the diatom record, and carotenoids track biogenic silica content extremely well (Figure 2).

A principal goal of paleolimnology is, of course, to use such biotic tracers to decipher past conditions in the lake, in an attempt to determine how planktonic communities and the ecology of the system have responded to changes in climate, ecosystem structure, evolutionary pressure, and both naturally occurring (e.g., forest fires) and anthropogenic (e.g., watershed development) processes (e.g., Meyer et al. 1992; Kilham et al. 1996). In Yellowstone Lake, all of these types of processes are potential contributors to changing lake ecology.

Climate Changes

Temperate lakes, and perhaps high-altitude lakes in particular, are especially susceptible to changes in climate. One of the principal reasons for this is the annual physical cycle of most temperate lakes, which is driven by the annual temperature oscillation. A high-altitude lake in one of the coldest regions of the U.S., Yellowstone is ice covered for nearly six months of the year. Inter-annual changes in the temperature climate can vary the temporal extent of ice cover and of stratified and unstratified periods by several weeks or even longer. The ice free season begins with an isothermal, well mixed water column in the spring. As solar heating increases the lake shifts to a thermally stratified, stable water column in the summer, followed by overturn and mixing upon cooling again in the fall.

Determination of a climate signal in lake sediments is confounded by the variety of potential forcing functions. Correlations with other climate records, however, may be useful. Using the analysis of tree ring data, Douglas and Stockton (1975) reconstructed a long term seasonal temperature and precipitation record for the Yellowstone National Park region. This reconstruction dates back to 1750 with both seasonal and annual coverage. Of interest here is their reconstruction for winter temperatures and precipitation (Figure 3). A simple examination of this record shows what appears to be an anomalous period during the late 1800s. Prior to about 1860 and after about 1905, this record shows predicted winter tem-

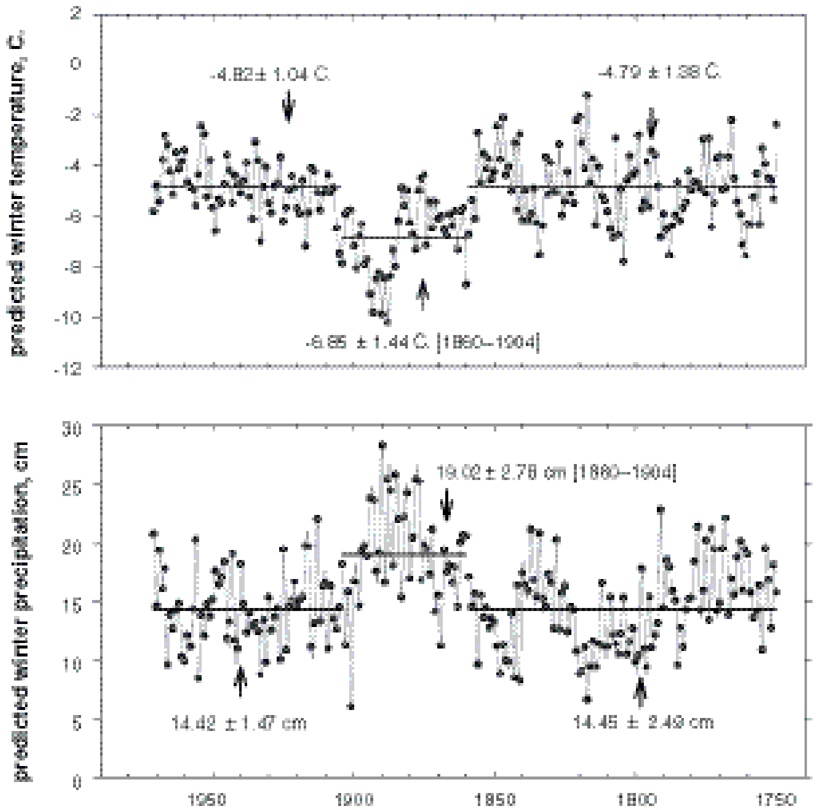

Figure 3. Paleoclimate predictions for winter (November-March) temperatures and precipitation in Yellowstone based upon tree ring climate reconstructions (from Douglas and Stockton 1974). Both below-average temperatures and above-average precipitation are predicted for the late 1800s, particularly during the period 1885–1894 when temperatures were nearly 4˚C lower and precipitation 8 cm higher than "normal" conditions prior to 1860 and after 1905.

peratures to vary about a remarkably constant mean value of ~4.8° ± 1.4°C. Predicted winter precipitation likewise varies about a relatively constant mean of ~14.4 ± 2.5 cm for these two long periods. During the late 1800s, however, there is a significant drop in predicted temperatures by at least 2°C, to a mean of –6.85° ± 1.4°C, concomitant with a significant increase in predicted winter precipitation by at least 4.5 cm. to 19.0 ± 2.8 cm. Assuming this is snow cover, this would be equivalent to ~45 cm of additional snowfall. Both of these would appear to be, in this region, significant climate variations. In fact, a closer examination of the data for 1860–1905 shows that for shorter periods of 10 to 20 years, the departures from the long-term means are even greater. For example, for the period 1885–1894, the average predicted winter temperature is –8.81° ± 0.89°C, 4°C below "normal," and the average predicted winter precipitation is 22.34 ± 3.88 cm, nearly 8 cm above "normal." The combined effect of colder-than-normal temperatures and above-average snowfall could easily extend the ice-cover period on Yellowstone Lake by weeks. Typically, ice-out occurs in late May or early June. Prolonging ice cover, even by two or three weeks, could have dramatic effects on lake ecology. Results from regional climate models for the impact CO_2 doubling on the thermal regime of Yellowstone Lake are indicative of the sensitivity of the lake to climatic-scale temperature changes. For example, the average annual surface temperature is increased by 1.6˚C for a $2xCO_2$ scenario (Hostetler and Giorgi 1995). This warming reduces the annual duration of ice cover by over six weeks, from 196 days to 152 days.

Primary production during the spring bloom is particularly important in deep lakes such as Yellowstone. During the spring transitional period, the lake is isothermal and well mixed. Because of mixing, algae throughout the water column may be exposed to light and have sufficient nutrients to sustain rapid growth. Once the lake warms, however, and begins to stratify, hypolimnetic nutrients are largely out of the reach of the photic zone and photosynthetic primary production is limited to the fairly shallow region of the epilimnion where nutrients, no longer being replenished from deeper waters, can be rapidly depleted. The spring bloom is triggered, in general, by light. Prolonged ice cover may have multiple effects. First, it insulates the water column from solar radiation, limiting algal growth, and secondly, it contracts the length of the isothermal spring bloom period. In the latter case, by the time ice-out occurs, solar heat inputs may be near their maximum and the lake can stratify very quickly, perhaps in a matter of days. The result: there is little time to extract stored hypolimnetic nutrients before they are "sealed off" by the rapidly forming thermocline, and the productivity of the spring bloom is significantly limited. Similar climatic-forcing effects have been observed as a consequence of El Niño events in Castle Lake, a temperate, subalpine lake in California. Year-to-year changes in the amount of snowfall from February through April, which determine the date of ice thawing (by up to more than one month later in the spring), coupled with early heating and stratification, resulted in significant interannual variations in heat stored within the lake (Strub et al. 1985). This ranged from early thaws with extended mixing and high productivity, to late thaws with incomplete mixing, a failure to renew photic zone nutrients, and consequent low productivity. During 1983, for example, when the lake remained ice covered until 6 July, primary production during the summer was only 25% of normal. In a similar situation, interannual variations in zooplankton abundance (principally the herbivorous *Daphnia hyaline)* in Lake Windermere, United Kingdom, strongly correlated with the timing of thermal stratification (George and Harris 1985). Interestingly, zooplankton biomass was higher in cool years coinciding with the period of maximum food availability, whereas in warm years the preferred algal food species tended to appear earlier and may have been in decline by the time Daphnia begin to reproduce.

The paleo-record of zooplankton is much less robust in lakes. Cladocerans, however, are a major component of the zooplankton in Yellowstone Lake and the sediments contain abundant ephippia, or winter-resting eggs. Recently, there is renewed interest in paleoecological studies using these resting eggs, including genetic and evolutionary histories (Hairston 1996). Here, however, we report only our observations on numbers deposited and preserved through time. Although this record is highly variable (Figure 4), it does appear that prior to about 1900 there are episodes of high and low ephippia production. One of the highest of these correlates to a date in the 1870s and 1880s, a period of low diatom production in the lake and cold, wetter winter weather. Three of the eight intervals in which numbers exceed 300 per g occur within this period. Coincidence, perhaps, but this observation may relate to spring bloom timing effects, low primary production, or changes in speciation. Daphnia stressed by low food resources, for example, may shunt more energy into egg production, resulting in greater ephippia abundance in years in which primary production is decreased. The clearest trend in the ephippia record, however, is the decline in numbers after about 1910. Speculations for the reason for this drop could include all of the above, as well changes in ecosystem dynamics, such as abundance shifts in planktivorous fish populations, an impact that can be triggered by the invasion of non-native species.

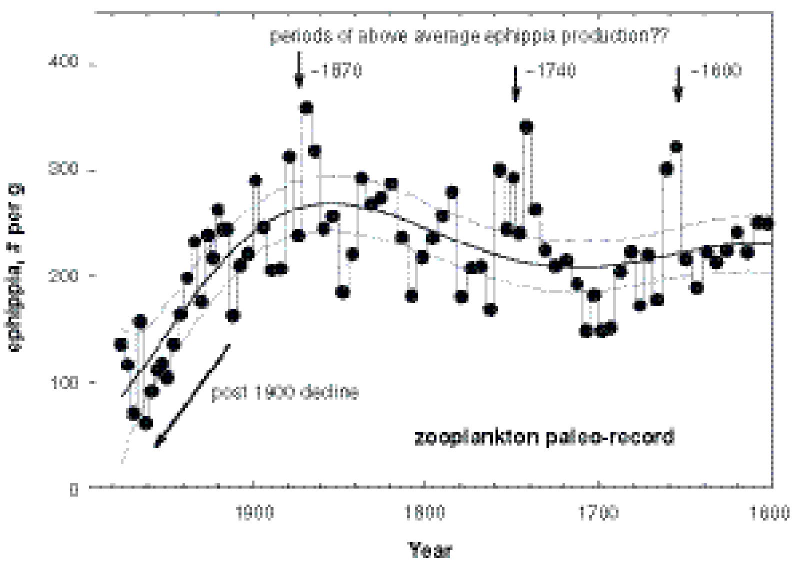

Figure 4. The abundance of ephippia (number per gram dry weight) in West Thumb sediments (WT-85) as a function of the year of deposition.

Geochemical Budgets and Geothermal Inputs

Its location within the Yellowstone caldera and over a geothermal hot spot makes Yellowstone Lake unique. Studies over the last 15 years have revealed a sublacustrine plumbing system made up of diverse underwater hot springs, fumaroles, and seeps (Klump et al. 1988). Could the geothermally enriched fluids emanating from these features have the potential to "fertilize" the lake to a degree sufficient to alter primary production? How much would be required? One approach is to simply calculate backwards from the known diatom accumulation rates. For example, if we assume that significant deposition only occurs at depths greater than 40 m, then slightly more than 50% of the area of the lake is depositional. Further, if we assume that the sediment accumulation rate averaged over this area is ~10 mg cm^{-2} y^{-1} (or roughly one-half of the 22 mg cm^{-2} y^{-1} measured in West Thumb), then the average biogenic silica removal rate (at 50% biogenic silica by weight in the sediment) for the whole lake is on the order of 2.5 mg (42 umol) Si cm^{-2} y^{-1}. The average depth of the lake is 42 m; hence, the average silica removal rate from lake water via burial is ~10 umol L^{-1} y^{-1}. Silica concentrations in Yellowstone Lake average over 150 umol L^{-1}. Hence, this rate of removal would hardly be detectable in lake water. Even if silica deposition were more widespread, e.g., at depths >20 m (i.e., 75% of the lake floor), and average sedimentation rates more rapid, e.g., 20 mg cm^{-2} y^{-1}, then annual silica depletion would rise to 30 umol L^{-1} y^{-1}. Although the data are infrequent and variable, this number approaches the depletion we have observed between inflow and outflow concentrations in the Yellowstone River.

Since the volume of the lake is ~1.4 x 10^{10} m^3, a 20% change in diatom production (i.e., in burial) would likewise require a mass of diatom silica of ~3 x 10^7 mol Si y^{-1}. Since silica is not limiting in this system, changes in the flux of another micronutrient would have to be responsible for any hypothesized "fertilization" effect, i.e., changes in new nutrient inputs over time. Take, for example, nitrogen or phosphorus. Average stoichiometries for diatom production vary, but an approximate Si:N ratio of ~1–2 and Si:P ratio of ~20–25 are reasonable (Redfield ratios are 16:16:1). To produce 3 x 10^7 mol Si y^{-1} would therefore require roughly 10^7 moles of nitrogen and 10^6 moles of phosphorus. To date the *highest* dissolved inorganic nitrogen and phosphorus concentrations we have measured in vent fluids are ~100 and 30 umol L^{-1}, respectively, measured in 1987–1989. Since that time the concentrations we have observed in vent fluids have been considerably more dilute. Thermal ponds on shore often have extremely high concentrations of inorganic nutrients. In Mary Bay, for example, we have measured dissolved ammonium concentrations in small ponds in excess of 600 umol L^{-1}. Assuming vent waters contain inorganic nutrients at the high end of our measurements in the lake, the hydrothermal flux required to effect a 20% diatom productivity shift from changes in nutrient supply is on the order of 0.3-1 x 10^8 m^3 y^{-1} or ~2%–7% of the riverine inflow. Silicon itself is a major constituent in hydrothermal vent waters, being readily leached from volcanic rocks rich in silicon at high temperatures. We have measured dissolved silica concentrations as high as 3 mmol L^{-1} in waters emanating from shallow vents in Sedge Bay (Remsen et al. 1990).

Chloride is a conservative element highly enriched in geothermal waters, and its flux into surface waters has been used as an indication of fluctuations in regional geothermal activity (Norton and Freidman 1985). Comparison of average chloride concentrations in the major inflow (<10 umol L^{-1}) and outflow

(~150 umol L^{-1}) shows that chloride is enriched by up to fifteenfold within the lake. Chloride concentrations in undiluted geothermal source waters in the park have been estimated to be as high as ~10–20 mmol L^{-1} (Truesdell et al. 1977; Fournier 1979). The highest we have measured in sublacustrine vents in the lake is ~3 mmol L^{-1} (Klump et al. 1992). At these levels it would require the addition of ~10^7 m^3 of vent water annually (~1% of river inflow) in order to raise the concentration in the Yellowstone River outflow by 140 umol L^{-1} (ignoring inputs from precipitation, which are assumed to be minor based upon low Cl^- levels in rainfall). If this flow were concentrated in 0.0001% of the lake bottom (i.e., 1,000 cm^2 of vents per 10 ha, which implies 3,500 such vents fields) the flow in these vents fields would need to average ~5 L min^{-1}. Our observations to date would seem to indicate that vents of this magnitude are not this numerous, but the task of accurately characterizing and quantifying activity at an areal frequency of only 1:100,000 is problematic.

The fact remains, however, that lake water is enriched in Cl^-, requiring a contribution of 1.7 x 10^7 mol Cl^- annually. This is equivalent to a ~0.06% contribution to the hydrologic budget from undiluted geothermal source waters (at 20 mmol L^{-1}). A variety of additional sources may be considered, e.g., surface runoff from contiguous geothermal areas in West Thumb, Mary Bay, Sedge Bay, Turbid Lake/Sedge Creek, and other areas; diffusion from geothermally enriched porewaters (see Aguilar et al., this volume); and wind-blown minerals or other dry deposition processes. Norton and Friedman (1985) estimate that 93% of the total chloride flux out of the park derives from hydrothermal sources, with the remainder divided among atmospheric inputs (2.7%), rock weathering (4%), and human contributions (0.2%).

It is apparent that geothermal activity varies over time. Whether this variability is sufficient to drive productivity shifts within Yellowstone Lake is still an open question, but our current observations, at least with respect to conventional nutrients, would seem to indicate that it is not. However, we still have explored only a very small fraction of the lake bottom. High-precision bathymetric charts being produced by the U.S. Geological Survey may help us answer these questions by assisting in pinpointing potentially active regions of the lake floor for further exploration. Furthermore, numerous sublacustrine vent field concretions, relict vent plumbing, and the meter-scale spires discovered in Bridge Bay (see Cuhel, Aguilar et al. this volume) are composed almost entirely (95%) of amorphous silica, indicating that very active, high-concentration vents have been common in the lake in the past. Hence, the potential for significant geothermally active episodes in the lake's history appears to be real.

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Investigating the Microbial Ecology of Yellowstone Lake

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Abstract

Yellowstone National Park is well known for its geothermal features. Among microbiologists it is equally well known for its unique microbial ecology and extreme habitats associated with terrestrial hot springs, geysers, and fumaroles. Yellowstone Lake has also been shown to contain geothermal activity, and the presence of hydrothermal vents with water temperatures up to 120˚C have been reported. The vents emit a number of compounds which are important to microorganisms as nutrients for growth or substrates for energy. Thus, similar to the terrestrial habitats, Yellowstone Lake presents unique systems to assess microbial diversity and ecology. In order to examine the microbial ecology of the lake and its hydrothermal features, we have used both traditional culture and enrichment techniques to isolate bacteria, and modern molecular methods to assess the microbial diversity. For example, enrichment and cultural methods have yielded the characterization of a new genus and species of thermophilic sulfate-reducing bacteria, *Thermodesulfovibrio yellowstonii*, isolated from a hydrothermal vent in Sedge Bay.

Introduction

Microbial ecology is the study of microorganisms in relation to their biotic and abiotic environment. In practice, it has been described in a graduate student motto as “the study of physiology under the worst possible conditions” (Brock 1966). More recently, microbial ecology has also been indicated to be the link between all branches of microbiology (Zinder and Salyers 2001). In any case, similar to traditional ecology, microbial ecologists study individual organisms, populations (of individuals), communities (of populations), and ecosystems. This is done this with a variety of approaches and tools, including microscopy, culturing, molecular biology, and biochemistry. Much of what is studied by microbial ecologists revolves around three questions: (1) Who is out there? (2) How many are there? and (3) What are they doing?

Yellowstone Lake has been considered to be oligotrophic (e.g., Remsen et al. 1990; Gresswell et al. 1994). In other words, it has a low amount of productivity and is nutrient-poor. However, recent reports have suggested that the levels of nutrients indicate it should be considered more mesotrophic, or have a higher level of productivity than previously believed (Kilham et al. 1996; Theriot et al. 1997). When applying the above questions to Yellowstone Lake, the task of answering them might appear to be somewhat daunting. The sheer size of the lake makes it difficult to know just where a microbial ecologist should begin (Table 1). It gets even more complex if one considers that there are around a million bacteria per milliliter of water. In Yellowstone Lake, our focus has been on

Table 1. Characteristics of Yellowstone Lake. Data compiled from Pierce (1987), Kaeding et al. (1996), and Kilham et al. (1996).

Altitude above mean sea level	2,356.0 m
Surface area	341.0 km^2
Shore line length	239.0 km
Mean depth	48.5 m
Maximum depth	107.0 m
Estimated capacity	1.517×10^{13}

the geothermal activity exhibited by sublacustrine (i.e., at the bottom of lakes) hydrothermal vents and geysers (Marocchi et al. 2001; Remsen et al., this volume). However, even considering these locations presents some difficulties. The water and gases emanating from vents and geysers have influences that can extend some distance away from their origin (Figure 1). Water coming out of a vent forms a plume which mixes with the bulk water and transports vent material throughout the water column. The influence and the size of the plume depends upon the amount and periodicity of flow coming out of the vent orifice. Gas bubbles from a vent adsorb microorganisms and carry them to the water surface, where, after the bubble bursts, bacteria can be deposited at the air–water interface on what are called *film drops*, or transported into the atmosphere on what are known as *jet drops* (Maki and Hermansson 1994). Solid objects, such as rocks or aquatic plants that intersect the plume or gas flow, can also develop microbial communities directly influenced by vent emanations. In addition, there are also influences on the sediments that surround the vent, starting at the tube leading to the vent orifice and extending outwards. Thus, to get a complete picture, a variety of factors must be examined.

The presence of the hydrothermal vents provides another factor to consider for a microbial ecologist: temperature. The lake contains a range of temperatures that extend into the extreme. The lake generally becomes stratified in July and the thermocline may exist through mid-September with surface temperatures very seldom going above 18°C (Gresswell et al. 1994; Kaeding et al. 1996). Ice cover occurs from mid-December through May or even June, providing plenty of low temperatures (e.g., <4°C). On the other end of the temperature range, the hydrothermal vents have waters that reach up to 120°C (Buchholz et al. 1995; Klump et al. 1995). This allows for the presence of the entire range of optimal-growth temperature categories of microorganisms (Table 2) in Yellowstone Lake. Some microbes in the domain *Eucarya* can grow up into the thermophilic range, but most have lower (mesophilic) temperature requirements. Of the procaryotes, members of the domain *Bacteria* are found in all categories. Procaryotes that fall into the hyperthermophile category belong primarily in the domain *Archaea* (Brock 1994).

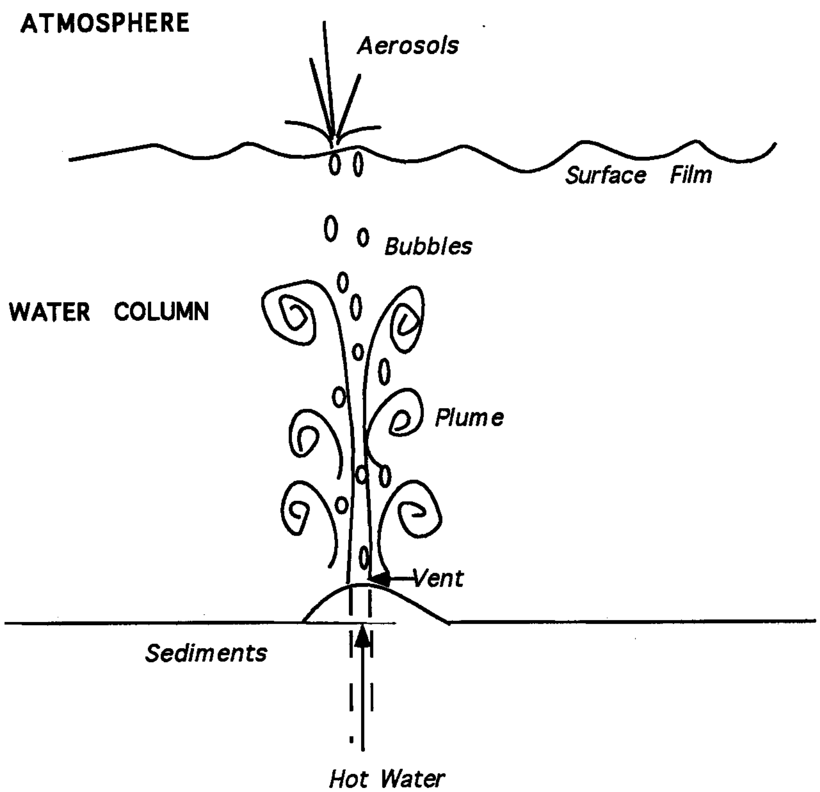

Figure 1. Schematic of the influence a hydrothermal vent may have on the water body into which it flows.

Table 2. Categories of growth temperature optima for microorganisms.

Description	*Growth temperature optima*
Hyperthermophiles	>80˚C
Thermophiles	45-80˚C
Mesophiles	15-45˚C
Psychrophiles	<15˚C

Of the three questions listed above, "What are they doing?" has been addressed elsewhere (Cuhel, Aguilar, Anderson et al., this volume), so the focus here will be on some of our work to determine "Who is out there?" and "How many are there?" in Yellowstone Lake. Our interest has been primarily on the procaryotic microorganisms of the domains *Bacteria* and *Archaea,* although it will be clear that our work did not exclude the *Eucarya*.

Sampling

Most of our collection of hydrothermal vent and bulk waters on the lake was accomplished using the National Park Service research vessel *Cutthroat*. Both SCUBA divers (in shallow waters) and a remotely operated vehicle (ROV; in deeper waters) have been used to collect the vent water samples (e.g., Klump et al. 1992; Buchholz et al. 1995). Over the years, we have been on a learning curve using the ROV; after each sampling season, discussions with Dave Lovalvo (Eastern Oceanics, West Redding, Connecticut), who operates the ROV for us in the lake, have resulted in modifications to enable better collection of water and other samples. Some idea of the changes involved have been presented elsewhere (Marocchi et al. 2001; Remsen et al., this volume) and will not be discussed in detail.

Who is Out There? How Many are There? Quantitative Analyses

Analysis of hydrothermal vent water chemistry reveals that not only are the vents in various regions of the lake different, but vents within the same region appear distinct from each other (Klump et al. 1988; Remsen et al. 1990; Klump et al. 1992; Buchholz et al. 1995). The chemistry data suggest that each of these vents could represent a different microbial habitat, and thus should have different microbial communities. Initially, some of our research examined these communities using quantitative methods.

We assessed microbial communities quantitatively by two means. First, we used multiple staining techniques and fluorescence microscopy to count microbial cells directly (e.g., Sherr and Sherr 1983). Second, we used culture methods where a water sample is serially diluted and each dilution is used to inoculate a solid growth medium that is incubated, and after a certain amount of time the colonies that arise (called *colony-forming units*, or CFU) are counted. In the latter case, the medium we have used is Castenholz TYE (Castenholz 1969) and is solidified using agar for mesophiles or Gelrite for thermophiles and hyperthermophiles (see Table 2 for temperature ranges involved). Using these methods to compare samples from different vents in Sedge Bay revealed that the numbers of distinct types of microorganisms determined by direct counts and CFU vary between vents and are different from those in the bulk waters (Figure 2). These data support the idea of each vent being able to maintain different microbial communities. Some types of microorganisms (e.g., phototrophs, algae excluding the cyanobacteria) were only visible in the bulk water samples. All other types were present in all samples examined. One important type of microbe present everywhere was the heteroflagellates. These are eucaryotic microorganisms that feed upon the bacteria and provide the beginning link from procaryotes to larger organisms in the food chain, eventually leading to zooplankton and fish.

However, the data presented in Figure 2 also illustrate the major problem associated with using only a culture approach for isolating bacteria and other microorganisms—or with examining any form of microbial diversity. As can be seen when comparing the number of bacterial CFU and the total counts of bacteria in the different vent samples, the number of CFU is around two orders of

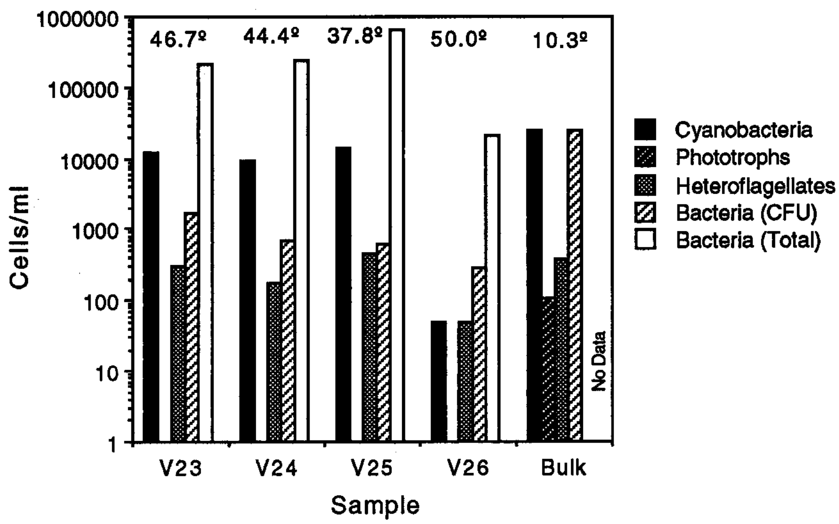

Figure 2. Comparison of the microbial communities of four separate hydrothermal vents in Sedge Bay. "V" followed by a number indicates the vent sampled while "Bulk" indicates a non-vent sample from the water column. Temperatures listed above each sample are in °C. No direct count data of bacteria in the bulk water sample were available.

magnitude less than (or ~1%) the total count. This is because using growth media of any type selects only for the organisms that can grow on that particular medium, and the vast majority of bacteria out there are unlikely to all grow on the same medium. This low ability to culture microorganisms extends to just about every habitat that has been studied and has inspired the use of molecular approaches for assessing microbial diversity and ecology. These molecular approaches allow the assessment of microbial diversity and identification of microorganisms without cultivation (e.g., Amann et al. 1995).

We have been using a combination of enrichment culture and molecular methods to assess the procaryotic microorganisms from both hydrothermal vent and bulk water samples (Figure 3). These include members of both the *Bacteria* and *Archaea*. On the enrichment side, we can focus on groups of microorganisms that grow under very specific conditions and utilize the chemistry of the hydrothermal vent emanations for growth or energy (e.g., Remsen et al. 1990). We can then isolate individual microorganisms and characterize and identify them. This was generally the methodology used by microbial ecologists everywhere before the advent of molecular techniques. Now, however, to identify and characterize a single type of bacterium not only are phenotypic attributes used (e.g., morphology, fine structure, growth substrates, conditions for growth, etc.), but so are genotypic characteristics determined through molecular techniques. These allow the investigator to get a clearer picture of the bacterium in question.

Molecular Analyses for Identification and Diversity

One of the genes most used to deduce the position of a bacterium phyloge-

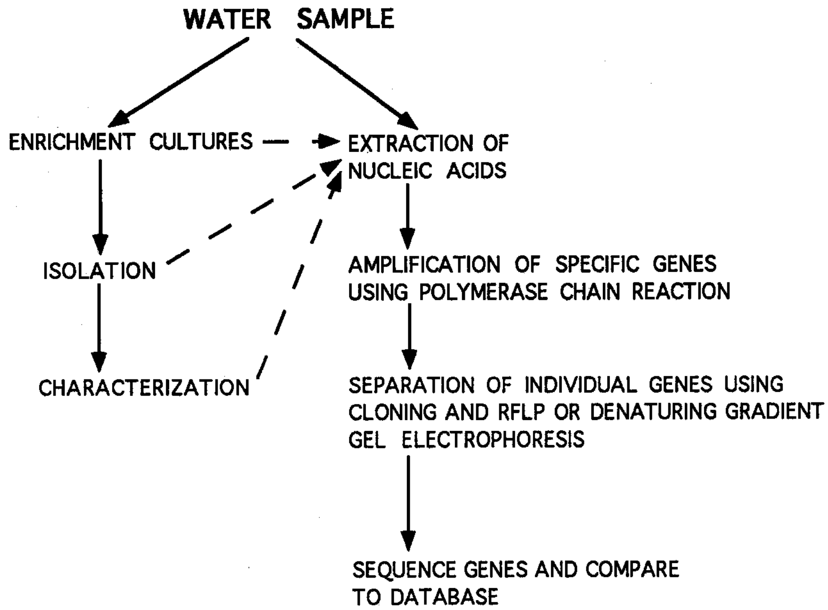

Figure 3. Flow chart showing combination of enrichment culture and molecular techniques used to examine hydrothermal vent and water column samples from Yellowstone Lake.

netically is the one that codes for a portion of the ribosome, a cellular structure where protein synthesis occurs that is found in all living organisms. In order to better study one gene, it is amplified using a process called the polymerase chain reaction (PCR). For a complete description of the process see the article by Mullis (1990). To amplify a certain gene, small pieces of DNA, called *primers*, are used. The primers are designed to be specific for the gene in question and are complementary to short sequences of the gene. They initiate making a copy of the gene of interest, which in the PCR is repeated many times. Amplification of the gene with the PCR results in billions of copies of the gene, making it easier to work with. After amplification, the sequence of bases that make up the gene is determined. So, if a bacterium has been isolated and we want to identify it using molecular tools, we determine the sequence of bases in the gene that codes for the subunit of the ribosome, called the 16S subunit, and compare this sequence to other known sequences that exist in databases. From this comparison we can examine the relatedness of one bacterium to another, or to a whole range of other bacteria, or even resolve its identity (Amann et al. 1995).

The strength of the molecular–noncultural methodology is that bacteria do not have to be grown or isolated before they can be studied. As illustrated in Figure 3, a sample can be directly analyzed starting with the extraction of nucleic acids followed by amplification of genes, most likely the 16S ribosomal DNA (rDNA) gene, with the PCR. The situation is somewhat different from that described above for a single bacterium. Instead of just having the gene from a single species of bacteria, when amplifying the 16S rDNA gene from the nucleic acids extracted from a natural sample, one presumably ends up with this gene from the DNA of every bacterium in the sample. This is analogous to having a large bowl of spaghetti, when what is wanted are the sequences on the individual strands of spaghetti that are each from different cells. Somehow, the strands must be separated before their sequences can be effectively analyzed.

Basically, two types of methods are used to get the single strands out of the bowl. The first is cloning. This is the insertion of the single strands into a small circle of DNA, called a *plasmid,* in a bacterium, usually a strain of *Escherichia coli*. As it grows and divides, the bacterium produces many copies of the plasmid containing the strand of DNA of interest. The gene of interest is recovered and analyzed with a treatment called *restriction fragment length polymorphism* (RFLP). This process uses enzymes called *restriction enzymes* that cut strands of DNA in very specific locations. These locations are in separate places in genes from different bacteria. Therefore, after treating the recovered cloned 16S rDNA with restriction enzymes, the patterns between clones are compared by separation in an agarose gel by a process known as *electrophoresis* (Figure 4). Because the locations where the restriction enzymes cut the DNA are in separate places in different bacteria, each different type should be represented by a distinct pattern on the gel, while those with the same pattern should represent the same bacterium. Examination of the different RFLP patterns from two vent water samples suggests that the bacterial diversity in the vents is quite distinct (Figure 5). However, this information needs to be confirmed after the 16S rDNA clones are

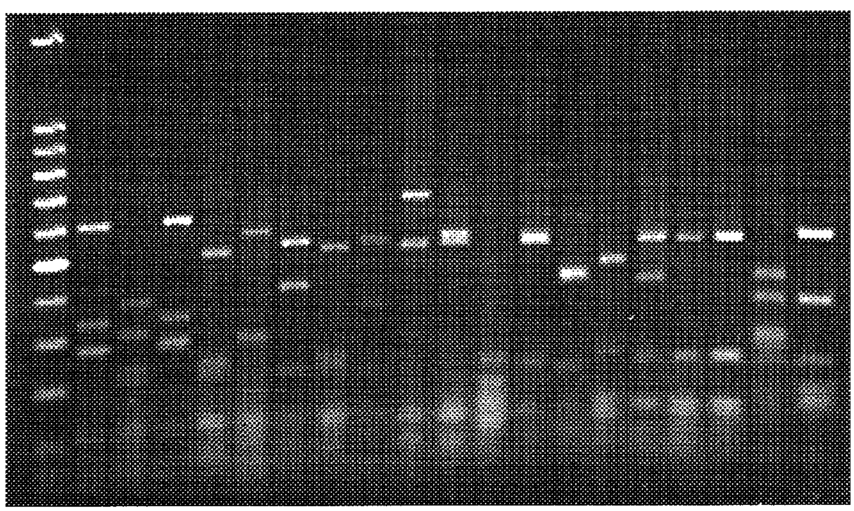

Figure 4. Example of a restriction fragment length polymorphism (RFLP) pattern from a clone library created after amplification using the polymerase chain reaction (PCR) of DNA extracted from a hydrothermal vent water sample. Of the 19 patterns generated, 15 appear to be distinct, indicating a diverse bacterial population.

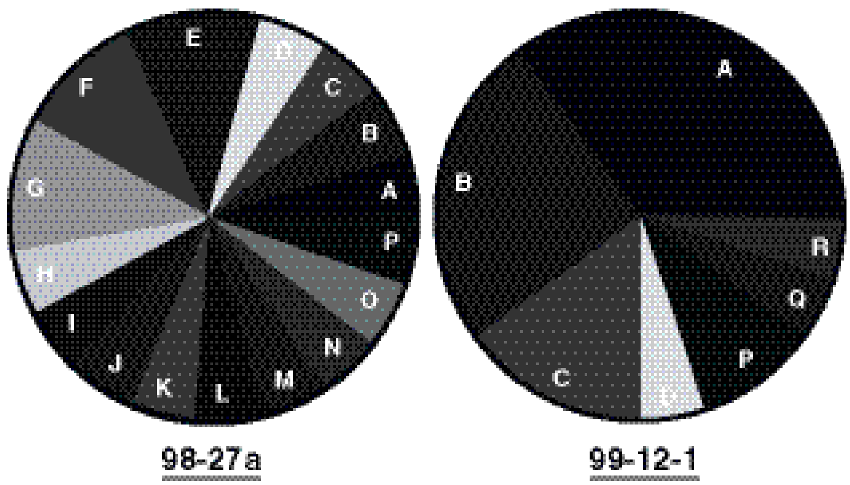

Figure 5. Comparison of RFLP patterns from two separate hydrothermal vents. The size of each pie piece indicates the proportion of the total number of clones examined with the same RFLP pattern. Clearly the diversity of bacteria in the two vents is different.

sequenced and the sequences compared. We have used, and are continuing to use, this approach to examine the diversity of *Bacteria* and *Archaea* both in hydrothermal vent waters and in the water column.

The second method involves separating the amplified DNA in gel electrophoresis. One way to do this is by what is called *denaturing gradient gel electrophoresis* (DGGE; e.g., Ferris et al. 1996). Each species of bacterium in a mixed microbial community will have a different sequence in its 16S rDNA gene. These can be separated into distinct bands in an acrylamide gel that contains an increasing gradient of a denaturant; due to their composition, each will denature and stop at a different concentration of denaturant in the gel. Each distinct band in the gel may represent a different type of bacterium. This can be confirmed by excising the bands and sequencing them. Currently, this technique is also being used on samples collected from Yellowstone Lake.

Molecular Analyses to Study Microbial Distribution

In addition to examining microbial diversity, molecular techniques can also be used to determine the presence and distribution of microorganisms with specific metabolic activities. One example is a gene for an enzyme that is involved in the oxidation of methane. The enzyme is called *methane monooxygenase* and is found in the bacteria that utilize methane as a source of both energy and carbon. These bacteria are called *methanotrophs* and may be important in parts of Yellowstone Lake because of the presence of methane in both water column and hydrothermal vent samples from some of the lake basins (Remsen et al. 1990). By taking the DNA extracted from a water sample (Figure 3) the genes for the methane monooxygenase can be amplified using specific primers (Cheng et al. 1999). By serially diluting the DNA before the PCR amplification, the number of copies of the gene in a sample can be determined by most probable number (MPN) PCR based on the analysis of replicates diluted to extinction (e.g., Fode-Vaughan et al. 2001). In other words, the dilutions in which a signal is detected after amplification are representative of the concentration of the gene in the sample. An example using the primers for the methane monooxygenase on a water sample from Yellowstone Lake is presented in Figure 6. This methodology will allow the comparison of the distribution of the gene copies with the concentration of methane in water samples.

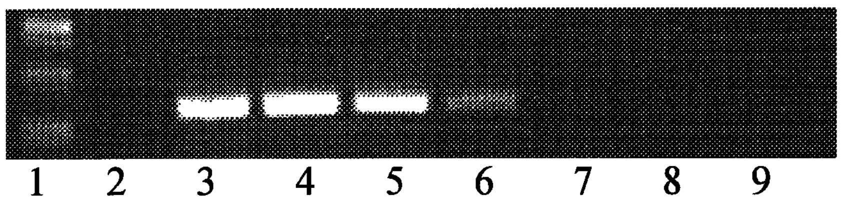

Figure 6. Example of a serial dilution of DNA extracted from a Yellowstone Lake water sample followed by amplification using the PCR of genes specific for the particulate methane monooxygenase enzyme, which is found in the vast majority of bacteria that utilize methane for both a source of energy and carbon. The last dilution (Lane 7, 1:10,000 dilution) in which a signal is amplified is representative of the concentration of the gene in the extracted DNA. Lane 1, DNA size markers; Lane 2, no DNA control; Lane 3, undiluted DNA from sample; Lane 4, 1:10 dilution; Lane 5, 1:100 dilution; Lane 6, 1:1000 dilution; Lane 7, 1:10,000 dilution; Lane 8, 1:100,000 dilution; Lane 9, 1:1,000,000 dilution.

A New Genus from Yellowstone Lake: Thermodesulfovibrio

Are there new microorganisms in Yellowstone Lake? In this case, the word "new" merely implies that they have not been previously isolated and characterized by humans. Any "new" microorganisms have probably been around for a very long time. The terrestrial thermal features of Yellowstone National Park have long been the source of a variety of novel microorganisms (e.g., Brock 1994). This should also be true for the hydrothermal features of Yellowstone Lake. An example of a new microorganism isolated from a hydrothermal vent in Sedge Bay is the obligate anaerobic thermophilic bacterium *Thermodesulfovibrio yellowstonii* (Henry et al. 1994; Maki 2001). This bacterium (Figure 7) has an optimum growth temperature of 65˚C, reduces sulfate to sulfide, and oxidizes some organic carbon sources (Henry et al. 1994; Maki 2001). Analysis of its 16S rDNA sequence reveals it to be a member of the phylum *Nitrospirae*, a deeply branching group of the *Bacteria* domain (Maki 2001). Since its isolation and characterization (Henry et al. 1994), the 16S rDNA sequence for the genus *Thermodesulfovibrio* has been reported from a terrestrial hot spring in Yellowstone National Park (Hugenholtz et al. 1998) and thermophilic granular sludges (Sekiguchi et al. 1998). In addition, a second species, *Thermodesulfovibrio islandicus*, has been isolated from a microbial mat in a thermal spring in Iceland (Sonne-Hansen and Ahring 1999). It's clear that this bacterium, originally isolated from Yellowstone Lake, represents a new genus that has a worldwide distribution.

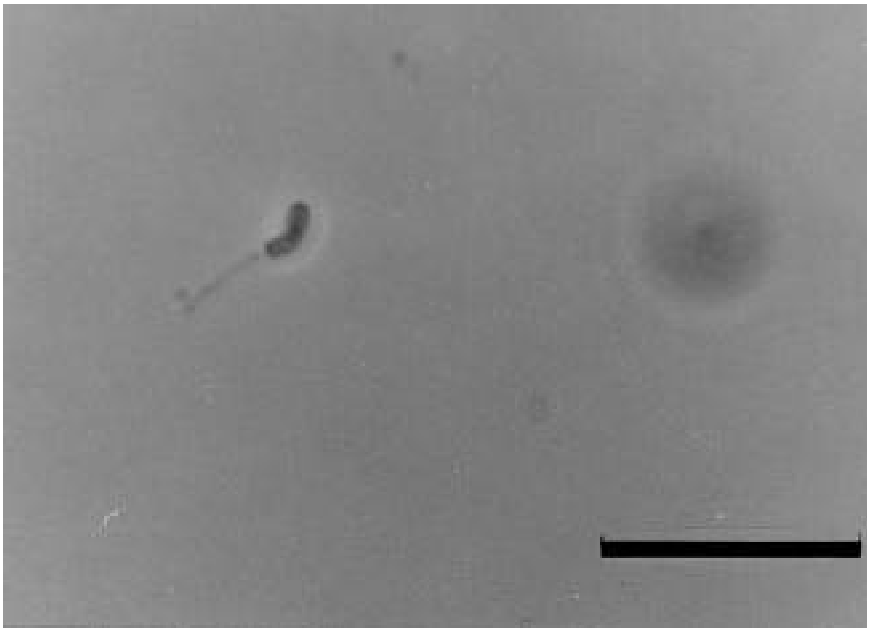

Figure 7. Photomicrograph of Thermodesulfovibrio yellowstonii taken with a phase contrast microscope after using a flagella stain. Bar = 10 µm.

Conclusions

For a microbial ecologist, Yellowstone Lake represents both a challenge and an opportunity. The challenge comes in effectively collecting samples from some of the difficult locations the vents are found in. The opportunity is in the potential of finding some unusual new microorganisms. The chemical variety of geothermal features on the bottom of the lake suggest that they will be as important to microbial ecology, and microbiology in general, as the terrestrial hot springs, geysers, fumaroles, and mudpots in the rest of Yellowstone National Park have been. The molecular approaches we have taken, although many of the studies are still preliminary in nature, have indicated a wide diversity of both *Archaea* and *Bacteria* associated with the vents. Although getting all of these bacteria into pure culture is highly unlikely, through enrichment cultures and isolations there is a strong possibility in finding some bacteria that have not been previously described. The lake and its hydrothermal features should be a source of fascinating results for some time to come.

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An Archeological Investigation of a Historic Refuse Dump Associated with the Yellowstone Lake Hotel

Megan McCullen

Abstract

In the fall of 2000, while installing a grease trap behind the Yellowstone Lake Hotel, contractors uncovered a historic trash dump overflowing with artifacts, now known as archeological site 48YE825. Cultural resources staff came to the site and collected diagnostic artifacts, such as those with distinct maker's marks, that would be useful in dating the trash pit. These artifacts included glass bottles, china, bricks, and metal objects. During early 2001, the artifacts were cleaned and analyzed in the Yellowstone National Park archeological laboratory. As analysis progressed, it became obvious that the assemblage was indeed associated with the Yellowstone Lake Hotel. It appears that the site dates to the early 20th century, approximately 1915 to 1920. This paper will present some of the more interesting information revealed by artifact analysis, together with some little-known facts about the early years of the hotel.

Historical Background

The Yellowstone Lake Hotel is the oldest standing hotel in the park, originally built between 1889 and 1891. It has undergone numerous renovations, additions, and subtractions over the years. The first addition was made in 1895, and the first major renovation occurred in 1904–1905 under the direction of Robert Reamer, the renowned park architect. Over the years, he did numerous other renovations on the building. The current hotel looks nothing like the original building, which was quite plain. Much of the following information was abstracted from the Yellowstone Lake Hotel National Register of Historic Places eligibility study, on file at the park.

When Yellowstone National Park was established in 1872, there was only one small hotel in the area, the McCartney Hotel, which was located near Mammoth Hot Springs. Shortly after, two individuals were given leases to build hotels, one along the road to Cooke City, and two along the Firehole River. In 1883, the Northern Pacific Railroad built a line to the northern boundary of the park, just west of current-day Gardiner, Montana. Now that they had access to the park, they wanted visitors to travel their lines and experience "Wonderland," as the railroad called Yellowstone. The interests of the railroad led to much of the building that occurred within the park in later years.

In the same year that the railroad to the northern boundary was finished, the Department of the Interior leased several plots of land to the Yellowstone National Park Improvement Company, with the intent of having them build hotels for visitors. Money problems held up construction, and by 1886 only one hotel, that at Mammoth Hot Springs, had been started. The Yellowstone Park Association (YPA), run by Charles Gibson, took over the leases and worked with the Northern Pacific Railroad Company to get money to build the hotels. In 1889, work on the Yellowstone Lake Hotel was begun.

The Yellowstone Lake Hotel was built over the course of two years. Although original blueprints for the hotel were not uncovered during this study, drawings of the floor plans were found. There were numerous complaints about the work being done; one writer claimed that he could kick the foundation out from under the building. There were other problems with shipments of supplies not coming in, or being incomplete, and workers who were drunkards (Dittl and Mallmann 1987). Two similar hotels were being built in the park at the same time: the Canyon Hotel, which opened in 1890, and the Fountain Hotel, which opened in the same year as the Lake Hotel. These buildings all had a similar design, and one foreman was in charge of all of the construction. However, the early version of the Yellowstone Lake Hotel was nothing like the Neocolonial monolith that Reamer eventually molded from it. Someone once described the original, simple building as “a Plain Jane three-story shoebox, with windows” (Mohr 1998).

Once open for business, visitors immediately started coming to the Lake Hotel. The hotels in the park were built to be about a day’s ride from one another, and business was brisk. Various minor renovations were made, and in 1904-1905, Reamer, who had just finished the Old Faithful Inn, started working on the Yellowstone Lake Hotel. He transformed this typical railroad rest stop into a stylish respite in the park’s interior. As with his other buildings, Reamer came back numerous times over the century to renovate and remodel the Lake Hotel. During his first attempt, he extended the roofline in three areas, with Ionic columns supporting it, added false balconies to some of the windows, and decorative moldings elsewhere. A wing was also added to the building at this time, as the hotel was far too small to house all of the people interested in visiting the park. While this was occurring, the original fireplaces were also taken out, as evidenced by floor plans and photographs. During a later renovation, Reamer put in another fireplace in a slightly different location, which is there to this day. Over time, the hotel has become more elaborate and is by far the most elegant hotel in the park today.

Mitigation of Archeological Site 48YE825

Yellowstone Lake Hotel and several nearby buildings have been listed on the National Register of Historic Places as a historic district. The site number for the historic district is 48YE825, and the trash dump is considered an archeological component of the district. The archeological site was uncovered during the installation of a grease trap behind the hotel. Maintenance staff noticed artifacts in the soil and stopped excavating. Ann Johnson and Lon Johnson, cultural resources staffers for the park, came to the site and collected what artifacts they could. As much of the soil had been pulled out by a backhoe, there was no context for the artifacts, and no stratigraphy was visible at the time of artifact retrieval. The majority of china was found piled together in one section of the site, but the other materials, such as glass bottles, appeared to be scattered about. Due to the lack of context and limited time, artifacts with distinct maker's marks or datable properties were the focus of collections at the site. Based on the diagnostic artifacts, it appears that the site was used for only a short time, perhaps a single dumping episode, except for two outlying artifacts, which will be discussed later.

Based on the soil consistency and odor, Ann Johnson believes the site to have been a cesspool at some point. For this reason, all artifacts were soaked in bleach water, and gloves and masks were worn throughout the artifact cleaning process. Artifacts were then labeled and catalogued, and are now part of the Yellowstone National Park museum collection.

Artifact Analysis

Over the course of several months, all of the artifacts collected from 48YE825 were analyzed in the Yellowstone National Park archeological laboratory. One of the first questions posed was the origin of the artifacts. Although they were found behind the Yellowstone Lake Hotel, evidence was necessary to determine that the artifacts were in fact associated with the hotel. The first identifiable artifact associated with the hotel was a metal key chain from Room 249 of the hotel itself. Although there is no key attached to it, the artifact was compared with a non-archeological key chain in the park's museum, which dates to the early 1920s. Both are the same shape and style, with slight changes in text presentation. Both items say "Yellowstone Lake Hotel" and "Y.P.A." (Yellowstone Park Association), although the archeological specimen has excessive punctuation ("Yellowstone, Lake. Hotel"), suggesting it is from a slightly earlier period (Susan Kraft, personal communication 2001).

Other artifacts confirmed the pit as being associated with the hotel. The majority of china (22 pieces) found in the midden had the maker's mark of the Greenwood China Company, Trenton, New Jersey. This company specialized in mass-produced hotel wares. The United States Army also used Greenwood china while it resided in the park until 1916, but it appears that the army added an additional mark to its china, such as "Quartermaster's Corps." It is interesting to note that almost all of the pieces of china from the site are virtually whole, with only a few chips on each one.

Other items found among the refuse included pieces of building materials, including some burned wood, a ceramic insulator, two firebricks, and a pressed tile. It was the two bricks and the tile that led to an unnecessary and overextensive study of the early period of the Yellowstone Lake Hotel. Firebrick, as the name implies, is generally used for fireplaces and chimneys. The two firebricks found at 48YE825 were made by the Evens and Howard Company of St. Louis. Many people know of the beautiful fireplace that Robert Reamer added to the Yellowstone Lake Hotel in 1923. It was first thought that the bricks were leftovers from this fireplace, but all of the other diagnostic artifacts suggest a pre-1920 date for the refuse pile. There are no other fireplaces in the hotel, so where did the firebricks come from? The Montana Historical Society's copies of the original floor plans showed that the original building had two chimneys. The first was associated with the bakeshop; the second was for three fireplaces, one in the first-floor lobby, and two on the second floor, in the parlor and the writing room. In 1904–1905, when Reamer renovated the hotel, he removed the fireplaces, along with the chimneys, as determined by floor plans and photographs. It is probable that the bricks found in the trash pit were from either the bakeshop chimney or one of these early fireplaces. In April 2001, Lon Johnson, the park's historical architect, and I searched the attic of the Lake Hotel looking for possible remnants of the chimneys, but to no avail. We also looked at Reamer's fireplace, and there were no maker's marks visible on the bricks. This is not the case for his fireplace at Old Faithful Inn, ca. 1903, where "Evens & Howard of St. Louis" is visible on every brick within the fireplace (yes, the beautiful stone fireplace at Old Faithful Inn is, in fact, lined with brick). At this point we can surmise that the firebricks found at 48YE825 are likely remnants of one of the original chimneys from the Lake Hotel, unless they are from a later, as of yet unknown fireplace.

The tile found at 48YE825 is also of interest, and also suggests probable evidence for an earlier fireplace. The tile is rectangular and has a plain, very dark green, almost black, appearance, and was made by the American Encaustic Tile Company, of Zanesville, Ohio. Photographs and a description of the tile were sent to several art tile collectors, who concluded that it appears to be the type used as fireplace border tile (Richard Mohr, personal communication 2001). Although tiles could also have been used for decoration in other areas, especially bathrooms, this particular type of tile is likely from a fireplace border. Reamer's fireplace has no tiles like this in association with it. Although the tile could not be dated to a particular year, the range for this tile does go back far enough that the tile could be from the first construction of the hotel. Could this tile then be from one of the three original fireplaces in the hotel? Unfortunately, no photographs or sketches of the original fireplaces have yet been found that can confirm or dismiss this possibility.

As interesting as all of this may be, as an anthropologist, building materials and architecture are not the main focus of my research. The real question I am interested in answering is, "What do the artifacts found tell us about the people who were here?" This question can be answered in part by a discussion of some of the other artifacts. Rather than sort them out by material, I will discuss various themes of use. The material from which an object was made is not as important as what it was used for. We must be cautious, however, in suggesting use, especially with the glass bottles. Until Prohibition ended, glass bottles were often reused and filled with materials other than those they were originally intended for. When discussing bottles, if there is no residue, I will only be talking about the original use of the bottle. It may or may not have been used for this purpose just before it was thrown out.

One of the most interesting themes is that of personal care, meaning hygiene, health, and cosmetic materials. A large quantity of material relating to these topics was found, including a soap dish, four Listerine bottles, several cologne and perfume bottles, a Vaseline jar, bottles for Bromo Caffeine and Bromo Seltzer, and several facial cream containers, including Richard Hudnut's "Marvelous Cold Cream." Numerous other bottles and containers appear to have been medicine or cosmetic containers, but they are not embossed, and no labels remain to identify their former contents. Both the Vaseline container and one of the Listerine bottles, which was corked, still held their original contents. A reliable date of post-1908 was put on the Vaseline jar, as it had a screw-cap finish, which was not used by its manufacturer until that year (Fike 1987, 186). With the large quantity of cosmetic materials, it is curious to wonder if guests brought all of these items in, or whether staff of the hotel used them. These could be remnants from the women's living quarters that were once in the attic of the hotel. Regardless, it seems that people in the interior of the park, whether visiting or residing there, were very concerned about their appearance and physical well-being.

Two other areas of interest that led to unusual artifact identifications were transportation and recreation. An engine crank was discovered, which may or may not be from a vehicle, along with several other items, which appear to be battery and hood parts. Automobiles were not allowed into Yellowstone National Park until 1915, and the other items, in conjunction with the engine crank, suggest that at least some of them are indeed from a vehicle. Two horseshoes were also found in the trash. Two recreational items of note are fishing rod ferrules. One is of an older style pole that had a solid wood shaft, while the other ferrule was from a pole that had six pieces of bamboo held together with a pin, which is the type of pole still used today. Both still had woody material in them.

The final theme I would like to look at is food and drink. By far, the majority of artifacts were beverage bottles. Several pieces of Greenwood china were found as well, most of them stacked together. These pieces ranged in size from small sauce dishes to dinner platters. Most pieces were whole, though they had a few chips. It is interesting to note that one teacup and one saucer both had burned material in them. Some china fragments not made by Greenwood were also found, though these were much smaller, incomplete pieces.

An unusual food item was the remnants of a chocolate box. Stuffed inside one cylindrical glass container were the remains of a paper chocolate box and its decomposed wrappers. The box was from J. G. McDonald Chocolates, out of Salt Lake City, Utah. The container that held the chocolate box is some sort of condiment container. Several varieties were found at the site, including a ketchup bottle. Two sawn bones of large mammals were also among the food-related artifacts.

Beverage bottles were some of the most numerous artifacts. Several alcohol bottles were found, from large whisky bottles to flasks to plain brown beer bottles. Three of the most unusual bottles were made by EJ Burke and company. These bottles were made with an automatic bottle machine, which dates them to post-1903, and probably a bit later, as large bottles could not be made with automatic bottle machines in the earliest years. The olive green glass has large air bubbles and wrinkles on it, a problem that only occurred during the first years of production on the automatic bottle machine. EJ Burke has a very unusual makers mark on the base, in the shape of a cat. These bottles were used to bottle either Guinness or Bass Ale (Toulouse 1971).

Another unusual collection was that of grape juice bottles. For some unknown reason, 11 embossed grape juice bottles were thrown in this trash midden, the largest quantity of bottles associated with one beverage type at the site. Each bottle was a small, clear, four-ounce bottle. Again, these proved to be a reliable dating tool. Two bottles were Welch's bottles, while the other nine were for Royal Purple Grape Juice. The trademark for Royal Purple was established in 1916 (registration nos. 75190, 276279, and 392008) by the United Grape Products Sales Corporation of Buffalo, New York. However, no information on the company has been found, and the history of this beverage remains hidden at this time. The form and quality of the bottles also match a post-1916 date.

Discussion

No conclusive reason for the disposal of the artifacts at site 48YE825 has yet come to light. Included in the collection are a manure pitchfork, pharmaceutical bottles, chipped china, building materials, and a wide variety of other artifacts one would rarely group together. The best explanation developed thus far for their common disposal is that these items represent an end-of-the-season clean out of the Lake Hotel. This would account for the wide variety and large quantity of complete items in the trash midden. The variety of items does not seem to correlate well with either living quarters alone or an area such as the kitchen; there is too much variety. There are probably other plausible explanations for the variety, quantity, and quality of artifacts in the midden, but this seems the most probable.

The two outlying artifacts found in the collection are a Mission Beverages bottle and the base of a vase or flowerpot with the mark of the Yellowstone Park Company. The Mission Beverages Company was not formed until the late 1920s, and the Yellowstone Park Company was not established until 1936. However, the majority of artifacts in the collection strongly suggest an earlier date for the site. After Prohibition ended, it was required that bottles be embossed with the phrase "not for reuse or resale," which is not on any of the bottles in the collection. Surely if the collection was from the late 1930s, the majority of bottles would have this mark. Many of the companies that were identified by maker's marks at this site went out of business during the Great Depression as well. Further, several of the bottles in the collection were not made on automatic bottle machines, and those that were so made showed signs of being from the earliest periods of its use. This combination of bottles suggests a date from the period 1910–1920. Also, the Royal Purple bottles and the automobile parts suggest a date after 1915. As this was a salvage excavation, artifact layers, had there been any, were mixed together by the backhoe. I believe the two anomalous artifacts to be outliers that were located above the trash midden and were mixed into the collection accidentally.

Conclusion

The Yellowstone Lake Hotel has a long and intriguing history, made more interesting by the use of archeology. Archeological site 48YE825, an early twentieth-century trash dump associated with the hotel, reveals information about part of the area's history that is often overlooked in documents: the everyday activities of visitors and staff in the park. It does not give us more information about presidential visits or unusual bear encounters; rather, the comings and goings of the average people at the Lake Hotel, what they ate, the perfumes they wore, and their passions for grape juice and gargling. Although some people chide historical archeologists about being "garbage-pickers" and "dumpster-divers," the information uncovered in archeological refuse can give new insights into the history of an area. When people throw items out, they do not expect anyone to come along 80 or 8,000 years later to look at them, so these objects are often less biased than historical documents. Thus, items in historic trash piles can tell us a little more about the people who stayed in the park, at places like the Lake Hotel. There are numerous historic sites in Yellowstone National Park; many of them are trash middens that are full of information if carefully studied as collections by archeologists. The next time you are on a backcountry trail, and you see one of these middens, don't look at it as a dirty pile of trash; think about the people who left that trash there and, unknowingly, left us a tangible piece of themselves that can be added to the historical record of Yellowstone National Park.

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Piscivorous Birds of Yellowstone Lake: Their History, Ecology, and Status

Terry McEneaney

Yellowstone Lake is truly one of the most recognizable geographic features of the Greater Yellowstone area, and, most importantly, the ecological nucleus for native fishes and piscivorous birds in Yellowstone National Park. It is home to the only current nesting colony of American white pelican *(Pelecanus erythrorhynchos)* in the National Park System. It is also unique for having the highest-elevation nesting records in North America for colonial nesting birds such as the American white pelican, double-crested cormorant *(Phalacrocorax auritis)*, California gull *(Larus californicus)*, common loon *(Gavia immer)*, and Caspian tern *(Sterna caspia)*. In excess of 50% of Yellowstone's bald eagle *(Haliaeetus leucocephalus)* and osprey *(Pandion haliaetus)* nesting pairs are currently associated with Yellowstone Lake and its piscine prey. The magnetism of this unique area for birdlife rests on its remoteness, inaccessibility, and abundant food resources. Only two native fishes are found in Yellowstone Lake: the Yellowstone cutthroat trout *(Oncorhynchus clarki bouvieri)* and the longnose dace *(Catostomus catostomus)*. But it is the cutthroat trout biomass that is the main attraction for the piscivorous birds of Yellowstone Lake.

The piscivorous birds and the cutthroat trout of Yellowstone Lake have undergone a kaleidoscope of management practices, public attitudes, philosophical differences, exotic introductions, population changes, and distributional shifts. This paper will intertwine these points while examining the history, ecology, and status of the piscivorous avifauna of Yellowstone Lake.

History

The history, ecology, and status of the piscivorous birds of Yellowstone Lake is best understood by reviewing three important timelines: those of the park itself, of fish management in the park, and of bird management in the park.

By reviewing the Yellowstone timeline, the following events are of significance to the piscivorous nesting birds of Yellowstone Lake:

- 1872: Yellowstone National Park established;
- 1872–1935: predator control era in Yellowstone (this included pelican and eagle eradication);
- 1883: hunting in Yellowstone prohibited;
- 1916–1918: changeover in management authority from the U.S. Calvary to the National Park Service (NPS);
- 1918: Migratory Treaty Act passed, affording some protection for birdlife;
- 1941–1945: World War II;

- 1945–1972: high use of DDT in North America following World War II;
- 1953–1957: DDT spraying in the park to combat spruce budworm;
- 1988: Yellowstone wildfires; and
- 1994: first discovery of exotic lake trout, New Zealand mud snail, and whirling disease.

A review of the fish management timeline reveals the following events that have had a bearing on food abundance for the piscivorous birds of Yellowstone Lake:

- 1872–1948: no fish limits;
- 1889: U.S. Fish Commission and fish stocking program established in the park;
- 1906: 20-fish limit;
- 1948–1953: five-fish limit;
- 1953–1970: three-fish limit;
- 1970–1973: two-fish limit;
- 1973: catch-and-release fishing with size limitations; and
- 2001: catch-and-release fishing for all native fishes.

And lastly, a synopsis of the bird management timeline emphasizes important events that have affected the status of the piscivorous birds of Yellowstone Lake:

- 1890–present: pelican census conducted on the Molly Islands (Yellowstone Lake);
- 1890–1931: era of visitor disturbance on the Molly Islands;
- 1924–1931: pelican control program on the Molly Islands;
- 1945–1959: boat disturbance on and near the Molly Islands;
- 1960–present: the Molly Islands closed to the public (Figure 1);
- 1960–present: no- and slow-motor zones established on the arms of Yellowstone Lake to protect colonial nesting birds and molting waterfowl; and
- 1978–present: campsite closures on Yellowstone Lake to protect nesting ospreys, Frank Island closure to protect nesting ospreys, and Stevenson Island closure to protect nesting eagles.

Ecology

The Yellowstone cutthroat biomass on Yellowstone Lake is what attracts the richness and abundance of piscivorous birdlife. The following birds have been documented as nesting in Yellowstone and feeding on the fish of Yellowstone Lake: Caspian tern, common loon, American white pelican, California gull, double-crested cormorant, osprey, bald eagle, common merganser *(Mergus merganser)*, American dipper *(Cinclus mexicanus)*, great horned owl *(Bubo virginianus)*, common raven *(Corvus corax)*, great blue heron *(Ardea herodias)*, great gray owl *(Strix nebulosa)*, and belted kingfisher *(Ceryl alcyon)*. However, the

Figure 1. Boat disturbance of the Molly Islands from 1945 to 1959 paved the way for a permanent half-mile closure of the islands to the public beginning in 1960.

principal piscine biomass consumers are the first seven species named. Long-term population data also exist for them, thus allowing an opportunity to review the status of each of these important piscivorous bird species. Due to space limitations, the following discussion will be limited to these seven species.

Interestingly enough, the combination of high elevation and harsh weather conditions make the Yellowstone plateau and Yellowstone Lake some of the most inhospitable places found in the temperate zone of North America for nesting birds. Yellowstone Lake typically freezes from December or January through May, thus forcing all seven species to migrate, with the exception of the bald eagle. Some pairs of bald eagles reside on the Yellowstone plateau throughout the winter, seeking out thermal and open areas with an abundance of waterfowl, fish, and carrion. Other pairs move to lower elevations of the Greater Yellowstone area, and carve out an existence there until additional areas open up on the plateau.

Fish biomass availability is critical for piscivorous birds, but the role weather plays in bird production in Yellowstone National Park cannot be overlooked. Flooding, drought, wind, snow load, rain, hail, lightning, and wildfires all play a role in the overall success or failure of each of these piscivorous bird species. These factors coupled with natural predation and human disturbance can influence the success or failure of a species in any given year.

How can these piscivorous birds feed on the same food biomass and in the same habitat without competing with one another? The answer lies in our understanding of the ecological role each piscivorous bird species plays within a community, enabling it to survive by achieving niche separation. Our first clues to understanding the ecological role of piscivorous birds lie in the knowledge of the bathymetry of Yellowstone Lake (Figure 2). The ecological role of these species is best explained through resource partitioning. In other words, these species carve out a different part of the resource which allows them to survive.

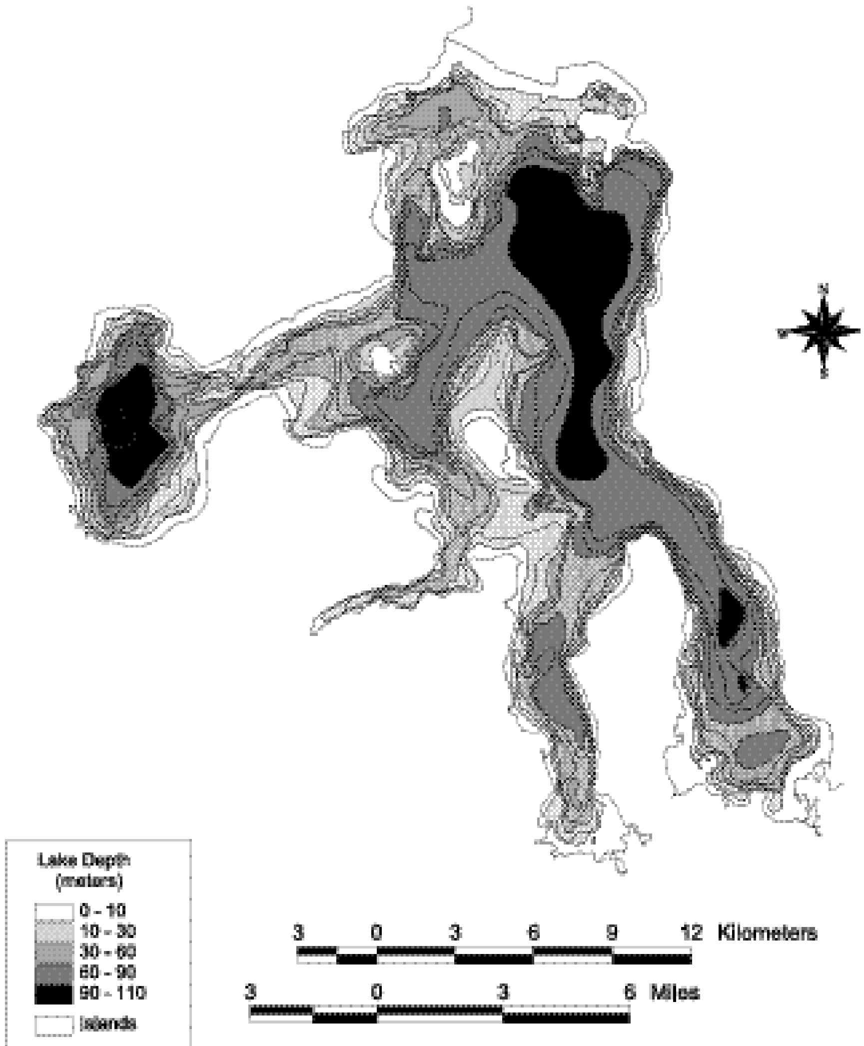

Figure 2. Bathymetry of Yellowstone Lake.

By examining resource partitioning of different lake depths by birds, we find certain birds forage or feed at different depths; thus the term *bathylacustrine foraging.* Species that are surface feeders include the California gull, American

Table 1. Resource partitioning through bathylacustrine foraging.

	Water depth, ft						
	Surface	0-2	2-4	4-6	6-20	20-60	60+
Common loon					•	•	•
Double-crested cormorant					•	•	•
California gull	•	•					
Caspian tern		•	•				
American white pelican	•	•	•				
Bald eagle	•	•	•				
Osprey			•	•			

white pelican, and bald eagle (Table 1). The above species also forage at depths of 0–2 ft, as does the Caspian tern. At depths of 2–4 ft, the Caspian tern, American white pelican, bald eagle, and osprey are often found foraging. Ospreys can dive deeper than bald eagles, and have been observed diving 4–6 ft into the water to secure piscine prey. Ospreys also have the ability to hover, allowing them to forage out in open waters such as are found over much of Yellowstone Lake. The deeper-water feeders are the common loon and the double-crested cormorant, foraging at levels ranging from 6 to over 60 ft deep.

Piscivorous birds have other means of resource partitioning, such as foraging for different-sized fish or allopiscine prey. Some are either specialized or generalized feeders of different-sized fish, depending on their morphology (Table 2). Common loons and double-crested cormorants usually feed on fish that are 2–9 inches in length, more commonly taking those around 6 inches in size. California

Table 2. Resource partitioning of allopiscine prey.

	Length of fish, inches				
	0-2	2-6	6-9	9-11	11+
Common loon		•	•		
Double-crested cormorant		•	•		
California gull	•	•	•	•	•
Caspian tern	•	•			
American white pelican	•	•	•	•	•
Bald eagle				•	•
Osprey			•	•	

gulls, on the other hand, are generalist feeders, consuming fish from 1 to 11+ inches in size, and can secure prey through either foraging or scavenging. Caspian terns take fish that are smaller, rarely if ever exceeding 6 inches in length. American white pelicans are opportunistic feeders and will take any size prey ranging from 1 to 11+ inches. Although they are often observed taking larger fish, smaller fish are also a part of their diet. Bald eagles typically take adult fish often exceeding 11 inches in size, and on occasion take fish as small as 9 inches. Osprey, on the other hand, take smaller, immature fish ranging from 8 to 11 inches in length.

The piscivorous birds of Yellowstone Lake also partition the resource through a variety of foraging habits or techniques (Figure 3). Bald eagles, for instance, typically hunt from an elevated perch, but also hunt in flight. Capturing fish requires diving into the water talons-first, using the wings as floats. If a fish is caught, eagles either take off with the fish in their talons or, if the fish is heavy, paddle to shore with the prey. American white pelicans stalk fish from the surface of the water. Most often they work in synchronous foraging groups, or flotillas, forcing fish to the shore by flaring their colorful feet and dipping their heads in water until they finally catch fish in their distensible pouch. Caspian terns hunt exclusively from the air, searching shorelines and shallow water areas for small schools of fish. When small fish are sighted, the terns plunge into the water before returning to normal flight with fish draped between their mandibles.

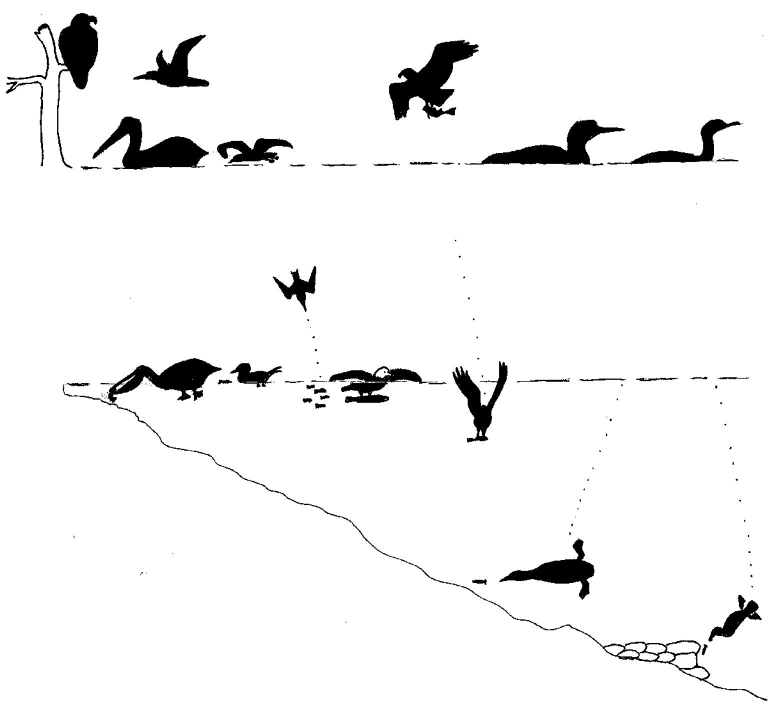

Figure 3. Resource partitioning—foraging habits.

Ospreys can hunt from an elevated perch, but most typically hunt by hovering. Once a fish is sighted, they “stair-step,” dropping in elevation until they finally plunge talons-first into the water. Osprey become totally submerged, then bob back up to the surface and use their wings to lift off. Once the fish is oriented head-first and secured, the osprey does a body shake to eliminate excess water. Common loons dive from a floating position on the surface of the water. They stalk their prey long-distance and catch up with the fish easily due to their speed. When a fish is caught, loons return to the surface where they swallow the fish whole, head-first. Double-crested cormorants also dive from a floating position on the surface of the water. They are best suited for searching the deeper, darker depths or rocky shoal areas, scouring nooks and crannies for prey at close distances. Once a fish is caught, cormorants return to the surface of the water where they, like loons, swallow their prey whole, head-first.

Lastly, resource partitioning of the nesting substrate is another way the piscivorous birds of Yellowstone Lake can exist in the same habitat (Figure 4). Bald eagles select large trees and build large platform nests down in the tree where the nest and young are shaded by the adults early in life and by branches later on. Ospreys typically build in the tops of trees or on rock pinnacles. Their nests have a telescoping profile, i.e., are smaller at the top than at the base. They normally shade the eggs and the young with their wings. Common loons nest on the water’s edge of lakes. Their nest is a simple floating mass of vegetation camouflaged and concealed by the shoreline. Caspian terns, California gulls, American white pelicans, and double-crested cormorants are colonial nesting birds, and all

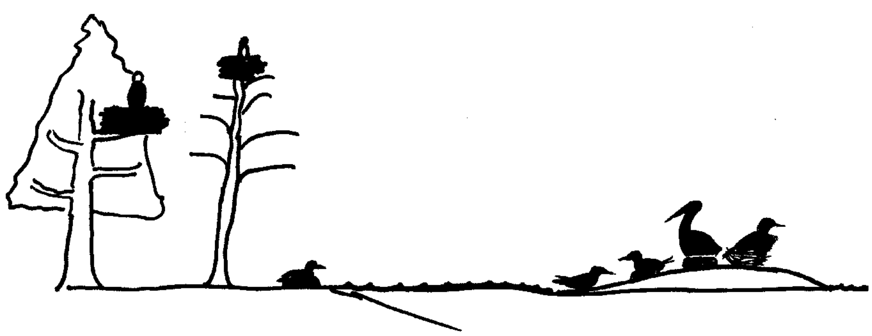

Figure 4. Resource partitioning—nesting substrate.

nest on the Molly Islands. Caspian tern nests are simple scrapes or depressions on a sandy substrate, usually on the lower points of the islands, but are heavily defended by the adults from avian predators. California gulls build very simple nests in rocky substrates midway up on the islands. American white pelicans build simple elevated mounds of sand debris and guano; they nest on the higher parts of the islands. Double-crested cormorants nest on the highest part of the islands. Their nest consists of elevated sticks and weeds cemented by guano.

Status

Determining the true status of birds requires an understanding of the many variables, both natural and anthropogenic, that influence population dynamics. A review of historical management actions, coupled with knowledge of the ecology of the bird, is of paramount importance since it fills in informational gaps regarding a particular species and creates a more complete picture of its status, both past and present.

Osprey. The osprey of Yellowstone National Park and Yellowstone Lake are doing remarkably well (Figure 5). Nesting pairs increased following the 1988 Yellowstone wildfires. Since food is highly abundant, the limiting factor continues to be availability of nest sites. Following the wildfires, snags increased and consequently so did the number of nesting pairs, since osprey most often select burned or dead trees for their nests. Heavy winds knocked down a large number of standing snags, and therefore contributed to the trough experienced in 1995 and 1996. DDT is no longer a threat as it was midway through the last century. Osprey productivity is dynamic and remains weather dependent. In 2001, there were 59 nesting pairs of osprey on Yellowstone Lake, fledging a total of 26 young.

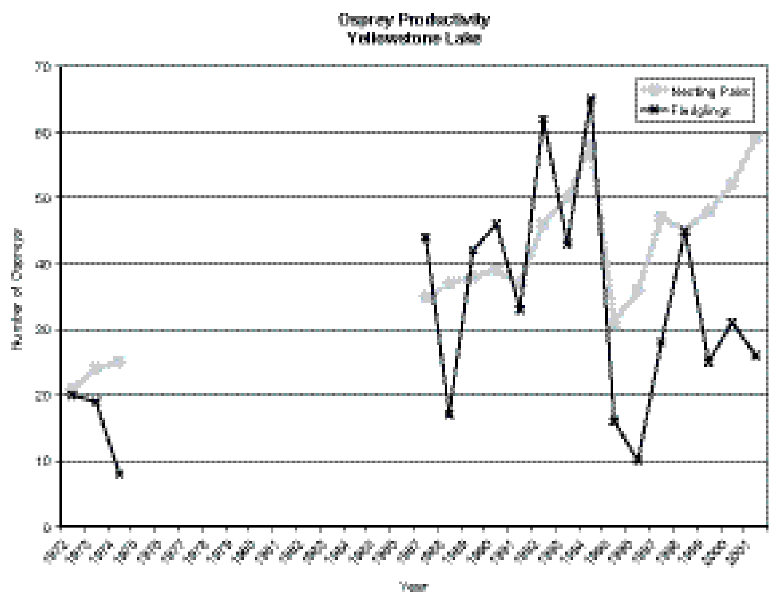

Figure 5. Osprey productivity, Yellowstone Lake, 1972–2001.

Bald eagle. Bald Eagle nesting pairs continue to gradually increase on Yellowstone Lake and throughout the park (Figure 6). Fledgling numbers rarely if ever exceed one per nest. The elimination of DDT in 1972 paved the way for the increase in numbers we experience today. Large nesting trees continue to fall down, contributing to the annual fluctuation of nesting pairs. Bald eagle produc-

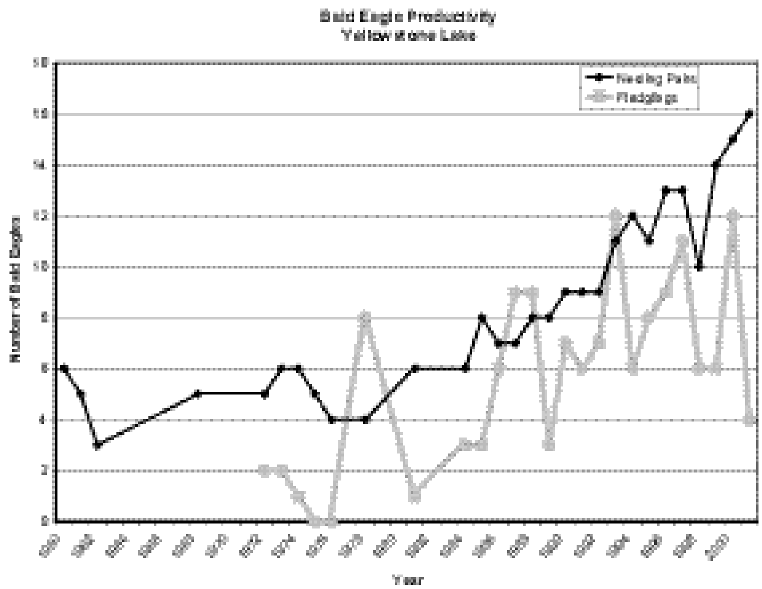

Figure 6. Bald eagle productivity, Yellowstone Lake, 1960–2001.

tivity is dynamic and highly influenced by weather. In 2001, 16 nesting pairs fledged only four eaglets.

Common loon. Only one to two common loon pairs nest on Yellowstone Lake in any given year (Figure 7). Their numbers remain relatively stable with minor fluctuations from year to year. Flooding and drought can have similar negative effects when it comes to nesting. Fledgling loons vary from 0 to 4 in any given year. In 2001, three loonlets fledged from two nests. Yellowstone Lake loons show nearly identical trends parkwide.

Caspian tern. In recent years, Caspian tern numbers have declined (Figure 8). A total of three nesting pairs fledged three young in 2001. In 1990, there were 28 nesting pairs fledging 28 young. Causes for the decline appear to be twofold: weather, in the form of flooding; and disturbance of the islands. Caspian terns are extremely sensitive to disturbance, whether it be from predators or humans. One visit to the islands during incubation or early hatching can result in failure. Even though the Molly Islands are technically closed to the public, occasionally boaters are caught on or close to the islands in a closed area. A concerted effort needs to be made to better educate the boaters of Yellowstone Lake as to the sensitivity of the Molly Islands and to better enforce the closure.

California gull. California gull numbers moderately fluctuate from year to year (Figure 9). During the 1940s, their numbers were significantly higher, which corresponded with the period of boat disturbances on the Molly Islands, allowing a feasting on eggs by predators such as gulls. In 2001, a total of 90 California gulls nested, which resulted in 95 fledglings. Since California gulls nest on the

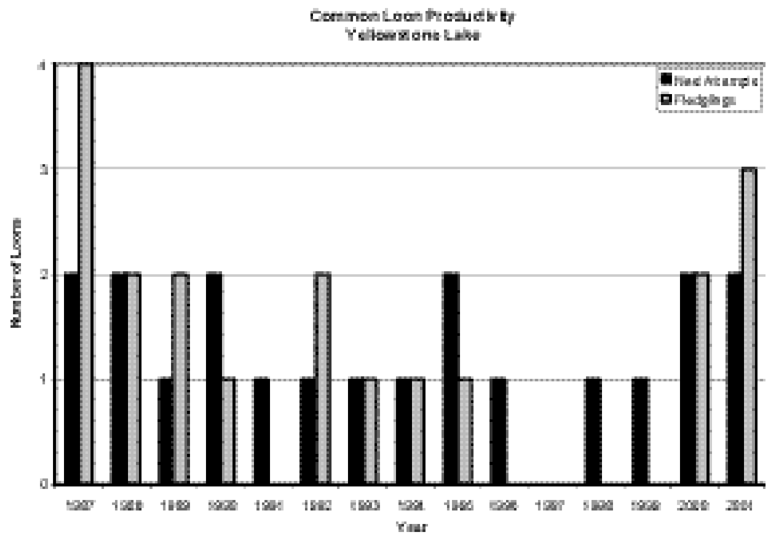

Figure 7. Common loon productivity, Yellowstone Lake, 1987–2001.

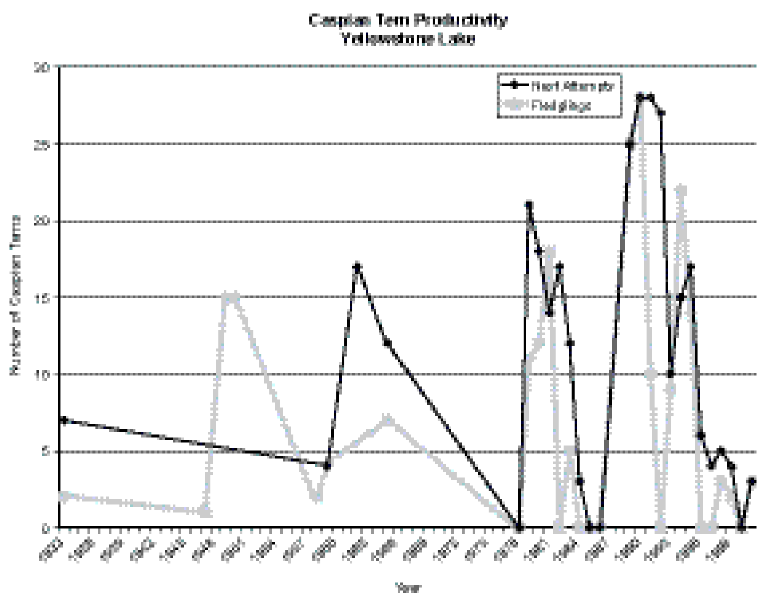

Figure 8. Caspian tern productivity, Yellowstone Lake, 1933–2001.

lower topography of the Molly Islands, they are subject to water-level fluctuations on Yellowstone Lake.

Double-crested cormorant. The double-crested cormorant has increased in Yellowstone National Park since the era of nest disturbance and DDT use ended

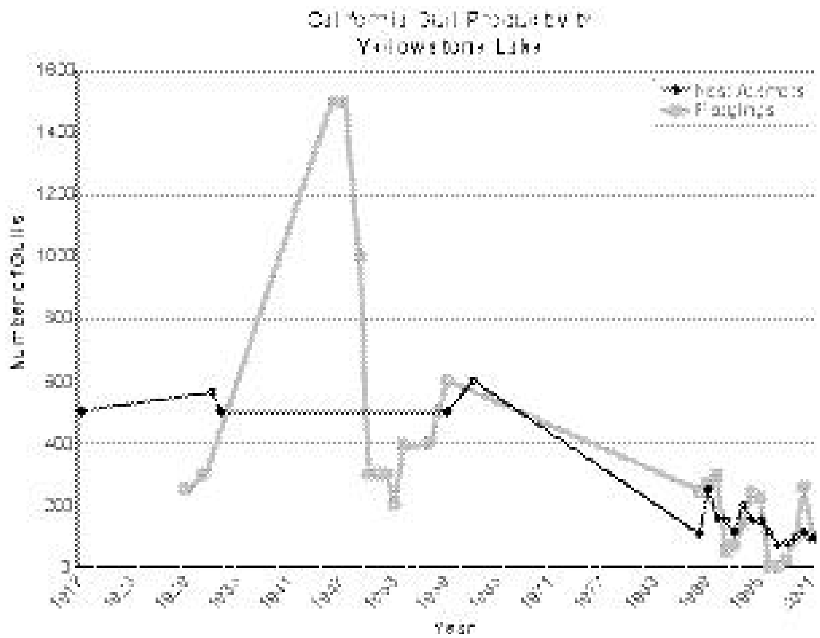

Figure 9. California gull productivity, Yellowstone Lake, 1917–2001.

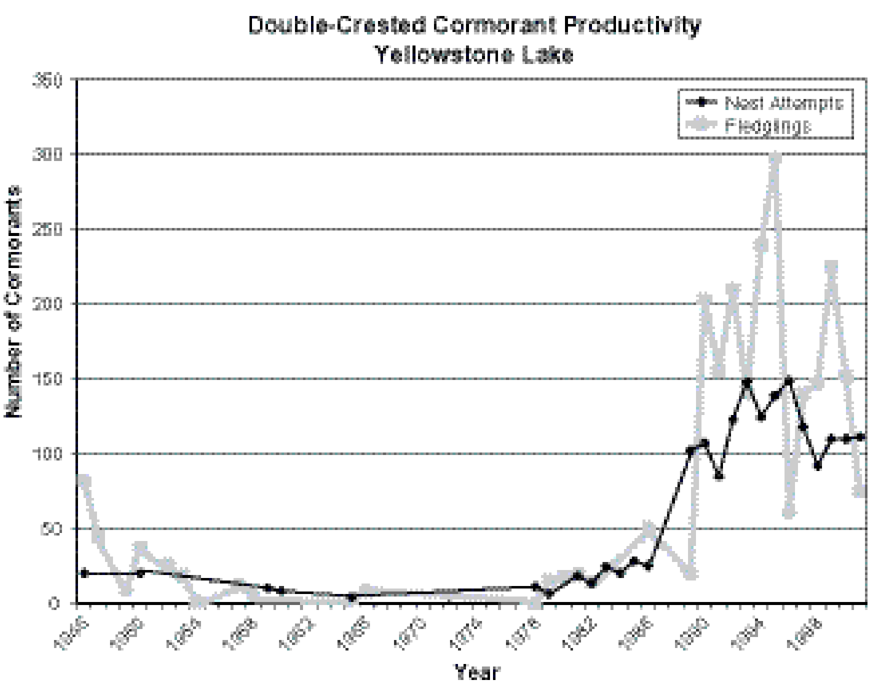

Figure 10. Double-crested cormorant productivity, Yellowstone Lake, 1946–2001.

(Figure 10). Today, the number of nesting pairs and fledglings fluctuates from year to year. Flooding and disturbance are the two principal factors affecting production. In 2001, a total of 111 double-crested cormorant nests were constructed, fledging 75 young.

American white pelican. Of the piscivorous birds found on Yellowstone lake, none have a more pronounced annual fluctuation than the American White Pelican (Figure 11). Pelican control in the 1920s, followed by human disturbances in the 1940s and 1950s, kept the population at low levels. Since that time, pelican numbers have fluctuated greatly from year to year, both in the number of nesting attempts and fledged juveniles. Flooding takes its toll on pelican production, as does disturbance from either humans or predators. Pelican nest attempts

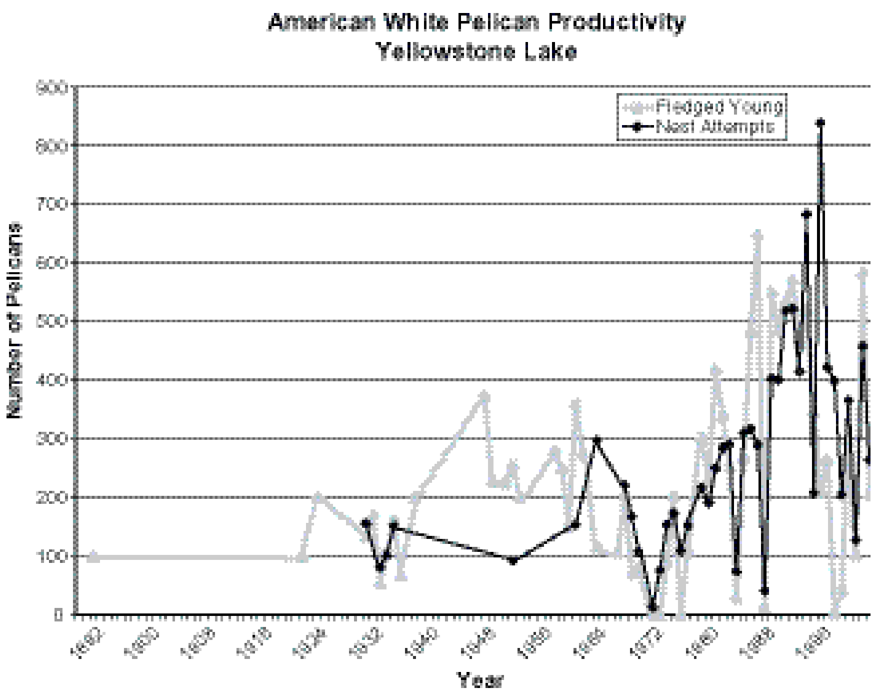

Figure 11. American white pelican productivity, Yellowstone Lake, 1892–2001.

reached their peak in 1994, when 839 pairs nested, whereas peak production occurred in 1985, with 650 fledged juveniles. In 2001, a total of 264 pelicans nested, fledging 205 young.

Yellowstone Lake is a unique, natural, dynamic environment. The importance of fish and fish biomass for the piscivorous birds of Yellowstone Lake cannot be overemphasized. The shallow-spawning cutthroat trout of the lake provide tremendous food biomass for birds and mammals. The discovery of lake trout in Yellowstone Lake in 1994, combined with that of the New Zealand mud snail and whirling disease in the same year, only add fuel to concerns about the ecology of aquatic environments in Yellowstone, such as Yellowstone Lake. On the horizon are other serious threats, such as acid rain, global warming, climate change, methyl mercury contamination from geothermal deposits and natural wildfires, and increases in human visitation to the park.

Making doom-and-gloom predictions about the future of Yellowstone Lake piscivorous birds is not recommended, since there are too many variables to comprehend. Yellowstone Lake is a dynamic aquatic environment, so it is important that we let it play out as naturally as possible with little human intervention.

Summary

The piscivorous birds of Yellowstone Lake have undergone a kaleidoscope of management practices, public attitudes, philosophical differences, exotic introductions, population changes, and distributional shifts. When reviewing the history, ecology, and status of the piscivorous birds of Yellowstone Lake, we find bald eagle and osprey numbers incrementally increasing in recent years. Double-crested cormorant numbers have improved since the first half of the 20th century; however, these numbers show that their populations are starting to stabilize. On the other hand, Caspian tern numbers are decreasing, primarily due to weather and disturbance. California gull numbers have decreased from the mid-20th century, but have now reached a more natural condition. Common loon numbers fluctuate ever so slightly from year to year, whereas American white pelican numbers have improved from the first half of the 20th century. However, they fluctuate wildly from year to year. After 16 years of study, it becomes apparent that weather highly influences bird productivity in Yellowstone.

How do the piscivorous birds of Yellowstone Lake occupy the same habitat? What type of niches do they occupy? This is best explained through resource partitioning of fish prey sizes, foraging at different water depths, foraging using specialized techniques, and selecting different nest substrates, to name a few.

What about the doom-and-gloom predictions for the piscivorous birds of Yellowstone Lake? Does the presence of exotic organisms in an environment automatically mean a decline in indigenous species? Will we lose bird species richness? Probably not. What about species abundance? Perhaps, but we don't know to what degree and what time frame we are talking about. Predictions are useless without completely understanding the byzantine variables involved. The safest action one can take is to just let things play out. Only time will tell. We have no idea what other variables are on the horizon. But in the meantime, we need to keep the human variables to an absolute minimum.

Two thousand years ago, the Roman prescient Lucretius proclaimed, "Once something changes it can never be again what it was before." The same can be said for the ecological complexity of Yellowstone Lake. Monitoring and mitigating for the degree and rapidity by which Yellowstone Lake changes will be the ultimate challenge for this generation of ecologists and those yet to come.

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Recent Changes in Population Distribution: The Pelican Bison and the Domino Effect

Mary Meagher, Mark L. Taper, and Christopher L. Jerde

Abstract

Bison apparently have wintered for centuries in the Pelican Valley area of Yellowstone National Park. Compared with the other locations where bison winter in the park, Pelican Valley routinely experiences the most severe conditions. Nevertheless, a population has survived there because of the presence of geothermally influenced sites. Until 1980, these bison were isolated in winter by deep snows. Both winter and summer range use showed broadly consistent and predictable patterns, as did seasonal movements between range use areas. In the early 1980s, gradual but escalating changes in the bison population became apparent. Annual winter use of foraging areas by the Pelican bison expanded west from traditionally used, geothermally influenced places near the shore of Yellowstone Lake to sedge areas near the mouth of Pelican Creek, Lake area, and on to Hayden Valley. Because Hayden Valley (part of the Mary Mountain unit) was occupied already by wintering bison, as more shifted from Pelican Valley, more bison moved into the Firehole. They also moved earlier. The process of winter range expansion was coupled with a population increase, and more bison moved further west to Madison Junction and beyond, to spill over the park's west boundary into Montana. We term this cascading pattern of population increase *the domino effect.* Concomitantly with the winter westward shift, summer distributions also changed dramatically. The Pelican bison no longer crossed the Mirror Plateau to reach subalpine areas in the upper Lamar country in early summer. Instead, increasing numbers of bison concentrated in Hayden Valley during the breeding season. Some then moved back to the Pelican area before winter set in. With an increased bison population park-wide, numbers also spread across the Lamar Valley in midsummer, and appeared in meadows west and north of Madison Junction where summer use was not recorded previously. Over roughly 20 years, an apparent ecosystem change has occurred involving the bison of the interior of Yellowstone National Park. Although complex and interactive factors involving climatic variation and bison social behavior seem likely to have had a role, another element may have been human-generated. In recent decades, recreational use by people of the park's interior road system in winter resulted in compacted snow surfaces that, in certain locations and times, provided ready-made travel linkages between locations where bison preferred to be. This was seen first in 1980 with bison located on the packed road surface west from the Mary Bay site of the traditional Pelican winter range. The observed changes may not have reached their maximum expression, but the future for the Yellowstone bison does not appear reassuring.

Introduction

A bison *(Bison bison)* population has wintered for centuries in and adjacent to Pelican Valley at the northeast corner of Yellowstone Lake (Figure 1). Compared with the other bison wintering locales in Yellowstone National Park, this area routinely experiences the most severe conditions in terms of snow depths and length of season. However, bison apparently have utilized this winter range for at least 800 years, as suggested by bones at a dated archeological site (Cannon et al. 1997). Winters toward the latter part of the 1800s frequently were more severe (Meagher and Houston 1998) than those in recent decades (and surely were during much of the Little Ice Age, roughly 1450–1750 AD), but regardless, wintering bison survived in this locale. The presence of scattered geothermal sites appears to have been key to the ability of a bison population to survive success-

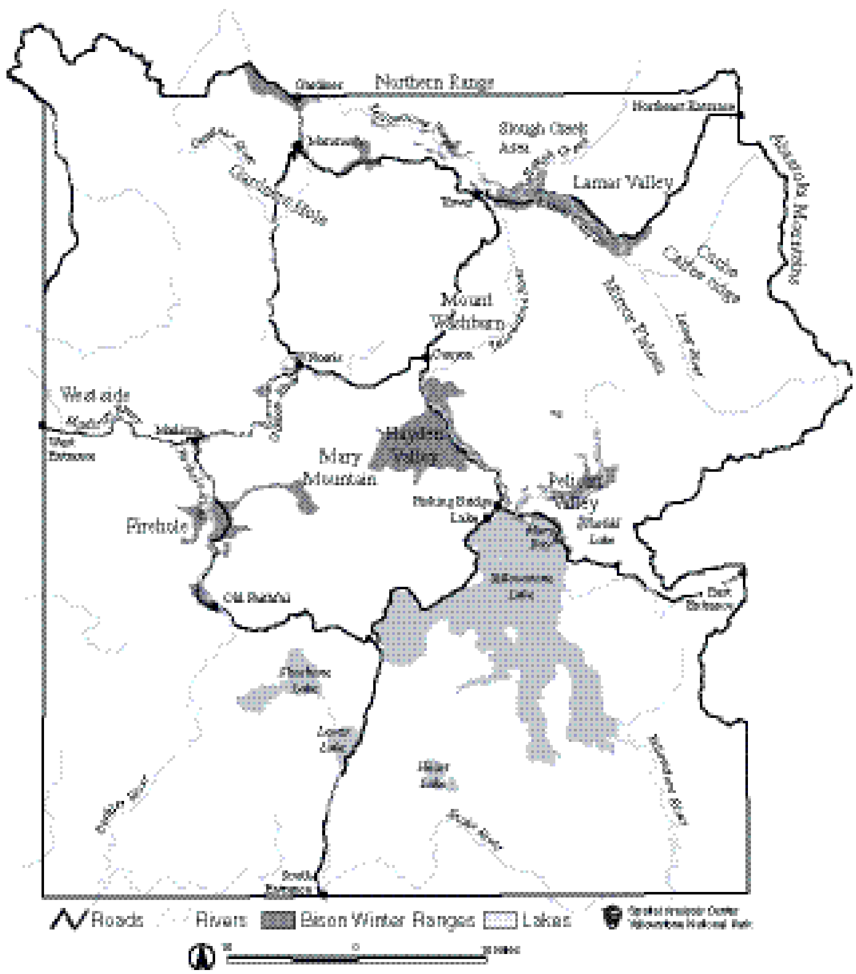

Figure 1. Key bison winter ranges and road system in Yellowstone National Park. (Yellowstone National Park GIS.)

fully through the most severe winters. (The term *geothermal sites* includes a spectrum of geothermal activity that ranges from features such as geysers to geothermally influenced foraging areas where snow depths are less, comparatively, and snow cover lasts a shorter time.) As winter progressed, mixed groups (predominantly females with juveniles and calves) commonly would forage on geothermally influenced sedge areas, and some groups would begin to fragment (stress dispersal) and scatter into small, remote geothermal sites. As conditions moderated, the bison would regroup (Meagher 1971, 1973, 1976). Since park establishment in 1872, limited historical information and subsequent administrative accounts suggest that the seasonal land-use patterns for the early park years were comparable with those described by Meagher (1973), with the Pelican bison wintering apart from other park bison, isolated by deep snows (Figure 2).

In spring (early to mid-June) the Pelican bison traditionally would leave their winter range and move in a generally northeasterly direction, sometimes traversing more than 32 km of snow and melt-water on the Mirror Plateau to cross the Lamar River, and go upward to the greening subalpine vegetation on the westward-facing lower slopes of the Absaroka Mountains. As green-up progressed, the Pelican bison would move higher, usually arriving at the east boundary of the park toward the end of July and early August (Figure 3). By this time, breeding

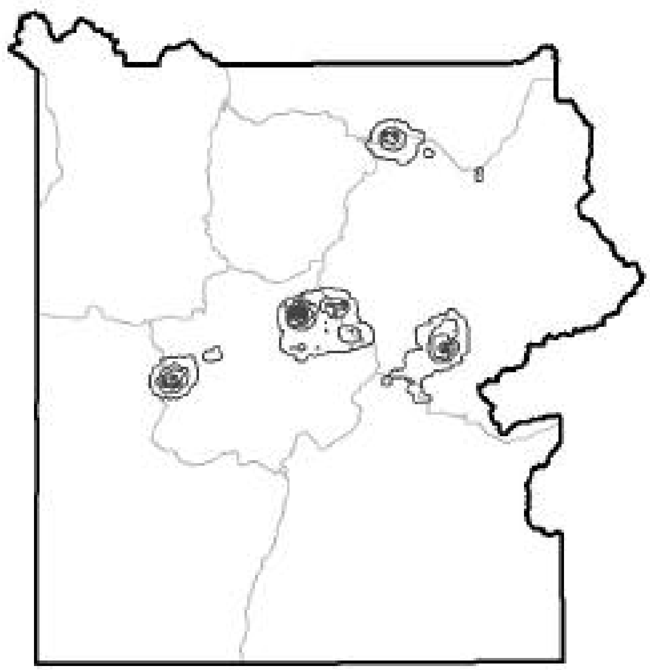

Figure 2. Typical winter distribution in the 1960s and 1970s. The plotted lines indicate contours of proportional use. The outer ring contains 95% of the bison recorded for the flight. Air survey records show only bulls along the lakeshore. Flight 16; date: 14 February 1973; number of bison observed: 702.

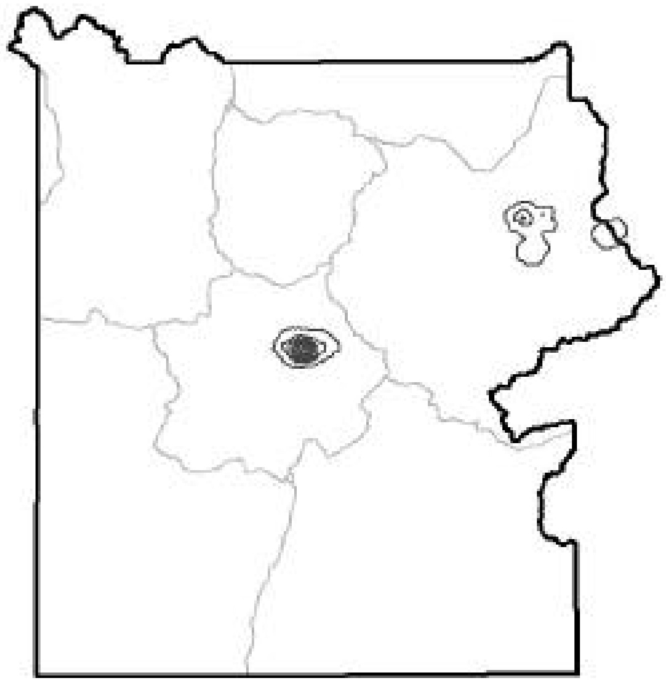

Figure 3. Typical summer distribution in the 1960s and 1970s. The roughly concentric lines indicate proportional use. Note concentration in Hayden Valley and bison presence on the east boundary. Flight 25; date: 29 July 1974; number of bison observed: 832.

season would be underway and the Pelican bison would mix (and interbreed), at least to some extent, with bison from the northern range. Subsequently, groups of bison would recross the Lamar River to the Mirror Plateau. Movements back and forth across the river would continue as the bison utilized various subalpine foraging sites, but they did not stay in the Lamar Valley bottom during spring and summer. Rather they would make large circular movements down and back up, usually spanning 12 to 24 hours. Most of the time they stayed in subalpine areas until storms pushed them down to winter in the lower-elevation valleys of the northern range and Pelican Creek sometime in November. This was the typical land-use pattern that was described for the 1960s (Meagher 1973) and that also prevailed during the 1970s.

In the early 1980s, interior bison land-use patterns began to change. The changes as described here emphasize the bison of the Pelican area, but include the centrally located Mary Mountain (Firehole and Hayden Valley) bison because changes that occurred first on the Pelican winter range appeared to have influenced subsequent changes throughout the interior of the Yellowstone plateau. Generalized descriptive overviews of these bison land-use changes were published earlier (Meagher 1993, 1998; Meagher et al. 1996).

Data Sources

The primary data were derived from 151 aerial surveys of bison numbers and distributions, made from 1970 through July 1997 using a Piper Supercub. The same pilot (Dave Stradley) and observer (Mary Meagher) worked as a team throughout, with rare exceptions for which at least one of those two people was aboard. The data were transferred to a computer, and analyzed as described in Taper et al. (2000). Supplementary ground surveys were made by horseback, foot (skis in winter), and vehicle travel on established park roads. Opportunistic information supplied by park personnel provided additional details. Comparable air and ground methods were used during the 1960s (Meagher 1973).

Bison Land-use Patterns, 1962–1980

In Pelican Valley, bison mixed groups would concentrate initially on sedge foraging areas. As winter progressed, deepening snows eventually closed them out of much of the sedge, and shifts would occur to upland sites, especially the extensive flats above the north side of Pelican Creek, which traverses the length of the valley. Travel trails would develop along south-facing bluff edges and between small hilltops and other accessible forage sites. Usually by the latter part of February, snow depths caused the mixed groups to break into smaller units, sometimes just a few animals, or perhaps a cow with a calf. Commonly, these small groups scattered into widely distributed geothermal sites. Some of these support very limited forage, but there are extensive, interconnected patches of warm, bare ground that allow minimal expenditure of energy (what could be termed a “stand-and-survive” strategy). Warmer parts of major creeks stayed ice- and snow-free and allowed travel and access to creek-bank forage. Some geothermally influenced sites that provided forage also aided travel, including a southward route to the geothermal areas of the lakeshore. Scattered bulls would be found on hilltops, particularly in the western third of the main Pelican Valley, and at various geothermally influenced sites, especially along the shore of Yellowstone Lake east of lower Pelican Creek. Sometimes by late March and early April (while the main valley was still covered with deep snows) mixed groups would move to Mary Bay and nearby geothermal sites. The presence of visible geothermal activity and geothermally influenced foraging sites (with lesser snow depths) appeared to function most years as the survival margin for a bison population in this deep-snow country, especially in late winter (Meagher 1971, 1973, 1976).

As spring developed, forage in geothermal locations in upper Pelican Valley would begin to show new green growth earlier than other places, luring the bison north and east toward the routes used to cross the Mirror Plateau to the subalpine meadows of the upper Lamar area. As the growing season progressed, these bison would move upward to the crest of the Absarokas (Figure 1), usually about the end of July. Thereafter they would make extensive summer range travels that utilized the larger subalpine meadows of both the upper Lamar and the Mirror Plateau.

After the reductions of the 1960s resulted in a park-wide population of approximately 400 bison (Meagher 1973), a moratorium on management actions allowed an increase in numbers. The bison that wintered in the Lamar Valley of the northern range reached ecological carrying capacity for that locale with the unusually compacted snow conditions that prevailed during the winter of 1975–1976, and expanded their range westward (as they did historically) down the topographic and environmental gradient formed by the Yellowstone River (Meagher 1973, 1989). *(Ecological carrying capacity* is the number of animals that a given area can support under current environmental conditions; see Caughley 1976 and MacNab 1985). Ecological carrying capacity will, of course, change yearly as conditions vary. The centrally located herd that utilized the Mary Mountain locale (Firehole and Hayden Valley combined) continued to increase, as did the winter-isolated Pelican bison. For both winter ranges the use patterns remained within traditional locales, as seen in Figure 2.

Changes in Bison Land-use Patterns, 1980–1997

Changes first began with the bison using the Pelican winter range. On 24 February 1980 (a below-average winter for snowfall in the Pelican area as recorded by the Lake snow course), 332 bison were tallied on that winter range. Of these, 157 were scattered among the relatively barren geothermal sites to the northwest of the main Pelican Valley. This number was unprecedented in those locations compared with prior air surveys. The unbroken snow surface and absence of travel trenches in the main valley suggested that they had been there for some time. Most of the remainder were in other geothermally influenced locations, with one striking exception. For the first time, two mixed groups, containing 13 and 29 bison, were seen on and adjacent to the snow-packed road west of Mary Bay (Figure 1). There was no evidence in the snow of bison movement down Pelican Creek to the road (e.g., of snow texture changes, travel indications that would have been apparent even after a new snowfall). The only travel route showing was that which moved southward out of the main valley to the lakeshore geothermal sites.

For comparison, in an air survey of 28 January 1956, 392 bison were counted for the Pelican winter range (after an early-winter reduction of 118). The winter of 1955–1956 was quite severe, and a review of the flight memorandum (D. Condon, unpublished memorandum, 30 January 1956) showed that the majority of the bison were located at geothermally influenced sites, including 64 at the relatively barren locations northwest of the main valley. Interestingly, only 24 were counted just above the mouth of Pelican Creek, with “some” noted as on the road. (At that time the road was seldom used in winter and the snow was not compacted, although a few park employees wintered at the Lake area and might have made an occasional ski trip to the valley). Also, apparently on 25 January 1956, when Hayden Valley was surveyed, perhaps two dozen bison (mixed group) had created a trail through the deep snow along the east side of the Yellowstone River. According to the pilot (J. Stradley, personal communication), these apparently had traveled from the Pelican area. No such movement from the Pelican area to Hayden Valley was known to be repeated before 1984.

On 22 February 1981 (with there being even less snow than during the preceding below-average winter), 482 bison were counted during the survey of the Pelican-area winter range. Of these, 105 were observed near the mouth of Pelican Creek, which included mixed groups of 14, 23, and 38. Again, there was no evidence in the snow of movement from the main valley southwest down Pelican Creek to the road. In 19 winters of air surveys, this was the first time mixed groups were seen in this location. The circumstances indicated that the bison accessed this location by use of the snow-packed road west from Mary Bay.

With the winter of 1981–1982, both interior bison populations (Mary Mountain and Pelican) reached ecological carrying capacity for the conditions of that winter, which was somewhat above average for snowfall. This was evidenced by an estimated 20% population loss (Meagher 1997), reflecting a recorded natural mortality of over 300 bison.

Continued winter air surveys after 1981 showed ever-increasing numbers of bison in mixed groups located on lower Pelican Creek near the mouth and for 1-1.5 km upstream. From there, Pelican bison winter range use expanded to the Fishing Bridge area and upstream for several kilometers on the east side of the Yellowstone River, and westward across the bridge to meadows in the Lake developed area (Figure 1). By the mid-1980s, it was increasingly apparent that Pelican bison were moving all the way to Hayden Valley during the winter. Occasionally they traveled parallel to the east bank of the Yellowstone River, crossing westward at geothermal sites at the south edge of Hayden Valley. More commonly, however, the snow-packed road that follows the Yellowstone River along the west bank served as the travel linkage between the Fishing Bridge–Lake road junction (Figure 1), and Hayden Valley. Repetitive air surveys indicated that movements occurred throughout the winter.

The Domino Effect

With above-average snow conditions for the winter of 1981–1982, small mixed groups, totaling perhaps 45, were seen at Madison Junction during the air survey of 18 February 1982 (Figure 4). Because the snow-covered road was packed between the Firehole and the junction, no travel trails had to be created through unbroken snow. Once before, during the severe winter of 1955–1956 (as shown by snow course records and narrative written comments by park personnel), perhaps 40–50 bison were known to have moved to meadows west of Madison Junction (Meagher 1973). At that time, none of the snow-covered interior park roads were maintained for travel, and use by people was rare.

After the winter of 1981–1982, with the continued absence of human interference with population numbers, the bison of Hayden Valley were at ecological carrying capacity for prevailing winter conditions. Traditionally, even before that winter, as the season progressed and snows deepened, the greater part of the Hayden Valley bison would cross the Mary Mountain divide to the Firehole, where snow depths were consistently lower. This annual shift would increase the numbers wintering on the Firehole, particularly during the latter part of winter. After Pelican area bison moved to Hayden Valley, thereby increasing numbers

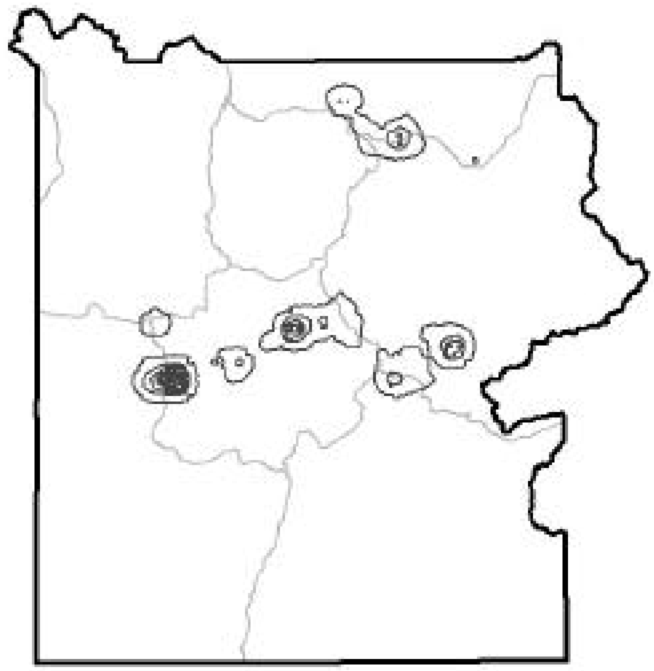

Figure 4. Bison mixed groups at Madison Junction. Note high use on the Firehole. Flight 56; date: 18 February 1982; number of bison observed: 1,907.

there, more bison moved into the Firehole area than would otherwise have been the case. Further, these movements occurred increasingly earlier in the season. Thus, generated by what became an increasing annual winter movement of Pelican bison to Hayden Valley, the distribution and range expansion continued westward (Figure 5). Over time, the interior bison use patterns have shifted westward, with more bison, more of the time, on the Firehole. The movement of Firehole-area mixed groups of bison to Madison Junction that first occurred the winter of 1982 (using the snow-packed road) became an annual occurrence thereafter. And, as more bison moved earlier into the Firehole, more moved earlier, stayed longer, and traveled further west of Madison Junction (Figures 5 and 6). With time, bison mixed groups were commonly seen, even in midsummer, west and north of Madison Junction, and did much shifting between the west side and the Firehole.

Finally, during a few of the winters of the 1990s, bison groups traveled the entire distance from Madison Junction north to Mammoth and the north boundary. During the exceptionally severe winter of 1996–1997, the timing and size of bison removals at boundary areas indicated that between 320 and 350 bison had done this (Taper et al. 2000). Bison have demonstrated a capacity to learn (Meagher 1989), and approximately 30 made this same trip in late October 2000, when the ground was as-yet essentially snow-free along the road corridor. Because the changes that have occurred in interior bison distributions and move-

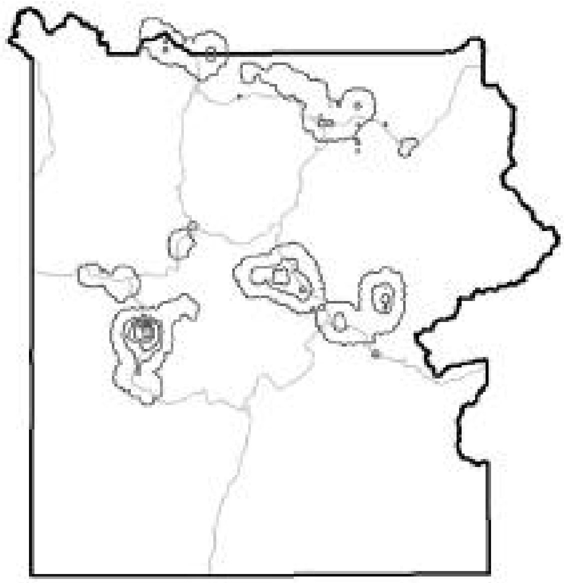

Figure 5. Pelican range expansion merged into Hayden Valley. Note bison west and north of Madison Junction. Flight 71; date: 11 February 1986; number of bison observed: 2,285.

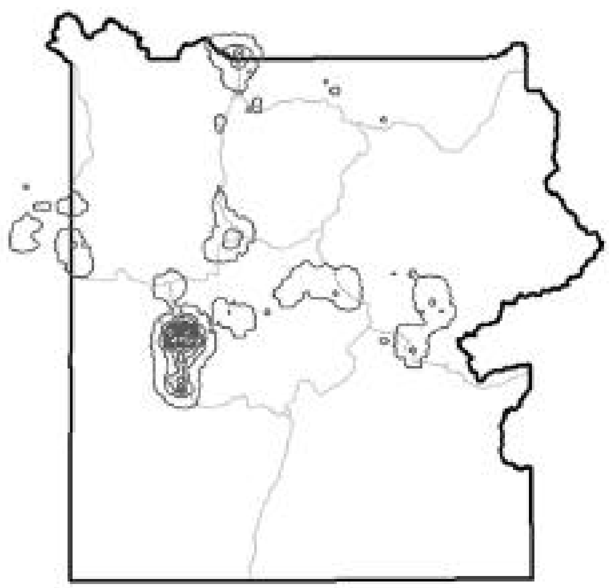

Figure 6. Bison distribution in late February 1996–1997. By this time hundreds had been removed at and outside park boundaries. Flight 145; date: 21 February 1997; number of bison observed: 1,718.

ments apparently began with a west-and-north winter range expansion by Pelican-area bison, and have escalated over the past two decades, we have termed the changes in use patterns *the domino effect.*

Changes in Bison Summer Range Patterns After 1983

The air survey of 21 July 1983 marked the last time bison groups were observed on the crest of the Absarokas south of the head of the Cache-Calfee ridge. Long-term experience indicated that these were probably bison that had come from the Pelican winter range. Some Pelican bison apparently did cross the Mirror Plateau to some of the lower slopes of the Absaroka Mountains during the summer of 1985, but they did not move higher to the crest of the range (D. Stradley, personal communication). Air surveys through the summer of 2001 have not located mixed groups of bison on the east boundary (Taper et al. 2000; J. Mack, personal communication), nor has there been any indication since 1985 that Pelican bison have crossed the Mirror Plateau.

The air survey of 9 August 1984 showed another major change in summer range use. Of 588 bison counted for the northern range unit, 477 were down in the Lamar Valley. These numbers must have included some of the bison that had wintered in the Pelican area, as only 119 bison were located in the subalpine meadows of the Mirror Plateau. This kind of distribution became an annual summer occurrence thereafter.

The seasonal shift of the interior population westward has resulted in enormous summer breeding season congregations of bison in Hayden Valley, sometimes reaching approximately 3,000 animals (Taper et al. 2000). In August, those with affinities for the Pelican winter range would begin to move back to that locale. However, as soon as winter set in, they would start to shift back to Hayden Valley. This seasonal shifting back and forth resulted in larger numbers of bison utilizing interior winter ranges earlier and in greater numbers than had been the pattern prior to the beginnings of winter movement of Pelican bison to Hayden Valley. Preliminary information indicated that this circumstance may be generating habitat degradation in at least some geothermal areas. Four comparative photographs taken from 1912 through 1997 appeared to show directional changes in quantity of vegetative cover that appeared to be supported by the particular characteristics of those soils (Taper et al. 2000).

Pelican-area Winter Use Patterns, 1998–2001

Pelican-area winter use patterns have become very fluid. Prior to the above-observed changes, long-term records suggested that a minimum of approximately 100 bison would remain to survive, regardless of winter severity (Meagher 1971, 1973, 1976). This was evidenced by the winter of 1942–1943 (a recorded 122 bison) and by the comparable winter of 1996–1997, when 94 bison were located in the air survey of 19 May 1997. Because movements from Pelican Valley to Hayden Valley went on throughout the winter, as indicated by decreased numbers with each air survey, the lowest count (minus new calves) in late May and very early June reflected the numbers that spent the entire winter in the Pelican area. Comparable surveys for May 1998 and 1999 (J. Mack, personal communication) showed some increase, with 145 and 152 counted, respectively.

In contrast, the end-of-winter Pelican-area surveys for 2000 and 2001 (J. Mack, personal communication) dropped to 50 and 47, respectively. For 2000, a detailed review of the Pelican-area survey, coupled with attached map coordinates, allowed scattered bulls that winter in certain sites apart from the rest of the bison to be separated from the total. When both scattered bulls and newly born calves were discounted, only 24 bison were recorded as mixed groups. This is nearly the same as the historically recorded low of 22 in 1902 (Meagher 1973), after cessation of poaching.

Major changes have been observed over the past two decades in the wintering numbers, distribution, and seasonal movements of the bison of the interior of Yellowstone National Park, beginning with those that wintered in Pelican Valley. The analyses of the computerized data from the air surveys of 1970–1997 (Taper et al. 2000) showed changes in bison numbers, distribution, timing of seasonal movements, and social behavior such as group size and cohesiveness. Additional analyses of the habitat data (Jerde et al. 2001) also showed changes in use patterns.

The continued decrease by Pelican-area bison to historic lows that were observed during the winters of 1999–2000 and 2000–2001 reinforce an interpretation that indicates a very fluid and perhaps unstable situation, geographically speaking, in the bison that inhabit the interior of the Yellowstone plateau. Key to this is the long-observed determination of bison to maintain group social bonds if at all possible. Although they can survive by breaking social bonds and scattering into geothermal sites, if presented with a choice they will move preferentially to maintain a higher level of aggregation. They will also shift toward less harsh winter conditions, as is usual with ungulates in mountain habitat. Over time, as this has occurred, many more bison have exited the park in an apparent effort to maintain social aggregations that the within-park habitat would not permit. In so doing, they have come into conflict with different land-use objectives outside the park. Although attempts have been made to force them back into the park, this has been a short-term solution at best, and most have been removed from the population under state legal authority. This situation can be expected to continue.

The data do not provide a cause-and-effect relationship for the observed changes. Interacting factors of environmental fluctuations and bison behavior likely are involved, even as those factors influenced the bison historically. But the air surveys and observational information suggest that another (and also interactive) element may have a role. This is the relatively recent addition of snow-packed travel linkages formed by sections of interior park roads between and within some areas of bison use. The use of snow-packed or plowed roads certainly represents some energy savings to the central herd, and even provides access to areas that would otherwise be inaccessible to bison. It is unclear if these energy savings have merely facilitated a population and range expansion that would have occurred anyway, or if an apparently minor change has upset a delicately balanced demography and caused the expansion. This raises the possibility that the changes in the bison population and their relationships with their habitat may have a human-caused influence.

The changes appear to be ongoing, and the fluidity of bison shifts suggests that large movements of interior bison across park boundaries likely will occur in the future. These bison probably will be removed from the population. This, coupled with the fluidity of movements and the possibility of habitat changes inside the park, suggests that overall numbers likely will decrease. The summation of the observed changes suggests an uncertain future for the interior park bison.

Acknowledgments

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Mapping the Floor of Yellowstone Lake: New Discoveries from High-Resolution Sonar Imaging, Seismic-Reflection Profiling, and Submersible Studies

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W. J. Stephenson, and S. Y. Johnson

"…we arrived at the summit of the first ridge…It was a pretty steep climb to the top of it, over a volcanic sand composed of broken down obsidian which composed the only rocks around us."

—Albert Peale, mineralogist,
U.S. Geological Survey, Hayden Survey, August 6, 1871.

Abstract

Recently completed multi-beam sonar-imaging and seismic-reflection surveys of the northern, West Thumb, and central basins of Yellowstone Lake provide insight into post-caldera volcanism and active hydrothermal processes occurring in a large lake environment above a cooling magma chamber. High-resolution mapping of the lake floor reveals an irregular lake bottom covered with dozens of features directly related to hydrothermal, tectonic, volcanic, and sedimentary processes. Newly mapped rhyolitic lava flows that underlie much of Yellowstone Lake exert fundamental control on lake geology, basin bathymetry, and localization of hydrothermal vent sites. Imaged and identified features include over 150 hydrothermal vent sites, several very large (>500 m diameter) and many small hydrothermal explosion craters (~1-200 m diameter), elongate fissures cutting post-glacial (<12 ka) sediments, siliceous hydrothermal spires as tall as 8 m, sublacustrine landslide deposits, deformed lacustrine sediments associated with domal structures and hydrothermal vents, submerged former shorelines, and a recently active graben, all occurring within the southeast margin of the 0.640-Ma Yellowstone caldera. Sampling and observations with a submersible remotely operated vehicle (ROV) confirm and extend our understanding of many of the identified features.

Introduction

Several powerful geologic processes in Yellowstone National Park have contributed to the unusual shape of Yellowstone Lake, which straddles the southeast margin of the Yellowstone caldera (Figure 1). Volcanic forces contributing to the lake's form include the 2.057 ± 0.005-Ma (1-σ) caldera-forming eruption of the Huckleberry Ridge Tuff followed by eruption of the 0.640 ± 0.002-Ma Lava Creek Tuff to form the Yellowstone caldera (Christiansen 1984; Christiansen 2001; Hildreth et al. 1984; U.S.G.S. 1972). A smaller caldera-forming event about 140 ka, comparable in size to Crater Lake, Oregon, created the West Thumb basin (Christiansen 1984; Christiansen 2001; Hildreth et al. 1984; U.S.G.S. 1972). Large-volume postcaldera rhyolitic lava flows are exposed west of the lake (Figure 1B). Several significant glacial advances and recessions overlapped the volcanic events (Pierce 1974; Pierce 1979; Richmond 1976; Richmond 1977) and helped to deepen the fault-bounded South and Southeast Arms (Figure 1B). More recent dynamic processes shaping Yellowstone Lake include currently active fault systems, erosion of a series of postglacial shoreline terraces, and postglacial (<12 ka) hydrothermal-explosion events, which created the Mary Bay crater complex and other craters.

Formation of hydrothermal features in Yellowstone Lake is related to convective meteoric hydrothermal fluid circulation above a cooling magma chamber. Hydrothermal explosions result from accumulation and release of steam generation during fluid ascent, possibly reflecting changes in confining pressure that accompany and may accelerate failure and fragmentation of overlying cap rock. Sealing of surficial discharge conduits due to hydrothermal mineral precipitation also contributes to over-pressuring and catastrophic failure. Heat-flow maps show that both the northern and West Thumb basins of Yellowstone Lake have extremely high heat flux compared to other areas in the lake (Morgan et al. 1977). Earthquake epicenter locations indicate that the area north of the lake is seismically active (Smith 1991), and ROV studies identify hydrothermally active areas within the lake (Klump et al. 1988; Remsen et al. 1990).

Objectives of this work include understanding the geologic processes that shape the lake and how they affect the present-day lake ecosystem. Our three-pronged approach to mapping the floor of Yellowstone Lake is designed to locate, image, and sample bottom features such as sublacustrine hot-spring vents and fluids, hydrothermal deposits, hydrothermal-explosion craters, rock outcrops, slump blocks, faults, fissures, and submerged shorelines. Chemical studies of the vents indicate that 20 percent of the total deep thermal water flux in Yellowstone National Park occurs on the lake bottom (Morgan et al. 2003). Hydrothermal fluids containing potentially toxic elements (As, Sb, Hg, Mo, W, and Tl) significantly affect lake chemistry and possibly the lake ecosystem. ROV observations indicate that shallow hydrothermal vents are home to abundant bacteria and amphipods that form the base of the food chain, which includes indigenous cutthroat trout, piscivorous exotic lake trout, and grizzly bears, bald eagles, and otters that feed on the potamodromous cutthroat trout during spawning in streams around the lake. Finally, our results document and identify potential geologic hazards associated with sublacustrine hydrothermal explosions, landslides, faults, and fissures in America's premier National Park.

Methods

Yellowstone Lake mapping and sampling conducted in 1999 through 2001 as a collaborative effort between the U.S. Geological Survey, Eastern Oceanics, and the National Park Service (Yellowstone National Park) utilized bathymetric, seismic, and submersible remotely operated vehicle (ROV) equipment as follows.

Figure 1A.

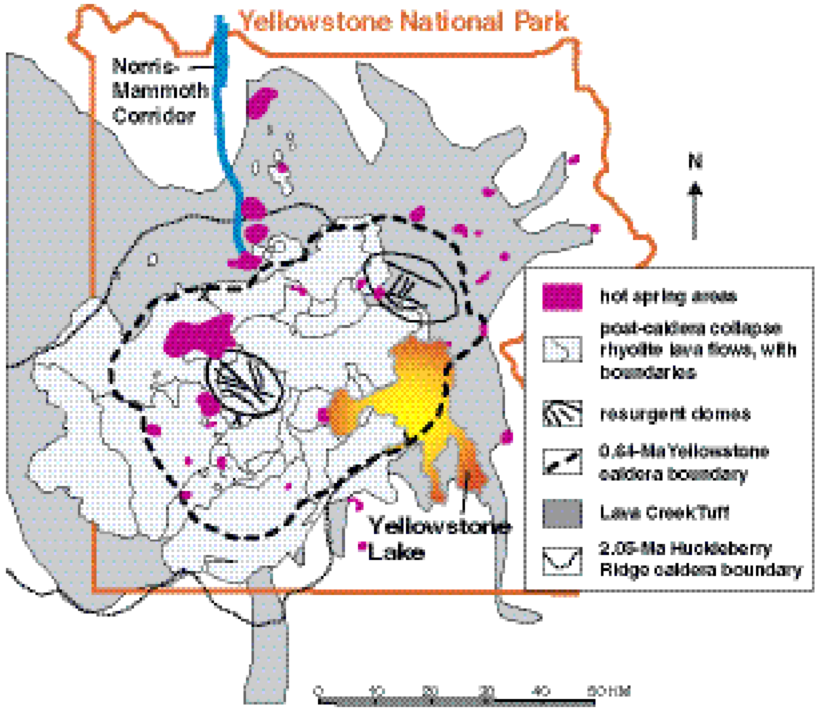

Figure 1B.

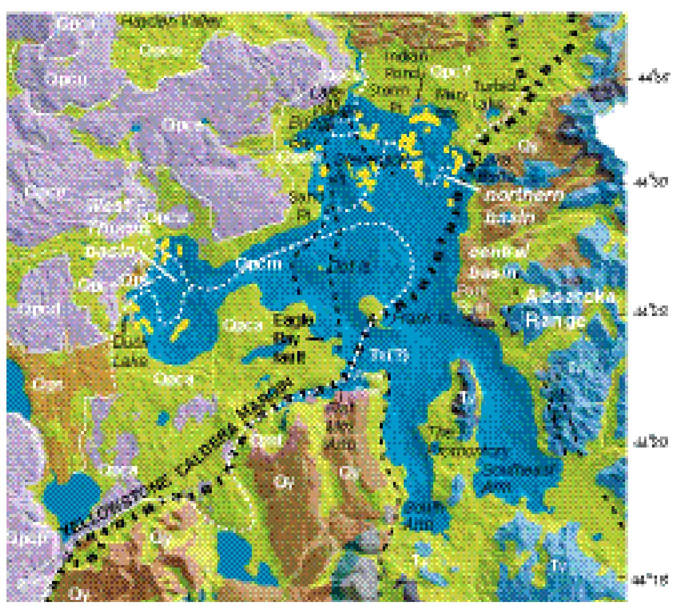

Figure 1. (A) Index map showing the 0.640-Ma Yellowstone caldera, the distribution of its erupted ignimbrite (the Lava Creek Tuff, medium gray), post-caldera rhyolitic lava flows (light gray), subaerial hydrothermal areas (red), and the two resurgent domes (shown as ovals with faults). The inferred margin of the 2.05-Ma Huckleberry Ridge caldera is also shown. Data are from Christiansen 2001. (B) Geologic shaded relief map of the area surrounding Yellowstone Lake in Yellowstone National Park. Geologic mapping is from USGS 1972 and Yellowstone Lake bathymetry is from Kaplinski 1991. Yellow markers in West Thumb basin and the northern basin are locations of active or inactive hydrothermal vents mapped by seismic reflection and multibeam sonar. The lithologic symbols are as follows: Tv = Tertiary volcanic rocks; Qps = tuff of Bluff Point; Qpcd = Dry Creek flow; Qpcm = Mary Lake flow; Qpca = Aster Creek flow; Qpcw = West Thumb flow; Qpce = Elephant Back flow; Qpch = Hayden Valley flow; Qpcn = Nez Perce flow; Qpcp = Pitchstone Plateau flow; Qs = Quaternary sediments (yellow); Qy = Quaternary Yellowstone Group ignimbrites (brown; Christiansen 2001; USGS 1972). Location of Yellowstone caldera margin is from Christiansen 1984, with slight modifications from Finn and Morgan 2002. *Funding for the color images printed in this article was provided by the U.S.G.S.*

Multi-beam swath-bathymetric surveys were conducted using a SeaBeam 1180 (180 kHz) instrument with a depth resolution of about 1% water depth. Water depth varied from ~4 to 133 m in the survey areas. The multi-beam instrument uses 126 beams arrayed over a 150° ensonification angle to map a swath width of 7.4 times water depth. In the West Thumb basin survey, 99% complete bathymetric coverage was accomplished using the multi-beam system whereas the northern Yellowstone Lake coverage was 95%. Sub-bottom seismic reflection profiling was done with an EdgeTech SB-216S, which sweeps a frequency range from 2 to 16 kHz and has a beam angle of 15–20°. Both the swath unit transducer and the sub-bottom unit were rigidly mounted to the transom of an 8-m aluminum boat used for survey purposes. The Eastern Oceanics submersible ROV is a small vehicle (~1.5 m x 1 m x 1 m) attached to the vessel with a 200-m tether that provides live videographic coverage and remote control of submersible thrusters, cameras, and sampling equipment. This vehicle has a full-depth rating of 300 m and is capable of measuring temperature, conductivity, and depth and of retrieving uncontaminated hydrothermal vent water samples and rock samples up to ~40 cm-long. Previous bathymetric mapping of the lake used a single-channel echo sounder and a mini-ranger for navigation (Kaplinski 1991) requiring interpolation between lines. The new swath multi-beam survey produced continuous overlapping coverage, producing high-resolution bathymetric images and seismic records of the upper 25 m of the lake bottom.

Flow modeling was carried out using the program Basin2, v. 4.0.1, 1982–1999, developed by Craig Bethke, University of Illinois. This program uses finite difference methods to solve Darcy's law for fluids of varying density. The program allows the user to model topographic, compaction-driven, and/or convective flow by setting parameters related to fluid density, heat capacity, heat flow, porosity and permeability. Lava flow schematic shown in Figure 4 modified from (Bonnichsen and Kauffman 1987).

Interpretation of Individual Features

Margin of the caldera: Mapping of Yellowstone Lake has been primarily in the 0.64-Ma Yellowstone caldera but it was not until the central basin was mapped that the margin of the caldera was identified, here as a series of elongate troughs. Geologic maps show the margin of the Yellowstone caldera entering the western part of Yellowstone Lake at the entrance to Flat Mountain Arm and resurfacing north of Lake Butte (Figure 1B). The location of the caldera margin between these points has had various interpretations, based primarily on lower resolution bathymetry. Previous interpretations include a margin trending north of Frank Island as well as an inferred margin south of Frank Island. Based on new data, we infer the margin of the Yellowstone caldera to pass through the southern part of Frank Island.

High-resolution aeromagnetic maps (Finn and Morgan 2002) of Yellowstone Lake show a series of discontinuous moderate amplitude negative magnetic anomalies in the southeast part of the central basin (Figure 2A). These anomalies coincide with bathymetric lows as identified in the new sonar image mapping. Careful examination of the bathymetry on Figure 3 shows these lows to extend as a series of elongated troughs northeast from Frank Island across the deep basin of the lake. Similar, though somewhat smaller, troughs emerge on the western side of Frank Island and continue toward the head of Flat Mountain Arm. Here, the caldera margin separates Tertiary andesitic rocks and pre-caldera and caldera rhyolitic rocks to the south from young, post-caldera rhyolites to the north and northwest.

Examination of the reduced-to-the-pole aeromagnetic map shows pronounced positive magnetic anomalies over the Absaroka Range along the eastern side of Yellowstone Lake (Figure 2A). Rugged topographic relief and predominantly highly magnetized rock give the area its high positive magnetic character. Similarly magnetized material occurs along Promontory Point where Tertiary andesitic lava and debris flows are prominently exposed in cliffs several hundred meters thick. The magnetic signature is repeated north and east of Plover Point in southern Yellowstone Lake and along the eastern shore of the lake near the outlet for Columbine Creek. Finn and Morgan (2002) suggest that this series of positive magnetic anomalies are caused by Tertiary volcanic rocks at the surface, as exposed at Promontory Point and in the Absaroka Range, or buried at shallow depths in the lake, such as north of Plover Point northward into the southern third of Frank Island or due west along the eastern shore (Figure 2A).

From west to east, we interpret the margin of the caldera within the lake to pass in a general eastern direction following Flat Mountain Arm, then northeastward cutting through the southern part of Frank Island, and then again northeastward (Figure 3). The amplitudes of magnetic anomalies on the northern part of Frank Island are similar in character as those associated with postcaldera rhyolitic lava flows, such as much of the West Thumb, Hayden Valley, or Aster Creek flows (Figure 2A). In contrast, the amplitude of the magnetic anomaly on the southern side of the island is steeper of greater magnitude and similar to that seen in the Absaroka or Promontory Point. This location of the caldera margin based on mapped geology on land and the series of magnetic anomalies in the lake is consistent with the recently acquired bathymetry (Figures 1, 2, 3).

Rhyolitic lava flows: A major discovery of the surveys is the presence of previously unrecognized rhyolitic lava flows on the floor of the lake. The lava flows are key to the control of many geologic and hydrologic features in the lake.

Areas of the lake bottom around the perimeter of West Thumb basin (Figure 3) have steep, nearly vertical margins, bulbous edges, and irregular hummocky surfaces. Seismic-reflection profiles in the nearshore areas of West Thumb basin show high-amplitude reflectors beneath about 7–10 m of layered lacustrine sediments (Figure 4A). We interpret these sublacustrine features to be buried rhyolitic lava flows that partly fill the interior of the 140-ka West Thumb caldera. Subsequent sampling with the submersible ROV collected rhyolite from an inferred lava-flow area in east-central West Thumb basin.

In the northern and central basins, similar features also are present. Sublacustrine rhyolitic lava flows in the northern and northeastern areas of the northern basin are inferred from the bathymetry and do not have mapped subaerial equivalents. These features also could represent shallow rhyolitic intrusions. A dominant lithic clast present in the hydrothermal explosion breccia of Mary Bay and prevalent in the alluvium of the lower Pelican Valley (Figure 1B) is a quartz-rich porphyry that has not been described before. These porphyry clasts may be derived from a buried volcanic unit in the lower Pelican Valley that may be producing the moderate positive magnetic anomaly seen here (Finn and Morgan 2002) (Figure 2).

Large-volume rhyolitic lava flows (10's of km^3) on the Yellowstone Plateau control much of the local hydrology. Stream drainages tend to occur along flow boundaries, rather than within flow interiors. Characteristic lava-flow morphologies include near-vertical margins (some as high as 700 m), rubbly flow carapaces, hummocky or ridged tops, and strongly jointed interiors. Spherulitic and lithophysal zones commonly include large cavities. Many flows have vitrophyric exterior rinds with shrinkage cracks and sheet-jointed crystallized interior zones. Breccias occur locally.

In many exposures of postcaldera rhyolite lava flows near the current margins of Yellowstone Lake, including West Thumb basin, and north of the lake in Hayden Valley, ample evidence exists for interaction between emplacement of hot rhyolitic lava flows and standing water. Clastic dikes, highly fractured perlitic vitrophyre, massive rhyolitic breccias with fine-grained and altered matrix, and entrained stream, beach, and lake sediments point to emplacement of lavas in an aqueous environment.

Magnetic signature of rhyolitic lava flows: Comparison of the new high-resolution aeromagnetic maps (Finn and Morgan, 2002) (Figure 2) with geologic maps (Figure 1B) (Blank 1974; Christiansen 1974; Christiansen and Blank 1975; Richmond 1973) shows a close relationship of magnetic anomalies to the mapped individual lava flows. Moderate-amplitude positive magnetic anomalies coincide with the mapped extent of subaerial post-caldera rhyolitic lava flows (Finn and Morgan 2002) and extend into the sublacustrine environment in many

Figure 2A.

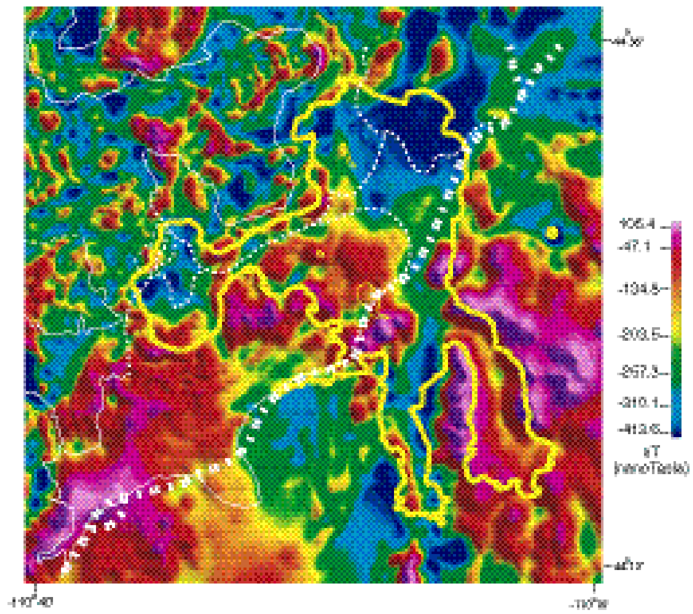

Figure 2B.

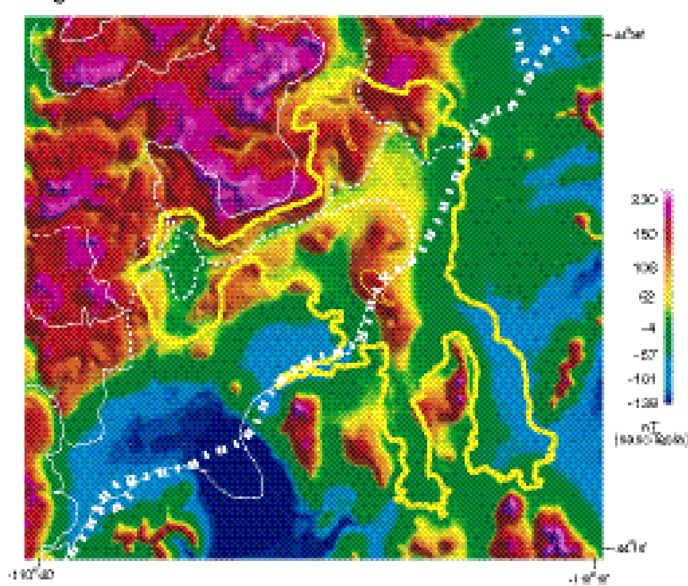

Figure 2. (A) Color shaded-relief image of high-resolution, reduced-to-the-pole aeromagnetic map (Finn and Morgan 2002). Sources of the magnetic anomalies are shallow and include the post-caldera rhyolite lava flows (some outlined in white), which have partly filled in the Yellowstone caldera. Commonly, rhyolitic lava-flow margins have impermeable glassy rinds that are not subject to hydrothermal alteration, producing distinctive positive magnetic anomalies. Extensive areas of negative magnetic anomalies in the West Thumb and northern basins and along the caldera margin northeast of the lake are areas of high heat flow and intense present and past hydrothermal alteration, as suggested by sublacustrine vent locations (Figure 1B). (B) Color-shaded relief image of the magnetic anomaly due to uniformly magnetized terrain in the present Earth's field direction of inclination =70° and a declination of 15° with an intensity of 2.5 A/m, and then reduced to the pole (Finn and Morgan 2002). Rhyolitic lava flows (outlined in white) underlying Yellowstone Lake are shown clearly on this map.

areas (Figures 1, 2, 3). For example, northwest of the northern lake basin, moderate-amplitude magnetic anomalies correspond to mapped subaerial postcaldera rhyolitic lava flows (Figure 1B) and extend from land into the lake (Figure 2A). Similarly, mapped subaerial lava flows around West Thumb basin and west of the central lake basin can be extended into the lake based on moderate amplitude positive magnetic anomaly patterns (Figure 2). These characteristic magnetic signatures, in combination with the new bathymetric and seismic data, allow identification and correlation of rhyolitic lava flows well out into the lake.

In the northern basin, negative magnetic anomalies (Figure 2A) are extensive. Excessively high heat flow in the Mary Bay area (1,550–15,600 mW/m^2) (Morgan et al. 1977), in part related to proximity to the margin of the Yellowstone caldera, indicates that hydrothermal activity has destroyed or significantly reduced the magnetic susceptibility of minerals in rocks and sediments producing the observed negative magnetic anomalies. Comparison of the reduced-to-the-pole magnetic anomalies (Figure 2A) with those caused by uniformly magnetized terrain (Figure 2B) draws attention to areas, such as in the northern basin at Mary Bay or near Stevenson Island, with buried magnetic sources or places where the surficial lava flows are not as magnetic or are thinner than expected. While the shape of the observed magnetic anomaly mimics that caused by terrain, the amplitudes of the anomalies are different, possibly implying that topography contributes to the observed anomaly but has a magnetization different than calculated. In this case, we interpret the topography as representing large, unidentified rhyolitic lava flows.

Variations in total field magnetic intensity and susceptibility (Finn and Morgan 2002) appear to correspond, in part, to the degree of alteration present in the rhyolite that produces the anomaly. In many exposures where a flow is glassy, flow-banded, and fresh, such as the West Thumb rhyolite flow due west of the Yellowstone River (Figures 2A, 3), the magnetic anomaly of the exposure generally appears as positive. In contrast, in many exposures where evidence for emplacement of the flow into water or ice is present, such as the West Thumb rhyolite flow exposed on the northeast shore of West Thumb basin (Figures 2A, 3), the magnetic anomaly is negative (Figure 2A). All of the postcaldera rhyolites have a normal magnetic remanence, being emplaced during the past 160 ka

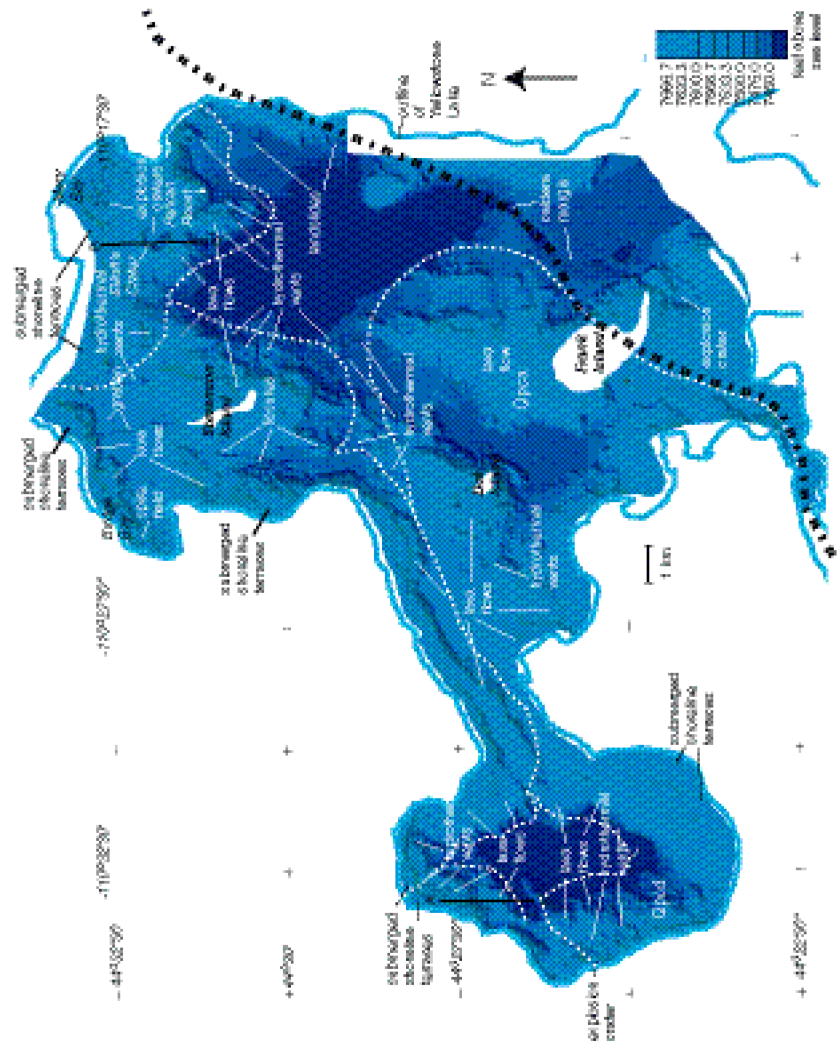

Figure 3.

Figure 3. High-resolution multibeam sonar imaging and seismic mapping of the northern basin was completed in 1999, of West Thumb basin in 2000, and of the central basin in 2001. (A) Index map using the new high-resolution bathymetric map, shown as colored contoured intervals, of the West Thumb, northern, and central basins of Yellowstone Lake, acquired by multibeam sonar imaging and seismic mapping, surrounded by gray-shaded relief DEM. (B) New high-resolution bathymetric map, showed as blue shaded relief map, of the West Thumb, northern, and central basins of Yellowstone Lake, acquired by multibeam sonar imaging and seismic mapping, surrounded by colored geologic map of the area around Yellowstone Lake. The new maps show previously unknown features such as a ~500-m-wide hydrothermal-explosion crater (east of Duck Lake), a 500-m explosion crater south of Frank Island, numerous hydrothermal vents, fissures, submerged lakeshore terraces, and inferred rhyolitic lava flows that underlie 7 to 10 m of post-glacial sediments in West Thumb basin. In the northern basin, large hydrothermal-explosion craters in Mary Bay and south–southeast of Storm Point, numerous smaller craters related to hydrothermal vents, landslide deposits along the eastern margin of the lake near the caldera margin (Figure 1), and post-caldera rhyolitic lava flows form the landscape of the northern basin. Fissures west of Stevenson Island and the graben north of Stevenson Island may be related to the young Eagle Bay fault (see Figure 1B). Subaerial lithologies include Quaternary sediments (= Qs), hydrothermal deposits (= Qh), hydrothermal explosion breccia deposits (= Qhe), tuff of Bluff Point (= Qps), Elephant Back flow (= Qpce), Dry Creek flow (= Qpcd), West Thumb flow (= Qpcw), Lava Creek Tuff (= Qyl), Tertiary Langford Formation volcanics (= Tl), and Tertiary Langford Formation intrusives (= Tli) (USGS 1972).

(Christiansen 2001); thus, susceptibility is the primary variable and ranges from 10^{-3} for relatively pristine rocks to 10^{-6} for extensively hydrothermally altered rocks (Finn and Morgan 2002).

Rhyolitic lava flows control geothermal activity: The floor of Yellowstone Lake, two-thirds of which is within the Yellowstone caldera, lies above a large cooling magma chamber (Eaton et al. 1975; Fournier 1989; Fournier et al. 1976; Lehman et al. 1982; Stanley et al. 1991; Wicks et al. 1998). The new high-resolution bathymetry of the northern, central, and West Thumb basins of Yellowstone Lake shows that many hydrothermal features in the surveyed areas are located within or along edges of areas of high relief, interpreted as rhyolitic lava flows (Figures 1B, 3). Based on our observations of the abundant present-day distribution of hydrothermal vents (Figures 1B, 3), we infer that the rhyolitic lava flows act as a cap rock exerting influence on the flow of thermal water. Upwelling hydrothermal fluids are focused preferentially through the basal breccia deposits and fractures of the rhyolitic lava flows whereas hydrothermal fluids conducted through lake and glacial sediments tend to be more diffuse (Figure 5A).

In order to evaluate the effect of rhyolitic lava flows on convective fluid flow in the sublacustrine environment, a pair of simple two-dimensional flow models was constructed (Figure 5B, C). The first model involves fluid flow in a sediment volume 1-km thick by 10-km wide (Figure 5B) covered by lake water 200 m deep. Both left and right edges of the sediment volume are open to flow. Vertical-direction (z) permeability is 0.001 darcy and horizontal-direction (x) permeability is 0.01 darcy, properties expected for lacustrine or glacial sediments. In order to simulate a magma chamber at depth, heat flow through the base of

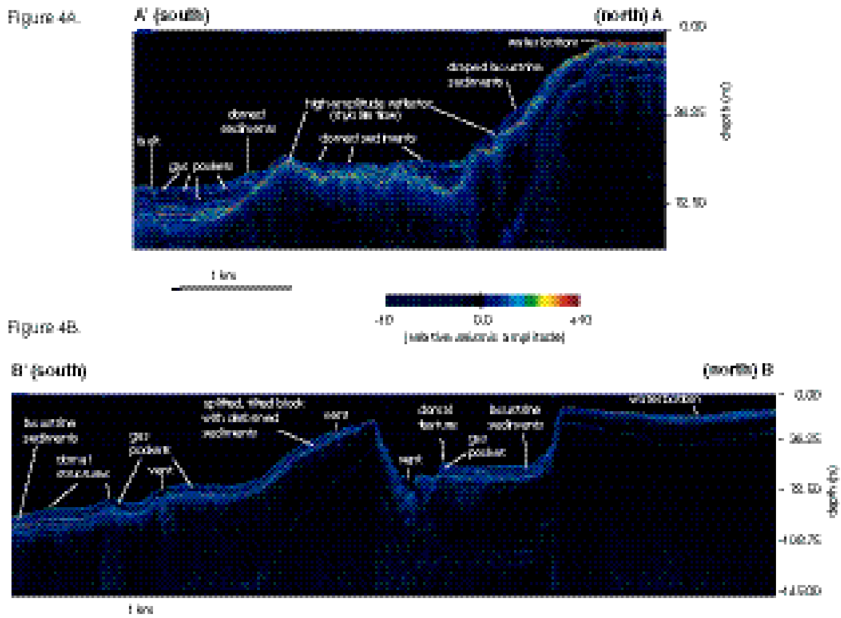

Figure 4. (A) High-resolution seismic-reflection image from northwestern West Thumb basin showing high-amplitude (red) reflector interpreted as a sub-bottom rhyolitic lava flow. Glacial and lacustrine sediments, marked in blue, overlie this unit. The data amplitudes have been debiased and spatially equalized only. No additional gain corrections or filtering are applied. (B) High-resolution seismic-reflection image (line YL72) across part of Elliott's explosion crater, showing small vents, gas pockets, and domed sediments in the lacustrine sediments that overlie the crater flank. Lacustrine sediment thickness in the main crater indicates 5,000–7,000 years of deposition since the main explosion. More recent explosions in the southern part of the large crater ejected post-crater lacustrine sediments and created new, smaller craters and a possible hydrothermal siliceous spire. Lava flow schematic modified from Bonnichsen and Kauffman 1987.

the section is set at 4 HFU or about 167.6 mW/m^2 (1 heat flow unit = 10^{-6} cal/cm^2/sec = 41.9 mW/m^2), much higher than a typical continental value of 40–70 mW/m^2. Results indicate uniform increase of temperature with depth, recharge at the surface, flow out both ends, and flow rates of <1 mm/yr. The basal heat flow value used in these calculations produces the highest possible thermal gradient without violating the assumptions of the modeling approach (boiling not allowed, fluid density and viscosity extremes not allowed, fluid temperature <300°C).

Addition of a sublacustrine 200-m-thick cap rock, in this case a fully cooled lava flow, on top of the model sedimentary section (Figure 5C) produces dramatic changes in fluid flow. The lava flow is assigned permeabilities of 0.02 darcy in the z-direction and 0.045 darcy in the x-direction, within the range measured for fractured volcanic rocks. Results indicate that a thick cap rock, in this case a sublacustrine lava flow, atop the sediment causes localization of intense thermal upflow through the lava flow and strong discharge at the surface of the flow. Fluid flow rates in the model range up to 160 mm/yr and temperatures to >130°C. In the natural situation, localization of upflow is expected along fracture zones, producing focused hydrothermal vents. Field observations and this physical model may explain the preferential distribution of hydrothermal vents and explosion craters located within or at the edges of rhyolitic lava flows in Yellowstone Lake.

Large hydrothermal explosion craters: Large (>500 m) circular, steep-walled, flat-bottomed depressions are mapped at several sites in the West Thumb, central, and northern lake basins (Figures 3, 5) and are interpreted as large composite hydrothermal explosion craters. A newly discovered 500-m-wide sublacustrine explosion crater in the western part of West Thumb basin near the currently active West Thumb geyser basin is only 300 m east of Duck Lake (Figure 3), a postglacial (<12 ka) hydrothermal explosion crater (Christiansen 1974; Christiansen 2001; Richmond 1973; U.S.G.S. 1972). Here, heat-flow values are as high as 1500mW/m^2 (Morgan et al. 1977) and reflect the hydrothermal discharge that contributed to the formation of this explosion crater. The 500-m-wide West Thumb explosion crater is surrounded by 12- to 20-m high nearly vertical walls and has several smaller nested craters along its eastern edge. These nested craters are as deep as 40 m and have more conical forms reflecting their younger ages relative to the main crater. Temperatures of hydrothermal fluids emanating from the smaller northeast nested crater have been measured at 72^{o}C by ROV.

In the northern basin of Yellowstone Lake, Mary Bay represents a roughly 1-km by 2-km area of coalesced explosion craters (Morgan et al. 1998; Wold et al. 1977) (Figure 3) in an area of extremely high heat flow (Morgan et al. 1977). Radiocarbon dates from charcoal in and carbonized soils below the ejected breccia deposit exposed in the wave-cut cliffs along the shore of Mary Bay indicate that eruption of this crater occurred at 10.8 ka (Morgan et al. 1998). Detailed stratigraphic measurements of the breccia deposit indicate that multiple explosions and emplacements occurred during formation of this large and complex feature. Submersible investigations show that hydrothermal vent fluids from a 35-m-deep crater in the Mary Bay complex have temperatures near the 120°C limit of the temperature probes.

One kilometer southwest of the Mary Bay crater complex is another large (~800 m diameter) composite depression we informally refer to as Elliott's Crater (Figure 6), named after Henry Elliott who helped map Yellowstone Lake in the Hayden survey (Merrill 1999) in 1871. Development of Elliott's explosion crater is best illustrated in a north-south seismic reflection profile (Figure 4B). Zones of non-reflectivity in the seismic profile on the floor and flanks of the large crater are probably hydrothermally altered and possibly heterolithologic explosion-breccia deposits, similar in character to those exposed on land and associated with subaerial explosion craters. Seismic profiles of the hummocky area southeast of Elliott's crater also are non-reflective and may represent a layer of

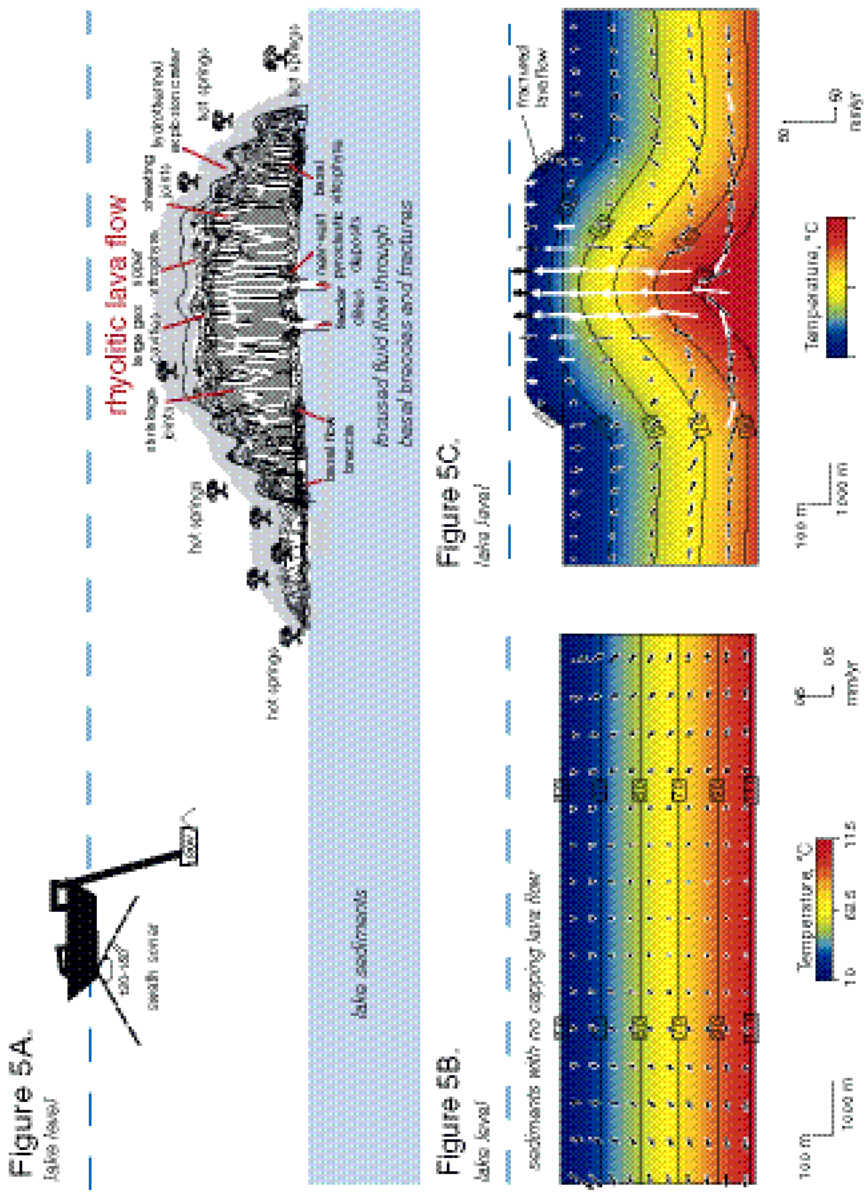
Figure 5A.
lake level
rhyolitic lava flow
hot springs
lake sediments
focused fluid flow through
basal breccias and fractures
Figure 5B.
lake level
sediments with no capping lava flow
Temperature, °C
Figure 5C.
lake level
Temperature, °C

Figure 5. (A) Schematic diagram showing physical features of a rhyolitic lava flow (modified from Bonnichsen and Kauffman 1987). (B) Fluid-flow model with simple sandstone aquifer (no caprock), which results in low flow velocities, recharge at the surface, and lateral flow out of both ends of the model aquifer. Even though heat flow is the same as in (C), subsurface temperatures in this model never exceed 110°C and strong convection cells are not established. (C) Fluid-flow model with a fully cooled rhyolitic lava flow acting as caprock. The underlying sandstone aquifer and heat flow are exactly the same as in (B). The addition of a 200-m-thick fractured crystalline rock cap strongly focuses the upward limb of an intense convection cell under the caprock. In this model, fluid temperatures reach 130°C, and flow velocities are 100 times higher than in the uncapped aquifer (B).

heterolithic and/or hydrothermally altered material erupted from this crater.

Following the initial major explosive event, lacustrine sediments, imaged as laminated reflective layers in the seismic profile (Figure 4B), accumulated in the floor of the crater and on its south flank. Opaque zones within the stratified sedimentary fill of the crater indicate the presence of gas. The presence of two V-shaped vents at the south end of the crater floor further indicates recent hydrothermal activity within the explosion crater. Two additional hydrothermal vents imaged in Figure 4B occur on the south flank, outside of the crater. These vent areas differ slightly in morphology from the nested vents within Elliott's Crater. These flank vents may have formed by collapse resulting from vigorous hydrothermal activity, extensive hydrothermal alteration, and structural failure of the overlying cap rock.

The seismic profile shows about 80 m of vertical relief between the current lakeshore and the average depth of the deeper lake basin several km south of Mary Bay (Figure 4B). We attribute most of this elevation difference to morphology associated with a previously unrecognized lava flow or shallow rhyolite intrusion present but unexposed in lower Pelican Valley (Figure 1A) and extending into Mary Bay, as discussed above. Slightly less than 10 meters of vertical difference in rim height is observed in the seismic profile of the explosion crater between the northern and southern rims. This nearly 10 meter difference may represent doming associated with hydrothermal activity. A currently active example of hydrothermal doming on a much smaller scale can be seen on the southern flank of the large explosion crater (Figure 4B). Here, a seismically opaque area interpreted as a large pocket of gas, probably steam, is present at shallow (<8 meters) depth below the sediment-water interface. Laminated lacustrine sediments show a slight convex-upward doming above this gas pocket that we attribute to uplift. Figure 4B also shows an area on the southern flank where we suggest that a gas pocket breached the surface and is now a hydrothermal vent. Note the attitude of the reflective layers dipping into and draping over the rim of the vent.

Hydrothermal explosions have occurred repeatedly over the past 12 ka in Yellowstone National Park and are primarily confined within the boundaries of the Yellowstone caldera (Figure 1). We interpret the large sublacustrine depressions as post-glacial hydrothermal-explosion craters similar in origin to those on land, such as Duck Lake, Pocket Basin, the 8.3-ka Turbid Lake crater, and the 3.0-ka Indian Pond crater (Figure 3) (Morgan et al. 1998; Muffler et al. 1971; Wold et al. 1977). In

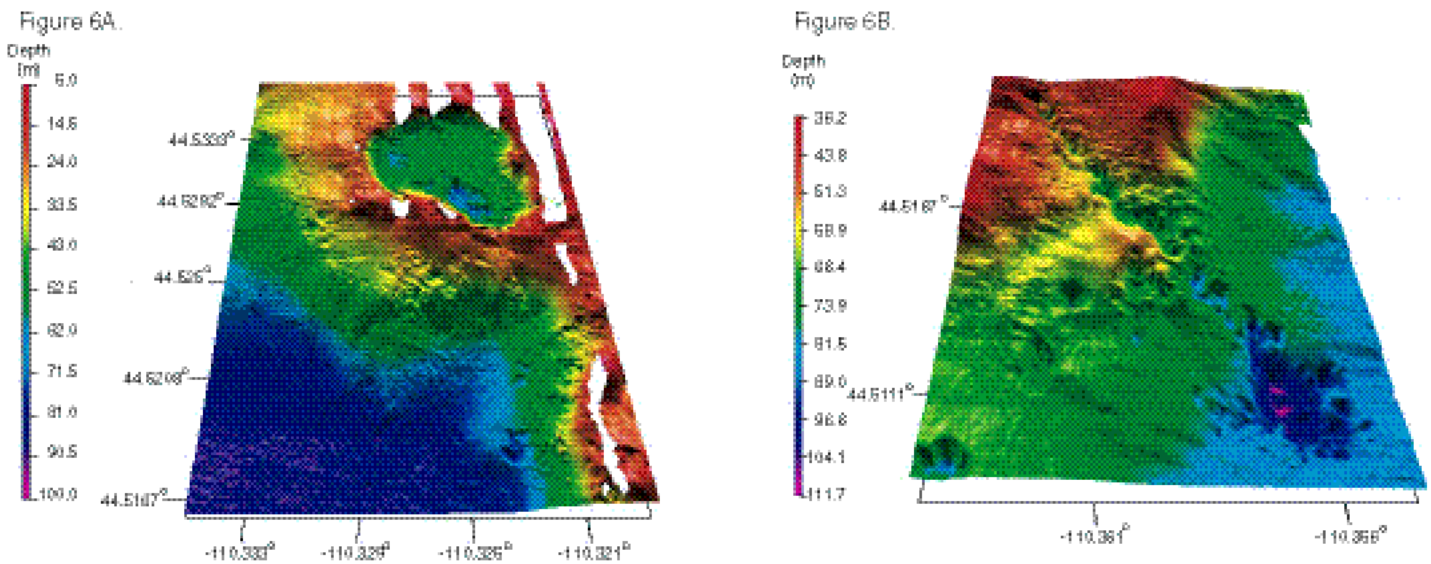

Figure 6. (A) High-resolution bathymetric image of the 800 m Elliott's Crater, an explosion crater in the northern lake. Note deeper, younger inter - nal craters within the large crater and small hydrothermal vent craters on the rim outside the large crater. (B) High-resolution bathymetric image of hydrothermal vent craters along a northwest-trending fissure east of Stevenson Island. The deep hole at the southeastern end of the trend is one of the largest hydrothermal vent areas in the lake and is also the deepest point in the lake at 133 m.

contrast to the subaerial craters, which have radial aprons of explosion breccia ejected during crater formation (Hamilton 1987; Love and Good in press), many of the sublacustrine circular depressions lack an obvious apron. This may indicate either more widespread dispersal of ejection deposits in the lake or that some process, such as collapse associated with hydrothermal alteration, created those depressions.

Small hydrothermal explosion craters on the floor of Yellowstone Lake: Seismic-reflection profiles of the surveyed areas in the northern and West Thumb basins of Yellowstone Lake reveal a lake floor covered with laminated lacustrine muds and diatomite, many of which are deformed, disturbed, and altered. High-resolution bathymetric mapping reveals that many of these areas contain small (<20 m) depressions pockmarking the lake bottom (Figures 3, 6B). In seismic-reflection profiles (Figure 4B), these features typically are imaged as V-shaped structures associated with reflective layers that are deformed or have sediments draped across their edges. Areas of high opacity or no reflection occur directly beneath these features and are interpreted as gas pocket, or hydrothermally altered zones. Evidence for lateral movement of hydrothermal fluids is seen beneath and adjacent to many of these features in seismic-reflection profiles as areas of high opacity or no reflection and in the high-resolution aeromagnetic data as areas of low magnetic intensity which represent a much larger area than seen in the surficial hydrothermal vents (Finn and Morgan 2002). Associated with these vent areas are smaller domal structures in which the laminated diatomaceous lacustrine sediments have been domed upward as much as several meters by underlying pockets of gas, presumably steam.

We interpret these features as sublacustrine hydrothermal vents with associated hydrothermal feeders. We attribute much of the deformation and alteration to hydrothermal vent channelways and subsurface migration of hydrothermal fluids. In contrast, areas devoid of inferred hydrothermal vents show well-laminated seismic reflections characteristic of lake sediments. Over 150 vents have been mapped in the northern lake basin. Several thermal fields also are identified in West Thumb basin including a large northeast-trending thermal-vent field in the southeast, another field in the northwest, and several in the west (Figure 3). These fields contain dozens of small hydrothermal vents.

Siliceous spires: Siliceous spires occur in Bridge Bay (Figure 3) in the northern basin of Yellowstone Lake, discovered in 1997 by Eastern Oceanics and the University of Wisconsin-Milwaukee. Approximately 12–15 spires are identified in water depths of ~15 m. These roughly conical structures (Figure 7A) are up to 8 m in height and up to 10 meters wide at the base. A small 1.4-m-tall spire collected from Bridge Bay in cooperation with the National Park Service on 1999 shows the spire base to be relatively shallow (~0.5 m below the sediment-water interface), irregular, and rounded; spire material above the sediment-water interface constitutes about 75% of the entire structure. The sediment-water interface is recorded on the spire as a zone of banded ferromanganese oxide-stained clay-rich and diatomaceous sediments. Below the sediment-water interface, the spire is non-oxidized. Above the interface, the spire has a dark reddish-brown oxide coating (Figure 7B). The interior of the collected spire is white, finely porous, and has thin (from 0.3 cm to <3 cm diameter), anastomozing vertical pipe-like structures through which hydrothermal fluids flowed. Little oxide is found in the interior of the spire structure but oxidation surfaces are present on former growth fronts (Figure 7B). Chemical and oxygen-isotope analyses, and scanning electron microscope (SEM) studies of the spires show them to be composed of silicified bacteria, diatom tests, and amorphous siliceous sinter associated with sublacustrine hydrothermal vent processes (Figure 7C). The Bridge Bay spires are strongly enriched in As, Ba, Mn, Mo, Tl, Sb, and W (Figure 7D). Oxygen isotopic ratios suggest formation at about 70–90°C. U-series disequilibria dating of two samples from one spire both yield a date of about 11 ka (ages were determined by Neil Sturchio, written communication, 1998); thus, the spires are immediately postglacial. Spires may be analogous in formation to black-smoker chimneys, well-documented hydrothermal features associated with deep-seated hydrothermal processes at oceanic plate boundaries (Delaney et al. 2001).

Landslide deposits: Multibeam bathymetric data reveal hummocky lobate terrain at the base of slopes along the northeast and eastern margin of the lake basin (Figure 3). Seismic-reflection data indicate that the deposits range in thickness from 0-10 m at the eastern edge of the lake and become thinner toward the interior of the lake basin. We interpret these as landslide deposits. Proximal deposits at the eastern lake edge are as thick as 10 m near the shore. The distal landslide deposits are much thinner and extend as far as 500 m into the deeper lake basin. The thickness of the lacustrine-sediment cap deposited above the landslide deposits varies and suggests that the landslides were generated by multiple events. We think it is likely that they were triggered by ground shaking associated with earthquakes and (or) hydrothermal explosions. The eastern shore of Yellowstone Lake, near where these landslide deposits occur, marks the margin of the Yellowstone caldera (Christiansen 1984; Christiansen 2001; Hildreth et al. 1984; U.S.G.S. 1972) and abuts steep terrain of the Absaroka Mountains to the east, both possible factors contributing to the landsliding.

Submerged shorelines: Several submerged former lake shorelines form underwater benches in the West Thumb and northern basins of Yellowstone Lake (Figure 3). The submerged, shallow margins (depth <15–20 m) of the northern basin are generally underlain by one to three relatively flat, discontinuous, postglacial terraces that record the history of former lake levels. Correlation of these submerged shoreline terraces around the lake is based primarily on continuity inferred from multibeam bathymetric data and shore-parallel seismic-reflection profiles. These data indicate that lake levels were significantly lower in the past. An extensive bench occurs south of Steamboat Point and along the west shore of the northern basin south of Gull Point. In Bridge Bay, submerged-beach pebbly sand 5.5 m below the present lake level yielded a carbon-14 date of 3,560 ± 60 yr B.P. (Pierce et al. 1997). Well-developed submerged shoreline terraces are present in West Thumb basin, especially along the southern and northern edges.

Relief on these terraces is as much as 2–3 m, a measure of post-depositional vertical deformation. Documentation of the submerged terraces adds to a data-

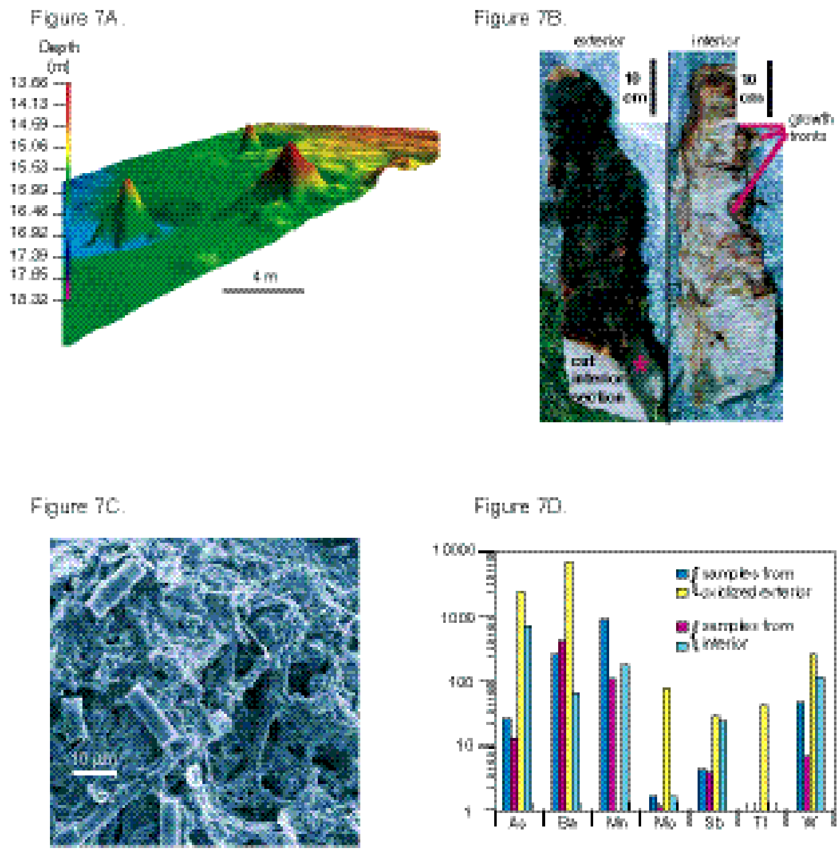

Figure 7. (A) Bathymetric image of spires in Bridge Bay, showing roughly conical shapes. Roughly a dozen such siliceous sinter spires occur near Bridge Bay, some as tall as 8 m. Many of the spires occupy lake-bottom depressions (possible former explosion or collapse craters). (B) Photographs of the exterior and interior of a 1.4 m-tall spire sample recov - ered from Bridge Bay by National Park Service divers. The sediment–water interface of this spire is apparent near the base of the exterior section, as seen in the dramatic change in color in the outer rind of red-brown ferromanganese oxide to the light gray interior. (The red asterisk on the photograph showing the exterior is on a natural external surface of the spire below the sediment–water interface.) Former growth fronts on the spire can be seen as shown in the photograph of the interior section. (C) SEM image of diatoms, silicified filamentous bacteria, and amorphous silica from a spire sample. (D) Summary bar graph of chemical analyses of spire samples showing substantial concentrations of potentially toxic elements: arsenic, barium, manganese, molybdenum, antimony, thallium, and tungsten.

base of as many as 9 emergent terraces around the lake (Locke and Meyer 1994; Locke et al. 1992; Meyer 1986; Pierce et al. 1997). Changes in lake level over the last 9,500 radiocarbon years have occurred primarily in response to episodic uplift and subsidence (inflation and deflation) of the central part of the Yellowstone caldera (Dzurisin et al. 1994; Pelton and Smith 1982; Pierce et al.

1997; Wicks et al. 1998). Holocene changes in lake level recorded by these terraces have been variably attributed to intra-caldera magmatic processes, hydrothermal processes, climate change, regional extension, and (or) glacioisostatic rebound (Dzurisin et al. 1994; Locke and Meyer 1994; Meyer and Locke 1986; Pierce et al. 1997; Wicks et al. 1998).

Fissures and faults: Features identified in the western area of the northern and central basins (Figure 2B) include a set of sub-parallel, elongate, north-northeast-trending fissures west of Stevenson Island extending southward toward Dot Island (Figure 3); a series of en echelon, linear, northwest-trending, fissure-controlled, small depressions east and southeast of Stevenson Island; and a downdropped graben north of Stevenson Island, nearly on strike with Lake Village.

Subparallel fissures west of Stevenson Island (Figure 3) plunge as much as 10-20 m into the soft-sediment lake floor 0.5-km southeast of Sand Point. These fissures represent extension fractures whose orientation is controlled by regional north-south structural trends, recognized both north and south of Yellowstone Lake. Active hydrothermal activity is localized along the fissures as shown by dark oxide precipitates partially coating the surfaces of the fissures and shimmering fluids upwelling from these. The fissures, inspected with the submersible ROV for about 160 meters along their NNE trend are narrow (<2 m wide) and cut vertically into soft laminated sediments with no vertical displacement. A parallel set of N-S-trending fissures also occurs 1.3-km northeast of Sand Point. Farther south along this trend, the fissures appear to have well developed hydrothermal vent craters, although investigations with the submersible show only weak or inactive vent fields in the central basin.

Inspection of the features east of Stevenson Island (Figure 3, 6B) using the submersible ROV indicates that small, well-developed hydrothermal vents coalesce along northwest-trending fissures. These may be similar to but more evolved than those to the west of Stevenson Island. The deepest part of Yellowstone Lake, at 133 m, is in the floor of a hydrothermal vent at the south end of the northernmost set of aligned vents; hydrothermal fluids from vents at this location are as hot as 120°C.

Finally, east-west seismic-reflection profiles across the down-dropped block north of Stevenson Island reveal a north-northwest-trending graben structure bounded by normal faults (Kaplinski 1991; Otis and Smith 1977; Shuey et al. 1977). Measured displacements along the two bounding faults vary, but displacement along the western boundary is generally ~6 m whereas that along the eastern normal fault is ~2 m. The eastern bounding fault cuts Holocene lake sediments indicating recent movement. Seismic profiles across the graben project (or strike) toward Lake Village, posing a potential seismic hazard in that area.

All of the above-described sublacustrine structures, the regional tectonic framework of the northern Rocky Mountains, and the still-active cooling sub-caldera magma chamber (Eaton et al. 1975; Fournier 1989; Fournier et al. 1976; Lehman et al. 1982; Stanley et al. 1991; Wicks et al. 1998) play important roles in shaping the morphology of the floor of Yellowstone Lake as revealed in the bathymetric map, especially of the western part of the northern lake basin. Many of the recently identified features, such as the active fissures west of Stevenson Island and the active graben north of Stevenson Island, are oriented roughly north-south, and may be related to a regional structural feature in western Yellowstone Lake on strike with the Neogene Eagle Bay fault (Figure 1B) (Locke and Meyer 1994; Pierce et al. 1997), perhaps coincident with the inferred margin of the 2.1-Ma Huckleberry Ridge caldera (Christiansen 1984; Christiansen 2001; Hildreth et al. 1984; U.S.G.S. 1972). Seismicity maps of the Yellowstone region (see U.S. Geological Survey Yellowstone Volcano Observatory website: http://volcanoes.usgs.gov/yvo) show concentrations of epicenters along linear N-S trends in the northwestern portion of the lake.

Summary and Conclusions

An important outcome of recent studies in Yellowstone Lake is the extension of the subaerial geologic mapping, allowing the lake basin to be understood in the geologic context of the rest of the Yellowstone region (Blank 1974; Christiansen 1974; Christiansen 2001; Richmond 1973; U.S.G.S. 1972). Rhyolitic lava flows contribute greatly to the geology and morphology of Yellowstone Lake. We infer from our high-resolution bathymetry and aeromagnetic data that Stevenson, Dot, and Frank Islands are underlain by a large-volume rhyolitic lava flows (Figure 3). Mapped late Pleistocene glaciolacustrine sediment deposits on these islands merely mantle or blanket the flows (Otis and Smith 1977; Richmond 1974; Richmond and Waldrop 1975; Shuey et al. 1977). Similarly, the hydrothermally cemented beach deposits exposed on Pelican Roost (Figure 3), located ~1 km southwest of Steamboat Point (Figure 3), may also blanket a submerged large-volume rhyolite flow. The margin of the Yellowstone caldera (Otis and Smith 1977; Richmond 1974; Richmond and Waldrop 1975; Shuey et al. 1977) passes through the central part of the lake and northward along the lake's eastern edge (Figure 1). Similar to most of the rest of the margin of the Yellowstone caldera (Figure 1A), we suggest that postcaldera rhyolitic lava flows are present along much of the caldera margin beneath Yellowstone Lake.

Additional and significant potential hazards inferred from the bathymetric, seismic, and submersible surveys of Yellowstone Lake include the effects of potential hydrothermal explosions and related phenomena, such as the ejection of debris, landsliding along the lake margins, and sudden collapse of the lake floor through fragmentation of hydrothermally altered cap rocks. Any of these events could result in a sudden and dramatic shift in lake level, generating a small tsunami that could cause catastrophic local flooding. Ejecta from past hydrothermal explosions that formed craters in the floor of Yellowstone Lake extend several kilometers from their crater rims and include rock fragments in excess of several meters in diameter (Hamilton 1987; Love and Good in press; Morgan et al. 1998; Richmond 1973; Richmond 1974; Richmond 1976; Richmond 1977). In addition to potential hazards to humans, such explosions are likely to be associated with the rapid release into the lake of steam and hot water (Fournier et al. 1991), possibly affecting water chemistry by the release of potentially toxic trace metals. Such changes could be significant to the fragile ecosystem of Yellowstone Lake and vicinity (Shanks et al. 2001).

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Documenting Trends in Yellowstone's Beaver Population: A Comparison of Aerial and Ground Surveys in the Yellowstone Lake Basin

Sue Consolo Murphy and Douglas W. Smith

Introduction

The beaver *(Castor canadensis)* is a keystone species that can affect ecosystem structure and dynamics beyond its own immediate requirements for food and space (Novak 1987) and thus may be of particular interest to researchers and managers of wildland ecosystems. This species is sometimes erroneously portrayed as missing from Yellowstone National Park, but the historical record contradicts this. Although there has been relatively little research or monitoring of beaver during the park's nearly 130-year history, earlier records (Warren 1926; Jonas 1955; Fullerton 1980; Houston 1982) provide information on beaver activity and distribution from the early 1900s until the 1980s (Consolo Murphy and Hanson 1993).

In 1988–1989, the senior author initiated a sampling survey to document the presence and distribution of beaver in the park and develop a monitoring scheme to assess changes in the status of the species over time. This was a ground survey similar to that most recently undertaken by Fullerton in 1979–1980 (Fullerton 1980). Beavers typically, but not always, construct large lodges built of sticks and mud, anchored most often on the banks of a lake or river, particularly on river bends where the water deepens or at the confluence of two streams. Beavers sometimes use dens in river banks rather than (or in addition to) constructed lodges. Beavers also cut woody vegetation, which is often consolidated and stored in a floating mat, called a cache, anchored to a lodge or located on the water surface near where a beaver colony winters (Jenkins and Busher 1979; Novak 1987). Lodges augmented with freshly cut trees and stems with stripped branches or newly placed mud, new food caches, bank dens, fresh slides down a bank, and recently built dams are also signs of current beaver activity easily observed in autumn, as the animals are then at the height of activity constructing lodges, repairing dams, and caching food for the winter.

Ground surveys were completed by one or two persons who hiked to lakes and along suitable riparian corridors of the park, recording signs of current beaver activity, including lodges, food caches, dams, bank dens, felled trees, stripped stems, beaver trails, and canals. Biologists recommended that beaver surveys be repeated at five-year intervals to build a database on trends in the number and distribution of colonies over time (Consolo Murphy and Hanson 1993), and the senior author and her field assistants did repeat the survey as planned in 1994 (Consolo Murphy and Tatum 1994).

In 1996, Doug Smith, a newly arrived park biologist, was able to obtain funds to conduct the park's first near-complete autumn aerial count of beaver colonies with food caches (Smith et al. 1997). His method was to survey watercourses, ponds, and lakes of suitable gradient from a fixed-wing Supercub plane, flying at an altitude of 100 to 175 feet at an air speed of 55 to 65 mph (Hay 1958; Payne 1981), a widely used survey technique. Every river system in the park was surveyed once, and repeat overflights were often used to census beaver colonies in high-density habitats. Lodges and food caches are easily visible in the fall from slow-flying aircraft after deciduous plants have shed their leaves and before snow and ice form on water surfaces. Smith repeated this survey in 1998 and recommended continuation of aerial surveys at two- to three-year intervals to monitor beaver distribution in the park (Smith 1998).

Since a third iteration of the ground survey was due to be completed in 1999, the park biologists with previous experience surveying beaver decided to compare efforts and techniques in order to build a long-term, affordable monitoring strategy for this species in the park. Some studies have found ground surveys to be more accurate in finding and censusing beaver in non-mountainous terrain, and this may be so in the park as well (Robel and Fox 1992), but they may be prohibitively costly in survey time and dollars. Aerial surveys of late-season food caches are easily conducted and cost-effective (Swensen et al. 1983; Robel and Fox 1992) but are not believed to document the presence of all bank-denning beaver nor those associated with an atypical cache pattern. We compared the effectiveness of the two methods by conducting both a ground survey and an aerial survey in the autumn of 1999 in an area of high-density beaver occupation: along the upper Yellowstone River from the southern park boundary to Yellowstone Lake.

Study Area

The Yellowstone River and its tributaries drain the eastern half of the park. The Yellowstone flows into the southeastern portion of the park (the Thorofare region) and meanders north-northwest for about 26 km (16 mi) to Yellowstone Lake along a mostly flat gradient. The inlet to Yellowstone Lake is a large, marshy delta that supports extensive tall willow communities *(Salix* spp.). Previous ground and aerial surveys have shown that several dozen beaver colonies are generally located in this corridor. Smith (1998) calculated the density of beaver colonies here as 0.35 per km (1.5 per 2 mi) of river surveyed, one of the two highest-density areas of occupation across Yellowstone National Park (the other being an 8.6-km stretch of the Madison River). The survey area included an estimated 9.54 km of streambank and lakeshore in the Yellowstone River delta, 1.97 km in nearby sloughs or ponds, and 19.25 km of streambank upriver along the Yellowstone and the lower reaches of its tributaries (Figure 1), for a total of 30.77 km.

Results

The ground survey of this study area was conducted on three days: September

14 and October 2–3, 1999. On September 14, two ground crews of two persons each initiated the survey from Trail Creek at the tip of Yellowstone Lake's Southeast Arm. One crew (including the senior author) departed via canoe, crossed the arm, and proceeded up the Yellowstone River for approximately 3.2 km, beyond which the upstream current of the river precluded progress. At a number of spots, the crew beached the canoe and searched from the ground, hiking through the dense willow patches. The second crew surveyed on foot between Trail Creek and the Yellowstone River upstream from the delta; initial plans to proceed all the way upriver to the park boundary at Thorofare were delayed due to an injury suffered by one member of this ground crew. Another two-person team thus completed the survey upstream of Cabin Creek in early October. Ground survey crews located a total of 17 active colonies: 13 lodges with food caches, two bank dens with food caches, and two lodges with freshly cut stems, mud, or other signs of current activity but no obvious food cache present (Figure 1). Ten of the colonies were within the Yellowstone River–Beaverdam

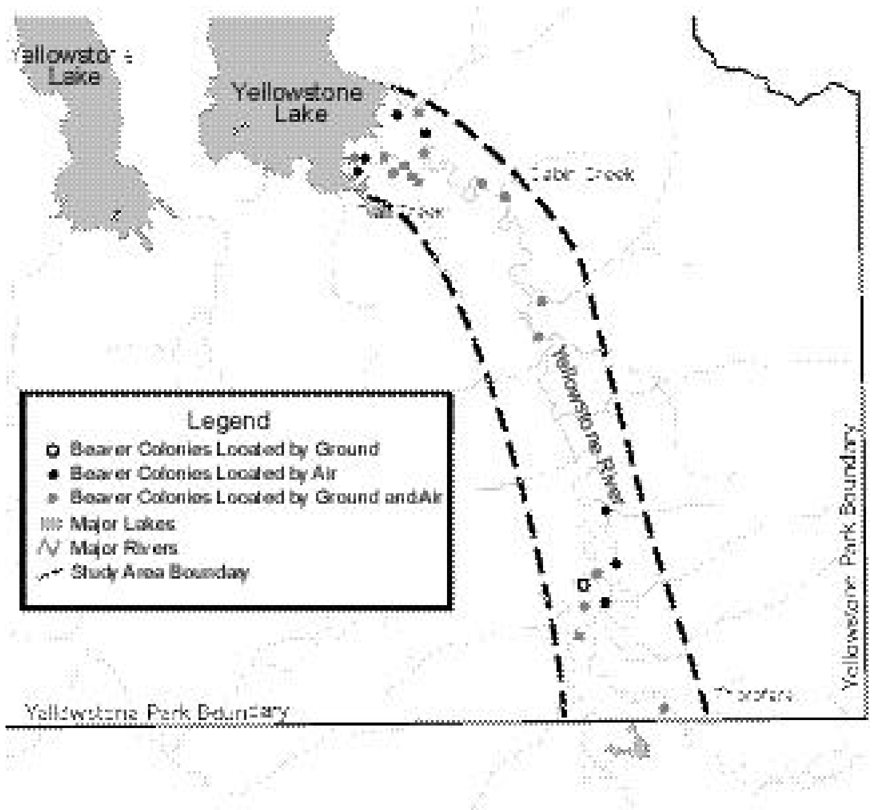

Figure 1. Study area from Yellowstone Lake upstream along the Yellowstone River to the park's southern boundary, and active beaver colonies found by ground survey, aerial survey, and both methods in September–October 1999.

Creek delta area, and seven were upstream of Cabin Creek. The ground survey took eight 10-hour person-days, since safety concerns compelled us to pair observers traveling in the backcountry by either foot or canoe. Total cost was $1,270 in personnel; equipment was already available for general park purposes.

The aerial survey was conducted on October 25, 1999, by one observer (the junior author) in addition to the contract pilot, flying in a Supercub at an average speed of 55–65 mph from 100 to 175 feet above the river and its main tributaries between the delta and the park boundary. (It was part of a parkwide survey flight.) They observed a total of 23 active beaver colonies in the study area. All of the aerial observations were of lodges or bank dens with caches; 14 of the colonies were within the delta and nine were upstream of Cabin Creek (Figure 1). The aerial survey took 1.5 hours of flight time at a cost of $115 per hour plus the salary of the park biologist observer, for a total cost of $212.

Comparison of Techniques

The ground and air observers co-located 16 active colonies: one was located only by the ground crew and seven were located only by the aerial observers, for a total of 24 colonies active within the study area in autumn of 1999. Using a capture/recapture double-count model, the probability of detecting an active colony was 94% by aerial survey and 69% by ground survey. The lower level of detection by ground observers was due to several reasons, none of which were unexpected, especially in this area. All the beaver colonies within the study area were associated with willow communities. The large expanse of flat, marshy habitat present in the Yellowstone River delta is extremely challenging to survey effectively from the ground. The tall willows block visibility and impede safe passage. Even upriver along the Yellowstone, there are extensive willow habitats that are time-intensive and risky to survey; crews were ever alert to the possibility of encountering moose or bears, particularly, in the thick vegetative cover. Also, scattered across the delta are small streams, backwaters, and ponds that are difficult to visit in an efficient manner; it is ideal country to survey from aircraft.

All four of the colonies not seen by ground observers within the delta were some distance from the shore of Yellowstone Lake or the main course of the Yellowstone River, in areas not effectively covered by ground crews. Of note, although two of the colonies within the delta called "active" by ground crews were not recorded as having food caches on September 14, they were recorded as having both an active lodge and cache during the aerial survey. This could be a result of the beavers not having yet begun to actively cache food in mid-September, or because caches are not always visible to ground crews, depending on how closely they can see a lodge; crews tried not to approach too closely lest beavers be disturbed during the survey.

Upstream from the delta, three colonies along the Yellowstone River were seen from the air but not by ground crews, due to the latter having exhausted their ability to cover the area effectively within a reasonable period of time. One colony observed from the air, near the confluence of the north fork of Cliff Creek and the Yellowstone River, was in an area noted by ground observers to have an abundance of sign but no evident lodge or cache; ground crews may have missed it, or it may been constructed after the ground survey occurred. The one colony found by ground observers but not seen from the air was a lodge near the river's confluence with the south fork of Escarpment Creek. Ground observers described the lodge as concealed within early-season flood debris. It had no food cache anchored to it, though a very large one was just upstream around the next river bend; during the October 3 survey the ground crew did observe a large beaver swimming between the two sites. This points out one of the situations where ground surveys may be more effective at finding beaver colonies that are hard to see from the air. Another situation that occurs in the park, but not in this study area, is one in which beaver colonies occupy less-typical habitats—particularly streams or lakes without willows, aspens, or cottonwoods. In these settings, such as ground crews observed at Heart Lake in 1999, beavers may rely on other foods such as pond lilies *(Nuphar polysepalum)* or submerged aquatic plants. A food cache, if present, may not be visible from the air.

Summary

Aerial surveys should not be construed as providing a complete count of beaver lodges and caches. However, the results of this survey indicate that, for most park purposes, aerial surveys have a high probability of detecting active beaver colonies in the autumn when beaver are most active and likely preparing to overwinter in the observed location. In comparison, a yearly ground survey is more costly and, at least in difficult-to-survey terrain, less likely to document as high a percentage of the existing beaver colonies (Table 1). In general, we find that aerial surveys are a cost-effective method to survey for trends in the number and distribution of beaver colonies that exist across Yellowstone National Park. Since the park's current budget and work plans call for biennial beaver survey flights, periodic ground surveys can help test the efficiency of flights to monitor colonies, especially in marginal or atypical beaver habitats. Ground survey data may augment the data from aerial counts, especially in areas where beavers are likely to bank-den or overwinter without building visible food caches. Ground surveys also permit observers to better view animal behavior and appreciate the

Table 1. A comparison of ground and aerial survey costs and results from the 1999 study.

Results Compared	Ground survey	Aerial survey
Number of beaver colonies found	17	23
Number not found by other method	1	7
Detection probability	17 of 24 (69%)	23 of 24 (94%)
Time required (10-hr person-days)	8.0	0.188
Cost of survey	$1,270	$212 w/o ferry time

extent of beaver cutting, construction, and habitat alteration that occurs in specific sites as a result of the animal's periodic presence and withdrawal. Since Yellowstone lacks data on relationships between the numbers of active lodges or food caches and the beaver population, we suggest that further research to estimate the average size of the beaver colonies in various park habitats would be of benefit to resource managers, interpreters, and others.

Acknowledgments

We thank Ryan Eisfeldt, Sharit Koser, Tom Zieber, Deb Guernsey, and Susan Chin for conducting ground surveys and/or completing data analysis and mapping. Pilot Roger Stradley was instrumental in completing a safe, successful aerial survey. Dan Reinhart and other Yellowstone biologists and rangers accompanied ground crews during surveys, providing an added measure of safety, and provided necessary logistical support and equipment to access the Yellowstone backcountry.

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Amphibian Diversity, Distribution, and Habitat Use in the Yellowstone Lake Basin

Debra A. Patla and Charles R. Peterson

Abstract

Global amphibian population declines are being investigated through four interdependent fields of study: distribution and status, ecology, causes of declines, and environmental contexts. In Yellowstone National Park, work on amphibians has proceeded in all four of these fields. This paper describes amphibian species occurrence, distribution, and habitat-use patterns in the Yellowstone Lake area; summarizes the findings of a field study on habitat use by spotted frogs; and describes the directions and goals of continued amphibian investigations. Tiger salamanders, western toads, boreal chorus frogs, and Columbia spotted frogs all occur in the subwatersheds surrounding Yellowstone Lake. Chorus frogs and spotted frogs are the most common species. Salamanders are uncommon. Toads are rare, and we are concerned about their status in Yellowstone and in the Greater Yellowstone Ecosystem. A large variety of wetlands in the Yellowstone Lake basin provide breeding sites. Foraging and overwintering sites are also crucial to amphibian persistence. A case study of spotted frogs in the Lake Lodge area exemplifies this and underscores the need to understand habitat requirements, movement capabilities, and the effects of human activities. Amphibian investigations in Yellowstone over the next several years will probably focus on completing distribution surveys for inventory and monitoring purposes, research into habitat use and amphibian movements, and habitat mapping and modeling. The practical goal is an integrated information system that Yellowstone National Park can use for environmental analysis, project planning, monitoring, research, evaluation of ecosystem health, and education.

Introduction

At the end of the 1980s, biologists began discussing the possibility that many amphibian populations were rapidly declining and disappearing worldwide. By the end of the 1990s, there was general consensus that alarming declines had in fact occurred (Alford and Richards 1999). Within the context of the global reduction of wildlife and biological diversity, amphibian declines stood out for several reasons: the evolutionary durability of amphibians (survivors of at least three mass extinction events), the ubiquity of amphibians in terms of geography and habitat, the rapidity of the reported declines, and the occurrence of declines in protected and relatively pristine areas (Mattoon 2001).

During the last decade, there has been a large effort to understand the phenomenon of amphibian declines. Four main fields of investigation support and draw on each other:

1. Investigation of amphibian distribution and status is necessary to understand where species occur and to determine if declines have taken place or are in progress. Investigators compile historical and recent records for comparisons, and engage in extensive surveys and monitoring.
2. Natural history and ecology studies of populations in the wild teach us about population dynamics and habitat use, and help explain why populations are vulnerable to certain human-caused changes in the environment.
3. Investigation of the causes of declines is taking place in the field and in the lab. Multiple causes of declines have been identified, including habitat loss and modification, air and water pollution, damaging ultraviolet-B radiation exposure due to stratospheric ozone depletion, climate change, disease, introduction of non-native species, and complex interactions among factors.
4. Analysis of the environmental context using recent advances in geographic information systems (GIS), landscape component analysis, and other technologies allow investigators to map and model habitat and environmental change.

The ultimate goal of these investigations is to conserve and restore amphibian populations, which are important components of natural ecosystems. Investigators seek to provide information to land managers and to society that will stimulate and guide actions needed to maintain amphibian biodiversity and abundance.

In Yellowstone National Park, work has proceeded in all four of these fields of investigation. The effort to understand current amphibian species distributions in Yellowstone began at Idaho State University in 1988. By the mid-1990s, researchers from the Herpetology Laboratory at Idaho State University compiled historical, museum, and recent observation records and published a field guide (Koch and Peterson 1995). We have continued compiling observation and survey records in a Greater Yellowstone Ecosystem amphibian database (Van Kirk et al. 2000). Studies of distribution and occurrence have proceeded through a variety of survey projects, including surveys of roadsides and other areas targeted for development (e.g., Peterson et al. 1995; Patla and Peterson 1997; Patla 1997a), the northern range (Hill and Moore 1994), backcountry wetlands (e.g., Corkran 1997, 1998), and native fish restoration study areas (Patla 1998, 2000). Annual monitoring continues at six sites in the park (Peterson et al. 1992). In 2000, we began park-wide surveys through a joint effort with the U.S. Geological Survey (USGS) and its national Amphibian Research and Monitoring Initiative (Corn 2000) and the Vertebrate Inventory and Monitoring Project of the National Park Service (NPS). Investigators have engaged in studies of the causes of declines (Hawk and Peterson 1999; Hawk 2000) and field ecology studies of local populations (Hill 1995a, 1995b; Patla 1997; Patla and Peterson 1999). Finally, researchers from various institutions are designing habitat mapping and modeling projects. While the state of knowledge about amphibians in the park has advanced considerably over the past decade, we look forward to achieving a more precise understanding in the future about status, trends, ecology, and conservation of amphibians.

With respect to amphibians of the Yellowstone Lake area, this paper will describe what is currently known about species occurrence, distribution, and general habitat-use patterns. We will summarize the findings of a field study in the Lake Lodge area illustrating amphibian vulnerability to human-caused habitat changes. Finally, we will describe current and future directions and goals of amphibian investigations in Yellowstone.

Amphibian Occurrence and Distribution

To assess amphibian occurrence around Yellowstone Lake, we employed subwatershed units known as 7th-level Hydrological Units (HUs). Boundaries of these units were defined by a GIS coverage prepared by Yellowstone's GIS department. There are 48 subwatershed units around the lake. When we plotted locations of all known historical and recent records, we found that 27 units, or 56%, are known to have hosted, or currently host, amphibians (Figure 1).

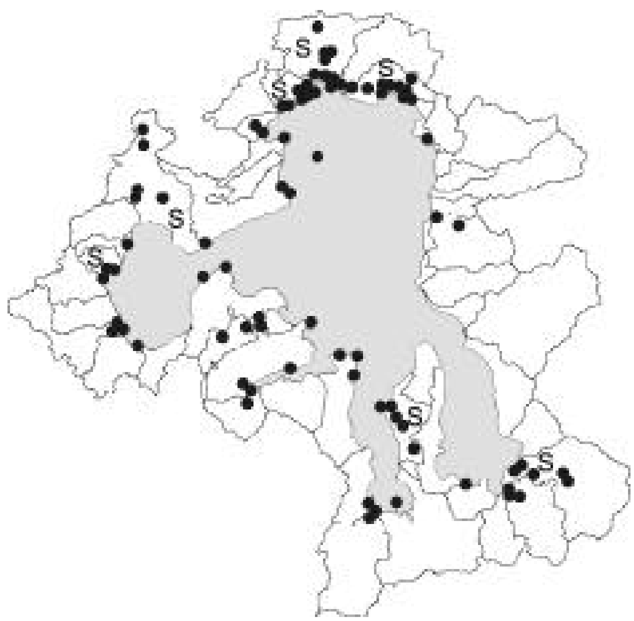

Figure 1. Yellowstone Lake with its 48 surrounding subwatershed units; dots show locations of historical and recent amphibian observations. Twenty-seven of the 48 units (56%) have amphibian records. The letter "S" indicates subwatershed units where formal amphibian surveys have been conducted in at least a portion of the unit within the past 10 years.

Formal amphibian surveys, following accepted protocols for detecting amphibian presence, have been conducted in only eight of the subwatershed units (Figure 1). One subwatershed (Arnica Creek) has been surveyed to identify amphibian breeding sites. Small portions of several other subwatershed units were surveyed during road improvement project analyses for the Arnica-to-West Thumb and Fishing Bridge-to-Canyon road sections. Portions of two subwatersheds, in the Promontory and Thorofare areas, were surveyed by volunteers in the late 1990s.

Knowledge about amphibian distribution in the Yellowstone Lake basin relies largely on incidental sighting reports. Incidental observations were provided by aquatic resources personnel doing fishery work, park rangers and other employees, exploratory surveys and observations by Idaho State University Herpetology Lab personnel, and other visitors. We regard distribution information for amphibians around Yellowstone Lake as incomplete, particularly for the east side of the lake and for roadless, remote areas.

The Yellowstone Lake area has a full complement of amphibian species: all those that one would expect to be present, based on their geographic range and occurrence elsewhere in the park, have been observed. While only four species occur, they are biologically diverse, representing two orders and four different families of amphibians. The tiger salamander *(Ambystoma tigrinum)* is from the order Urodela, the family of mole salamanders. In the order Anura, there is the western toad *(Bufo boreas)* from the family of true toads, the boreal chorus frog *(Pseudacris maculata)* of the tree frog family, and the Columbia spotted frog *(Rana luteiventris)* from the family of true frogs.

To judge from available data, the tiger salamander is surprisingly uncommon in the Yellowstone Lake area (Figure 2) given the abundance of this species in some other portions of Yellowstone, e.g., the northern range (Hill and Moore 1994) and Hayden Valley (Patla 2001). Some of this apparent rarity may be due to the fact that adult salamanders spend much of their time underground and are infrequently encountered by people except during periods of mass migration. Our Yellowstone Lake area dataset's reliance on incidental observation is thus likely to be biased against this species. However, the lack of observations of salamanders on the well-traveled roads north and west of Yellowstone Lake suggests that this species is in fact uncommon, or that salamander populations are much smaller than those of Yellowstone's northern range.

The western toad appears to be rare (Figure 3). We know of only two current breeding sites in the vicinity of Yellowstone Lake. There is much concern about this species because of dramatic declines elsewhere; in Colorado and southern Wyoming the western (boreal) toad *(Bufo boreas boreas)* is a candidate for listing under the Endangered Species Act. Toads and their tadpoles are conspicuous in comparison with salamanders. Adult toads disperse widely from breeding sites and may be seen basking in open areas on sunny days or crossing roads at night. Toad tadpoles and newly metamorphosed toadlets form large conspicuous congregations.

The boreal chorus frog is widespread (Figure 4), and probably common around Yellowstone Lake if the complete picture were known. Although adults are tiny and visually inconspicuous, the males call loudly in May and June, making this an easy species to detect at that time. Wetlands on the north side of Yellowstone Lake ring with the chorus of these frogs on spring evenings. Large

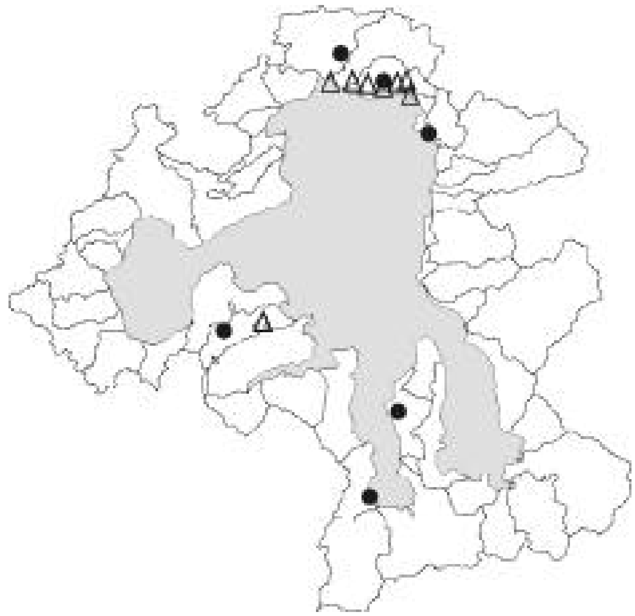

Figure 2. Locations of tiger salamanders, with triangles representing records prior to 1986, and dots indicating more recent records. Salamanders have been observed in a total of 7 subwatershed units (3 prior to 1986; 6 since 1986).

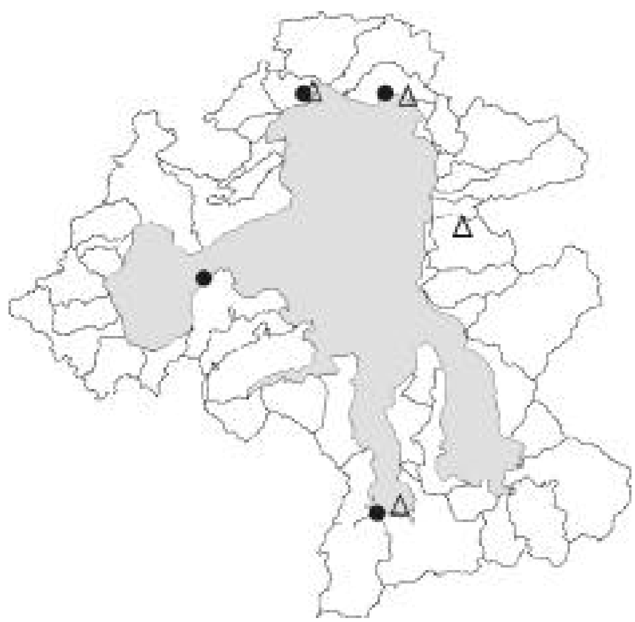

Figure 3. Locations of western toads, with triangles representing records prior to 1986, and dots indicating more recent records. This species has been observed in a total of 6 units (4 prior to 1986; 4 units since 1986).

numbers of metamorphs have been observed in lakeside wetlands on the south shore of Yellowstone Lake (Koch and Peterson 1995).

The Columbia spotted frog is also widespread (Figure 5). It is the most frequently seen amphibian in the Yellowstone Lake area and across much of the Greater Yellowstone Ecosystem. This is a visually conspicuous species: spotted frogs often bask on the edges of ponds and streams, producing a loud splash as

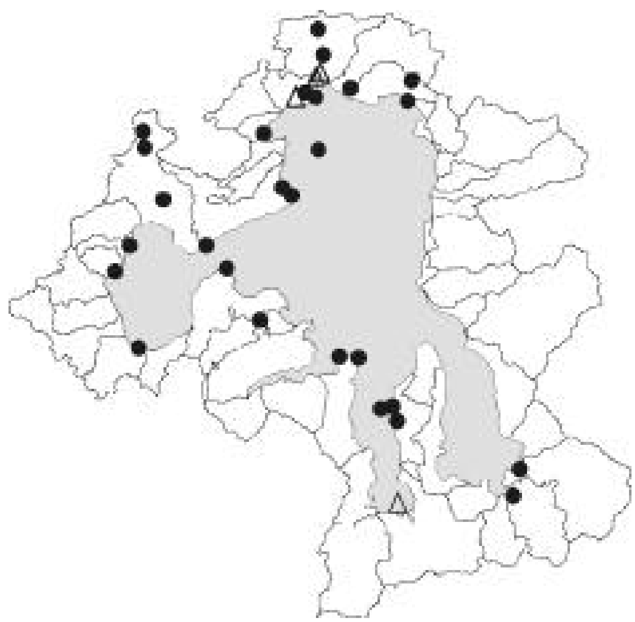

Figure 4. Locations of boreal chorus frogs, with triangles representing records prior to 1986, and dots indicating more recent records. This species has been observed in a total of 17 units (3 prior to 1986; 17 since 1986).

they hop into the water. Tadpoles of spotted frogs grow to a larger size than the other anuran species and are often easily visible in shallow water. Newly metamorphosed spotted frogs may be abundant as they emerge from breeding pools, although they tend to be more dispersed than toadlets.

In summary, based on the number of subwatershed units in which they have been observed, salamanders and toads are relatively rare around Yellowstone Lake, while chorus and spotted frogs are more common and widespread (Figure 6). Historical or pre-1986 information is so scant for most of the area that it does not reveal much about possible trends. For most amphibian species in Yellowstone, the more effort that is expended in searching for them and keeping track of observations, the more locations are recorded. However, this is only marginally true for toads, as is indicated by the relatively small difference between historical and recent records shown in Figure 6. We think it is likely that western toads have declined in the Greater Yellowstone Ecosystem, based on the records

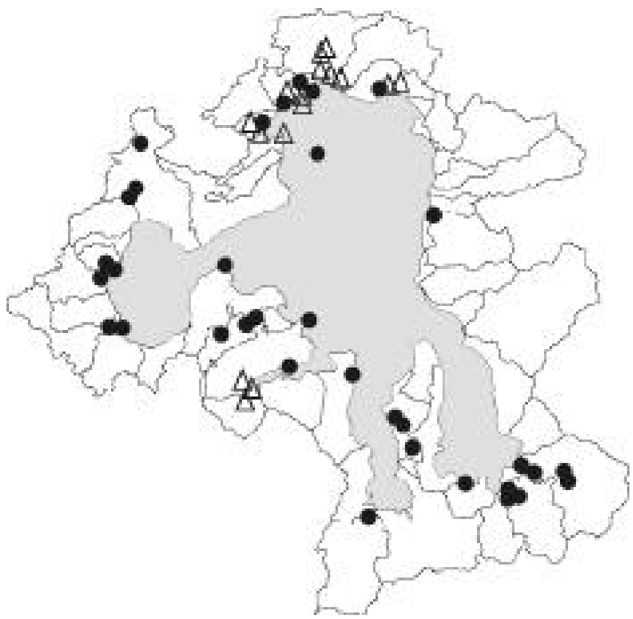

Figure 5. Locations of Columbia spotted frogs, with triangles representing records prior to 1986, and dots indicating more recent records. This species has been observed in a total of 22 units (8 prior to 1986; 18 since 1986).

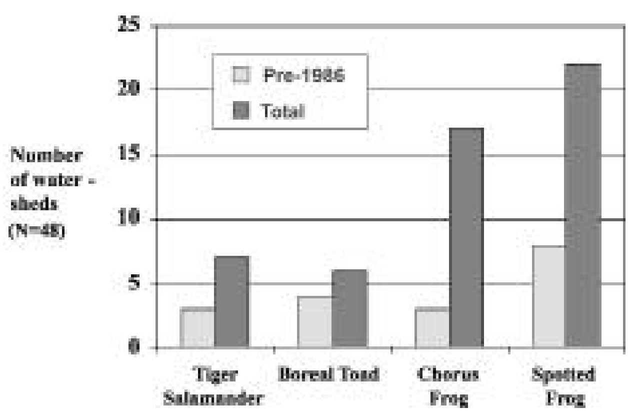

Figure 6. Number of subwatershed units around Yellowstone Lake where amphibian species were observed prior to 1986, and total number of watersheds (including all records, historical and recent) where species were observed.

and notes of earlier researchers and their current scarcity (Koch and Peterson 1995; Van Kirk et al. 2000).

Habitat Use

All amphibian species of Yellowstone rely on ponded or very-low-gradient water for reproduction. Eggs and larvae are aquatic obligates and will perish if breeding sites dry up before development is complete. The Yellowstone Lake area offers a variety of breeding sites for amphibians. Western toads in the Greater Yellowstone Ecosystem breed predominantly in water with high conductivity, often geothermally influenced (Hawk and Peterson 1999; Hawk 2000). These generalizations hold true for the two known toad breeding sites around Yellowstone Lake; toads breed on the west side of Indian Pond where conductivity often ranges above 1,000 FS (Patla and Peterson, unpublished data) and in a thermal pool at Breeze Point (reported by fisheries crew, 1999). The other amphibian species breed in a variety of temporary and permanent ponds in forests and meadows, generally with emergent vegetation. Acidic waters (< pH 6.0) are apparently not used as breeding sites (Patla and Peterson 1997), although this hypothesis needs more investigation. Lagoons and shallow-water marshes at the mouths of creeks draining into Yellowstone Lake, e.g., the mouths of Lodge and Pelican creeks, are known to provide breeding sites that produce large numbers of chorus frogs and spotted frogs.

Finding and documenting breeding sites is the focus of amphibian surveys. Amphibians have a very strong fidelity to breeding sites: some that were known to be used 50 years ago in the Yellowstone Lake area are still active. To monitor amphibians across the Greater Yellowstone Ecosystem and determine if statistically significant declines are occurring, investigators plan to track changes in the number of active breeding sites per species over time.

Breeding sites, however, are obviously only part of the habitat picture. It is quite common to find ponds inhabited by thousands of tadpoles, but with few or no adults in sight following the brief season of mating and egg deposition. The reason for this is very significant in the ecology of amphibians of the temperate zone. In many cases, habitat units that are necessary for amphibians to carry out their lives are spatially separated. Amphibians leave the breeding site to go to prey-rich areas for summer range, and then move on to places where they can safely winter. Biologists are just beginning to get an appreciation for how far amphibians can and do migrate to access breeding, foraging, and over-wintering sites (Pilliod 2001). Maximum migration distances range from 3 to 15 km for some populations (Sinsch 1990). Understanding of amphibian distribution will advance as researchers gain more knowledge about the spatial relationships of habitat components, natural history and habitat requirements that are unique to each species, and habitat-use and movement patterns in a variety of environmental settings.

Case Study at Lodge Creek

Habitat-use patterns of a spotted frog population in the Lake Lodge area have been the subject of historical and recent field studies. In the 1950s, Frederick Turner, a graduate student at the University of California–Berkeley, studied population dynamics and spatial relationships of the spotted frogs inhabiting a 28-ha area around the headwaters of Lodge Creek, between Fishing Bridge and Lake Village (Turner 1960). In the 1990s we repeated Turner's mark–recapture study of the population to compile comparable datasets. We found that the population had sharply declined and that habitat-use patterns had changed (Patla 1997b; Patla and Peterson 1999). Between the two study periods, the frogs' habitat was altered by several development projects, including reconstruction and relocation of the Grand Loop Road in the 1970s, increased residential development, horse-pasture use and maintenance, and increased development and use of Lodge Creek springs for the water needs of Lake Village. In addition to direct habitat losses, habitat fragmentation occurred. A migration corridor linking breeding and over-wintering habitat was interrupted by the path of the new section of the Grand Loop road. Breeding in the affected pool dwindled and finally ceased completely by 1995, and frog numbers in that portion of the study area have declined most severely (Patla 1997b; Patla and Peterson 1999).

This case study exemplifies how important it is for amphibians to have access to all habitat components. It also underscores the need to understand what habitats each species relies on to complete its life cycle, what constitutes constraints to amphibian movements, and how human activities and development projects may adversely affect amphibian populations. In the case of spotted frogs, it is likely that their dependence on non-freezing water (springs or spring-fed water bodies) for winter habitat limits their distribution and persistence in local areas as strongly as the availability of breeding sites (Pilliod 2001; Pilliod and Peterson 2001). Wintering and foraging habitat requirements, and their variability in different environmental contexts (e.g., at different elevations and in different plant communities), are as yet poorly known for Yellowstone amphibians.

Amphibian Studies in Yellowstone

As an overview of current and future amphibian studies in Yellowstone, we envision continued work in three main areas (Figure 7).

Distribution and status. We are conducting amphibian surveys in randomly selected 7th-level hydrological units (HUs) in Yellowstone and Grand Teton national parks. To achieve geographical distribution across Yellowstone, we selected HUs for survey from every third square in a grid placed over the park. As of the end of the 2001 field season, the surveys in Yellowstone are about 30% complete: 11 of the 36 targeted units have been surveyed. Supported by the USGS's Amphibian Research and Monitoring Initiative and NPS's Greater Yellowstone Area Inventory and Monitoring Program, this project will describe the distribution and abundance of breeding populations and considerably extend our current knowledge. The surveys are designed to serve as the basis for monitoring trends and answering questions about potential declines. Depending on funding levels, surveys of the selected units should be completed within three years. The project also includes targeted surveys for species of special concern in Yellowstone and more intensive population monitoring at selected sites.

Environmental context. One of the primary objectives of our amphibian studies is to develop GIS models and maps to indicate the probability of habitat

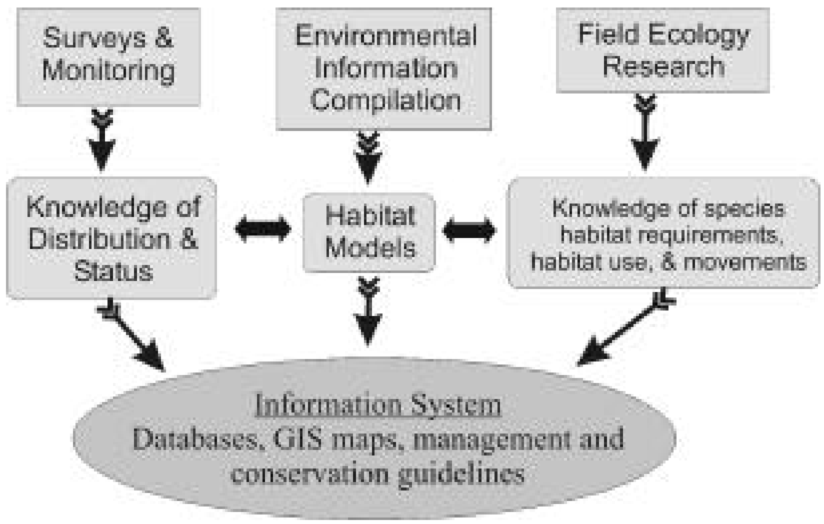

Figure 7. Overview of amphibian investigations. The information system resulting from integrated efforts will have multiple purposes, including amphibian conservation, resource management and protection, interdisciplinary research, and education.

use by amphibians at different times during their life cycle (e.g., breeding, foraging, dispersing, and overwintering). This requires information about environmental conditions (e.g., topography, temperatures, cover types, water quality, and the presence of other species) as well as information about amphibian natural histories (see below). The lack of high-resolution spatial and spectral data is probably the single most important factor limiting the use of GIS to design, analyze, and apply the results of amphibian surveys (Peterson et al., in press). Researchers from Idaho State University, Montana State University, the USGS National Mapping Division, and the Yellowstone Ecological Research Center are taking several approaches to address this issue, including: (1) using high-resolution hyperspectral imagery to identify small wetlands suitable for amphibians; (2) developing GIS and statistical models to predict wetland habitat (based on a variety of information sources, such as digital elevation models, hydrology, and remote sensing), and (3) combining the habitat data with amphibian-use information to develop statistical and GIS amphibian habitat models. These projects seek to integrate advances in landscape analysis with knowledge garnered from amphibian surveys and ecological field studies. With tools provided by these projects, we will be better able to identify and map amphibian habitat, predict amphibian occurrence, and assess potential effects of environmental change and proposed management activities.

Natural history and ecology. Researchers from Idaho State University and other facilities will carry out ecological field studies to elucidate habitat associations and requirements, habitat use, and amphibian movements. Investigations will include population-level studies using mark–recapture techniques, and focal animal studies employing radio-tracking and behavior observation. This labor-intensive field research is vital for the creation and verification of habitat models. Studies are also needed to determine how local populations are connected to each other through dispersal or immigration of individuals, and how important these connections might be for population persistence.

Information integration. These three fields of effort are interactive. Data from amphibian surveys will be used for habitat mapping and modeling, and the models will predict amphibian distribution and occurrence park-wide. Findings of amphibian ecology and movement studies will also contribute to mapping and modeling, which in turn can be used to develop and test hypotheses about habitat associations, ecological relationships, and the causes and patterns of population declines. The products of these investigations will be integrated to form an information system for the park and other agencies interested in amphibian declines and conservation (Figure 7). Uses of this information system could include environmental analysis, project planning and engineering, amphibian conservation at local and regional levels, monitoring, evaluation of ecosystem health and changes, interdisciplinary research, and public education.

Acknowledgments

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We are grateful to the many people in Yellowstone who have helped with amphibian and reptile work over the past 12 years. Our most recent work on park-wide surveys has been greatly facilitated by Lane Cameron, Ann Rodman, and Shannon Savage. We also owe thanks for years of support to Stu Coleman, P. Stephen Corn, Ann Deutch, Merlin Hare, Ted Koch, John Lounsbury, and the Lake ranger district, Dan Mahony and the Yellowstone Aquatics Section, Fred Turner, Jennifer Whipple, John Varley, and the Yellowstone Center for Resources. We greatly appreciate Dan Reinhart's long-term assistance with research and conservation in the Lodge Creek study area. We thank all those who have conducted or assisted with amphibian surveys in the Yellowstone Lake area, including Char and Dave Corkran, Matt Chatfield, Josh Jones, Karen Kitchen, Mike Legler, Brian O'Hearn, Tiffany Potter, Karen Reinhart, and Stephen Sullivan.

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Sublacustrine Geothermal Activity in Yellowstone Lake: Studies Past and Present

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Abstract

The discovery and description of hydrothermal features such as geothermal vents, gas fumaroles, and even geysers within Yellowstone Lake is presented. Research was carried out over a period of 17 years beginning in 1984 and employed SCUBA to observe the sublacustrine hot springs and microbial mats in Sedge Bay, Yellowstone Lake. These initial observations led to the use of a remotely operated vehicle (ROV) to observe, sample, and study hot springs and gas fumaroles in the deepest regions of the lake, off Stevenson Island, in waters over 120 m deep. Relict hydrothermal structures varying in size (from centimeters to meters in height) and shape (from solitary pipes or chimneys to irregularly shaped structures) were located and sampled in various areas of the lake, including Mary Bay, Bridge Bay, and West Thumb.

Introduction

Yellowstone Lake, at an altitude of 2,356 m and with a surface area of ~342 km^2, is the largest high-altitude lake in North America. The lake is a natural habitat for the cutthroat trout *(Oncorhynchus clarki bouvieri)* and provides an important sports fishery for tourists that pass through Yellowstone National Park each summer (Gresswell et al. 1994). The fishery, combined with the lake's pristine beauty, is enough to make it an important resource. However, because it is located in Yellowstone National Park, one of the most tectonically and geothermally active regions of the world, it has an additional characteristic that makes it even more interesting: hydrothermal vents.

The Yellowstone plateau, with an average elevation of about 2,000 m, overlies magma chambers that are the source of the heat for the well-known geothermal features in the park: geysers, hot springs, fumaroles, and mud pots (Eaton et al. 1975). Like the Hawaiian Islands, Yellowstone lies over a hot spot in the earth's crust. Over the last 2.1 million years there have been three major volcanic episodes in the Yellowstone area; the most recent of these, the eruption of the Lava Creek Tuff of the Yellowstone caldera, occurred approximately 0.65 million years ago. During this last episode more that 900 km^3 of rhyolitic pumice and ash erupted, resulting in the collapse of a 75 x 45-km area and the formation of the Yellowstone caldera. Following this collapse, the rising magma chamber uplifted the floor of the caldera and formed two resurgent domes within the caldera boundary (Christiansen 1984; Good and Pierce 1996).

Most of the park's well-known geysers and hot springs occur within the Yellowstone caldera (Figure 1). Groundwater within the park percolates down through cracks and crevices in the rock and is heated to above boiling when it nears vast underground reservoirs of magma (Fournier 1989). It then resurfaces to create the park's famous thermal features, such as Old Faithful and Mammoth Hot Springs. What was generally unappreciated until the 1980s was that much of this same activity also occurs in Yellowstone Lake.

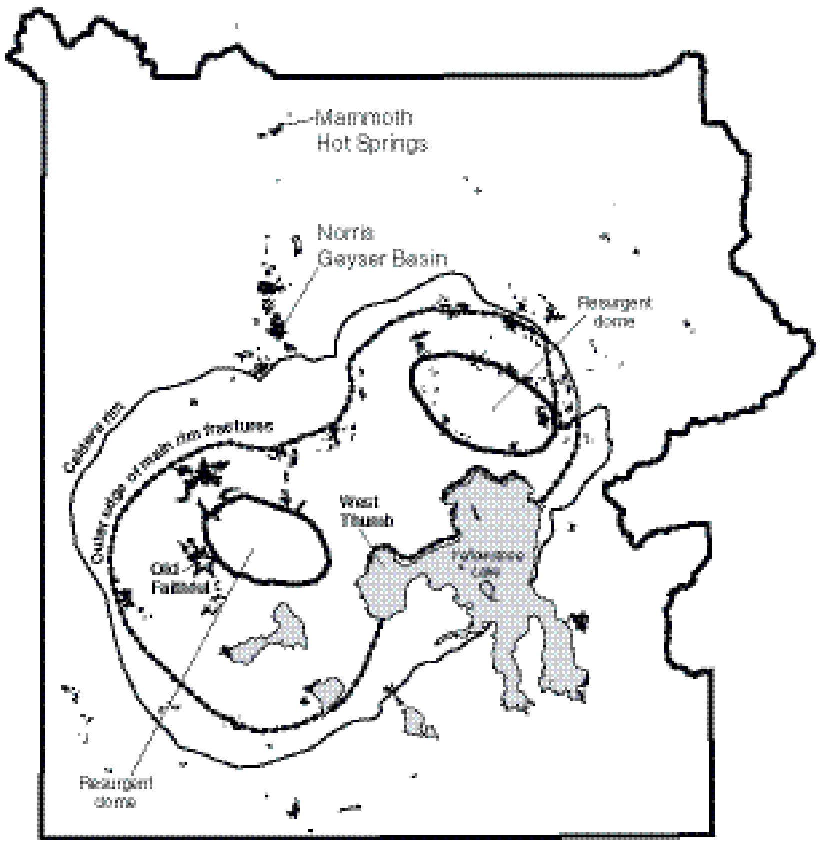

Figure 1. Line drawing of Yellowstone National Park showing Yellowstone Lake and various geothermal features nearby. Also shown is the boundary of the old caldera rim and its relationship to the lake. From Remsen et al. 1990.

In 1983, a small group of limnologists and other researchers from the University of Wisconsin–Milwaukee's Center for Great Lakes Studies visited Yellowstone National Park to collect some sediment cores from the West Thumb Basin and other areas of Yellowstone Lake. The objective of our work at that time was to examine these cores from a historical perspective and to see if we could re-create, or estimate, the productivity of the lake over the past several hundred years. The National Park Service (NPS) was interested in this study because other scientists (Shero and Parker 1976) previously hypothesized that Yellowstone Lake productivity had consistently decreased over the last 1,500 years and that this decrease might be related to long-term decreases in nutrient supplies. Declining nutrients available for the growth of algae—and, in turn, fish—had ominous overtones for the cutthroat fisheries in Yellowstone Lake. This appeared to contradict the norm, in that most lakes become more eutrophic over time and in some cases actually fill in, as in the case of bog lakes. Shero and Parker (1976) suggested that the decrease in total nutrient supply might be related to decreases in annual precipitation.

During this study in 1983, it was observed that some of the park's thermal basins literally rested on the shores of the lake, and, while working in the West Thumb Basin, bubbles were observed breaking the surface of the lake. These observations, combined with thermal gradient data from the lake floor (Morgan et al. 1977; Blackwell et al. 1986) indicated the presence of hydrothermal activity within the lake itself. Areas of geothermal activity were noted, and were examined in greater detail the following summer.

Thus began a study that continues until this day. At the time an initial research proposal was submitted to the National Geographic Society, very little was known about sublacustrine hydrothermal systems in Yellowstone Lake, or for that matter in other lakes around the world in which hydrothermal activity was known or suspected to occur. Presented here is a general review of the discoveries made while investigating the sublacustrine geothermal activity in Yellowstone Lake over the past seventeen years.

Research in Yellowstone Lake: Observations with SCUBA Divers

The first extensive search for underwater geothermal activity in Yellowstone Lake occurred from 1984 through 1986 in Mary Bay and in an adjacent bay to the south of Steamboat Point that we have called Sedge Bay (Remsen et al. 1990). Sedge Bay became an attractive site because there was a large emergent rock at the foot of a picnic area off the main road, where mobilization for our diving activities could occur. From the rock, approximately 12 ft from shore, diving excursions were made to the shallow-water vent areas (approximately 1 ha) and adjacent communities. SCUBA diver observations in these shallow bays (< 7 m deep) revealed a variety of geothermal features, including numerous fields of gas fumaroles, hot-water springs, and spectacular microbial mat communities (Remsen et al. 1990). Curtains of gas bubbles consisting mainly of carbon dioxide (plus, occasionally, some methane and hydrogen sulfide) and other nutrients were observed emanating from barren sandy sediments where temperatures reached 100°C at 5 cm below the surface (Klump et al. 1988). In these sandy areas, the gas fumaroles often formed a series of 10- to 12-cm domes created by the sorting of sandy sediments entrained in rising gas bubbles, resulting in the deposition of the finer-grained particles at the periphery of the gas vent. The hot gas vents were found dispersed over the barren sandy bottom as well as originating in areas of dense submergent plant growth. Gas fumaroles that contained hydrogen sulfide and also made contact with macrophytes *(Potamogeton, Ranunculus, Drepanocladus,* aquatic mosses, and filamentous algae) often produced conditions ideal for the colonization of chemolithotrophic bacteria: sulfide-oxidizing bacteria that actually use sulfur compounds as food from which they build new bacteria. When this occurred, white filaments could be seen attached to the plants (Figure 2). These particular bacteria (known as *Thiothrix* spp.) form long filaments that coil upon themselves. Similar bacteria have been found around hot vents in the ocean as well (Ruby and Jannasch 1982).

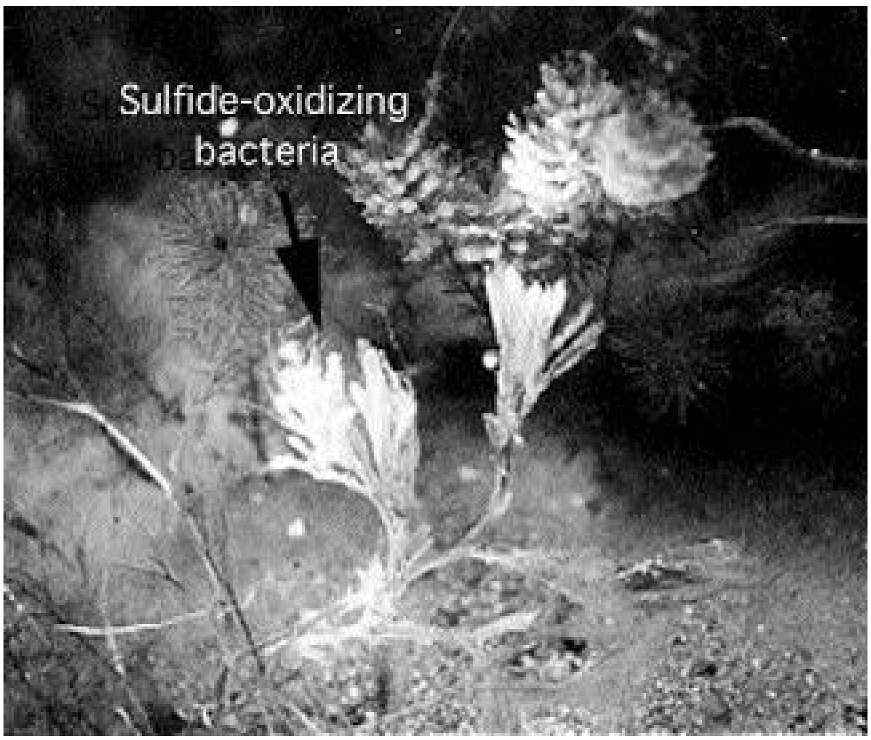

Figure 2. Photograph of macrophytes in Sedge Bay, Yellowstone Lake, coated with sulfide-oxidizing bacteria (arrow). Photo by J. Val Klump. ISWW/UWM Great Lakes WATER Institute.

Hydrothermal springs within the lake bottom create a range of thermal and chemical gradients that promote the growth of different types of bacteria as well as higher forms of microorganisms not typically found in deep, cold, nutrient-poor lakes. These gradients have resulted in the development of microbial mats (Figure 3) containing purple and green photosynthetic sulfur bacteria, sulfide-oxidizing bacteria, algae that can use the energy of the sun in the absence of oxygen (anoxyphotosynthetic cyanobacteria) as well as a wide variety of nematodes, protozoa, and other small animals that feed on these bacteria (Remsen et al.

1990). Enrichment culture techniques employed back in our university laboratories have yielded a diverse group of microorganisms, including methane-oxidizing bacteria, photosynthetic bacteria, thermophilic sulfate-reducing bacteria, and others. Similar types of microorganisms have been found attached to natural sur-

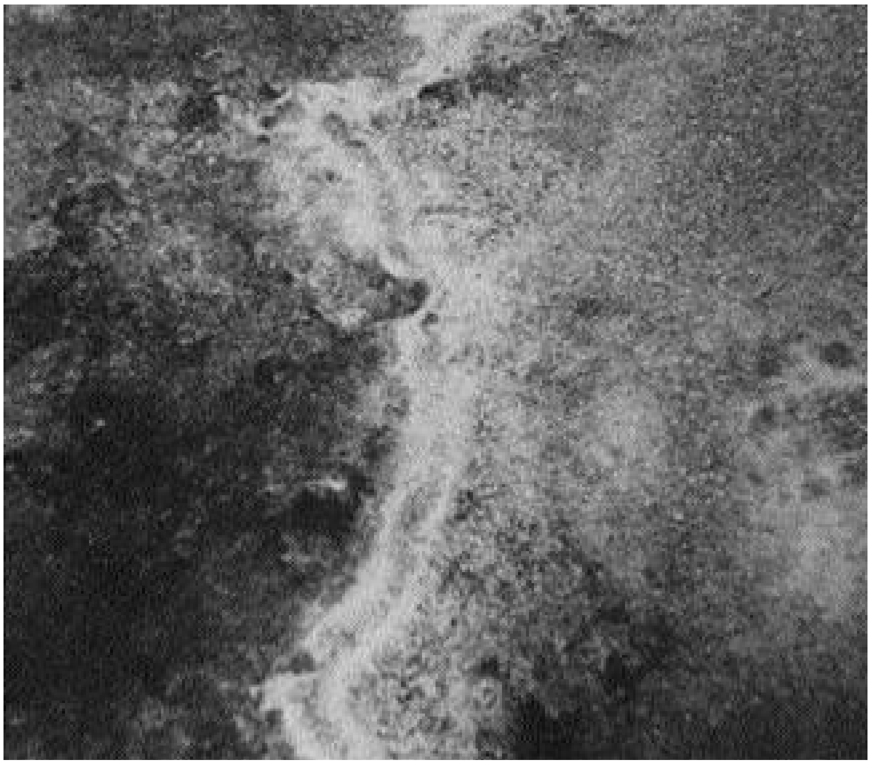

Figure 3. Photograph of a portion of a microbial mat located in Sedge Bay, Yellowstone Lake. The chemical and temperature gradients that exist in these mats determine the types of micro- and macro-organisms present in the mat. Photo by J. V. Klump, UWS/UWM Great Lakes WATER Institute.

faces near oceanic hydrothermal vents at the Galapagos spreading center in the Pacific Ocean, in the Quaymas Basin of the Sea of Cortez, and on sediments and rocks in Crater Lake, Oregon (Jannasch and Wirsen 1981; Tuttle et al. 1983; Dymond et al. 1989).

Dense populations of oligochaete worms were found congregated near many of the fumaroles on the down-current side. These fumarole colonies were circular, distinctly formed units compared with the sparsely colonized substrates away from fumaroles. Worm abundances were about an order of magnitude greater at the fumaroles than away from the vents. The fumarole worm colonies were made up of three tubificid oligochaete species, *Limnodrillus hoffmeisterii*, *L. udekemianus,* and *L. profundicola* (Brinkhurst and Jamieson 1971). The worms' normal orientation in the sediments is to have their front end (and mouth) pointed down in the sediment, while their back end is projected up and into the water. Usually their front end is as much as 1.5 inches deep in the sediment; however, it is unlikely that they are that deep when near hot-water vents, where the temperatures can reach nearly 80°C. The worms are most likely attracted to the vents in part because of the healthy bacterial flora supported by the nutrient and thermal activity of the fumaroles.

Generally speaking, when temperatures in sediments were less than 30°C, vegetative growth in the form of mosses and other macrophytes flourished; however, when temperatures increased and began to approach 40-50°C, then plant growth was absent. This phenomenon was quite evident in Sedge Bay, where ambient water temperatures approached 15°C at the time; the hypothesis for these observations was that the establishment of temperature and/or chemical gradients (radiating from the center of maximum vent activity) could provide hydroponic conditions conducive for plant growth. However, it is now known that the hydrothermally influenced waters are high in dissolved carbon dioxide, ammonium, silica, phosphate, and sulfide, and that fumarole gases are primarily carbon dioxide (Tables 1 and 2; Klump et al. 1988, Remsen et al. 1990).

Table 1. Concentrations of ions and nutrients dissolved in hydrothermal vent waters and surface waters in Sedge Bay, Yellowstone Lake. Source: Klump et al. 1988.

Sample Vent	Cl^-	SO_4^{2-}	Mg^{2+}	Ca^{2+}	Na^+	K^+	SiO_2	NH_4^+	ΣCO_2
	(μM)								(mM)
4	97	113			425	73	27	19.9	
5	100	99	176	196	532	63	150	2.2	
6	99	592	2,900	2,300	4,100	535	2,429	17.9	28.9
8	102	734	2,700	2,300		510	2,429	23.2	26.6
9	113	442	1,900	1,600	3,200	401	2,429	93.1	10.1
10	68	566					1,829	33.7	19.2
11	94	634					2,429	22.7	25.9
12	179	187					341	27.3	5.25
13	95	556	2,400	2,000	3,800	519	3,172	36.8	
14	87	503			3,800	496	3,074	39.7	
15	79	532	2,300	1,900	3,700	501	3,152	53.8	19.4
16	193	348	2,900	2,400	4,700	606	3,290	23.1	25.6
17	211	349	2,700	2,200	4,400	528	3,310	74.3	24.1
19	659	173	1,700	1,000	4,600	536	3,113	80.4	16.0
20	950	98	395	290	3,600	420	2,033	218.0	6.34
22	179	366	2,800	2,200	4,400	554	3,211	0.0	25.5
23	156	286	2,000	1,600	3,200	413	2,387	41.6	14.5
Lake water (average of all samples)									
	149	80	102	143	490	46	167	0.15	0.66
±	24	6	2	3	27	3	8	0.25	0.06

A New Technology: The Remotely Operated Vehicle

Starting in 1987, a remotely operated vehicle (ROV) has been employed in the underwater studies of Yellowstone Lake. Over 280 separate dives by the ROV were made over the period 1987–1999 (Table 3). It has provided direct observations of even the deepest areas of the lake, off Stevenson Island, in over 120 m of water.

Table 2. Chemistry of hydrothermal fluids collected from sublacustrine hydrothermal springs in Yellowstone Lake, 1988–1989. Source: Remsen et al. 1990.

	Cl^-	$SO_4^=$	NH_4^+	K^+	Na	pH	ΣCO_2	NH_4^+	SiO_2
	(mM)	(μM)	(μM)	(μM)	(mM)		(mM)	(μM)	(μM)
Mary Bay: Storm Point Vent (n = 11)									
High	3.30	45	82	1,157	3.91	7.20	16.13	22.4	1.620
Low	2.50	32	57	947	3.23	6.85	14.03	6.8	861
Mary Bay: Pipe Garden Vent (n = 13)									
High	0.171	111	11.1	51	0.83	6.18	5.34	30.6	355
Low	0.164	96	2.0	44	0.69	5.28	2.02	7.1	197
Sedge Bay Vents (n = 17)									
High	0.95	734	93.1	606	4.7	nd	28.9	nd	3,310
Low	0.07	99	17.9	401	3.2	nd	5.3	nd	2,030
Average ambient lake water									
Mean	0.16	87	0.15	45	0.64	6.89	0.80	0.44	
Sdev	0.01	4	0.25	3	0.06	0.11	0.06	0.23	8

Table 3. Number and location of ROV dives, Yellowstone Lake, 1987–1999.

	'87	'88	'89	'90	'92	'94	'95	'96	'97	'98	'99	Tot
Sedge Bay	3	2	1	2		2			1	1	3	15
Mary Bay	7	6	18	11	7	21	19	7	7	13	6	122
Storm Pt			4	3	1							8
Steamboat Pt			1	1	2		6	1	2		1	17
Pelican Roost	1	1									7	9
Stevenson Is	5	7	7	7	1	6	1		1	7	2	44
Off Lake			1									1
Bridge Bay				1		4		6	2			13
West Thumb	2				5		6	1	13	14	7	48
Pumice Pt					3							3
Dot Is					1							1
Breeze Pt								1				1
Wolf Pt								1				1
Southeast Arm					1							1
Total	18	16	32	24	21	30	34	16	30	37	26	285

With hundreds of small "microquakes" shaking Yellowstone every year, possibly triggering underwater landslides and changes in hot-water flows, sending a manned submersible into the depths of Yellowstone Lake would be very expensive and extremely risky. Thus, our little yellow submarine (Figure 4), later modified into a larger "open-frame" ROV (Figure 5), became vital to unlocking the

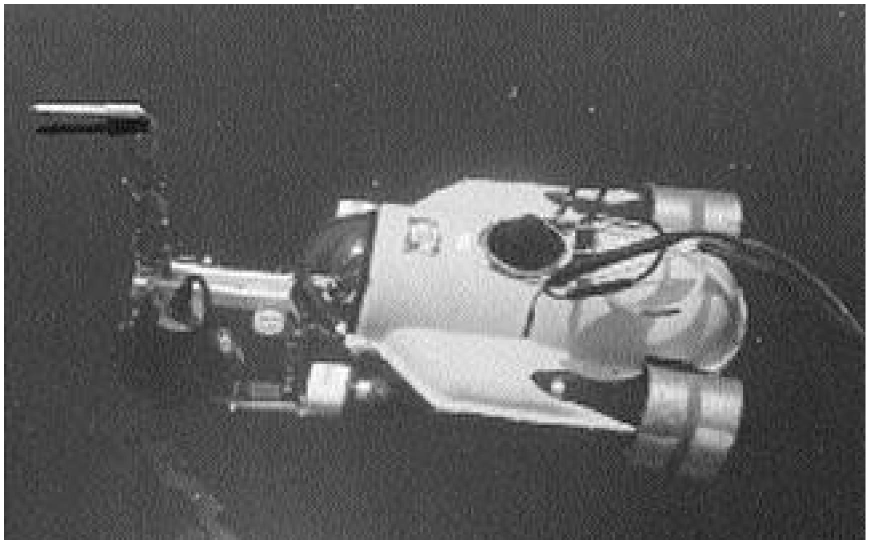

Figure 4. Photograph of early version (1987) of ROV used in these studies. Photo by C. C. Remsen, UWS/UWM Great Lakes WATER Institute.

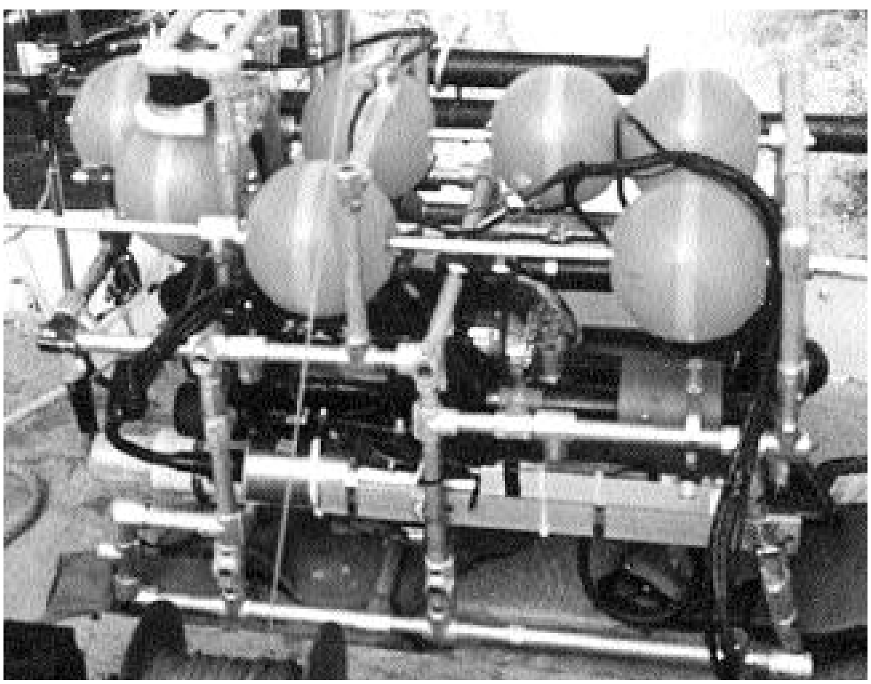

Figure 5. Photograph of a later version (1996) of ROV used in these studies. Note the use of an “open frame” which allows the attachment of various sensors, cameras, and water sampling devices. Photo by C. C. Remsen, UWS/UWM Great Lakes WATER Institute.

secrets of Yellowstone Lake, particularly in the deeper waters where SCUBA diving was not practical.

Early designs of the ROV, with a mass of ~18 kg, allowed us to take video footage and confirm the presence of hot springs and fumaroles at numerous locations and depths throughout the lake. However, the successors of the early yellow submarine, which have a mass of about 115 kg, have provided a more sophisticated and useful system (Klump et al. 1992). The growth and development of the ROV system was something that evolved over time and, like any evolutionary process, continues today.

Briefly, the main ROV pressure housing contains control electronics, a video camera, and a vertical thruster, with horizontal thrusters on either side of the housing. For navigation, combinations of sonar, fluxgate compass, and a magnetic compass are used, all housed separately on the open-frame ROV. At various times throughout its development and use, an array of sensors has been used on the ROV. Consistently, temperature sensors are used to monitor ambient and vent water temperatures (Figure 6). Conductivity sensors have also been used, and, as needed, a multi-probe (Hydrolab Model 4) has been attached to the ROV for extended sampling capabilities. Other instruments have included a three-function manipulator, a 16-loop water sampler (Lovalvo and Klump 1989), a Sipper system that uses a series of 60-ml syringes, and a motor-actuated pump from the surface to sample water. Prior to 1986, the largest water sample collected by the ROV was 10 ml. Subsequently, improvements in the system enabled us to collect 60-ml samples, and, finally, 1-l samples.

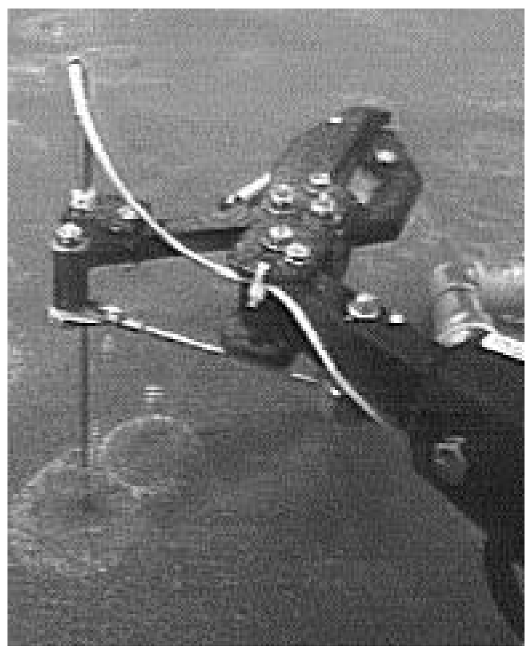

Figure 6. Photograph, grabbed from video, of ROV manipulator arm equipped with a temperature sensor, probing a small gas fumarole in Mary Bay, Yellowstone Lake. Note white "ring" around the fumarole; this is precipitated sulfur that has been produced by the oxidation of sulfide present in the fumarole gas. Video by David Lovalvo, Eastern Oceanics, Inc.

The manipulator is used for grasping objects or positioning equipment directly in a vent stream, or handling a scoop for collecting and storing larger objects, or as a "slurp gun" for collecting sediment samples. Having described all of this, anyone familiar with ROV technology and field research will know immediately that many, many hours in the field have been spent modifying equipment that failed or malfunctioned, or had to be improved or adapted on the spot. In this type of work, science definitely drives the technology, and many hours were spent late into the cool summer nights repairing and modifying equipment so that it would be ready at daybreak the following day.

The Underwater World of Yellowstone Lake: General Observations

In 1989, 30 dives over 12 days of "on the lake" work were completed. Seven stations in the eastern portion of the lake were occupied; however, the main focus of the study was on three stations in Mary Bay, the area of the lake with the highest heat fluxes (Wold et al. 1977) and highest excess radon concentrations (Klump et al. 1988), both indicators of considerable geothermal activity. In addition, a great deal of time was spent at a station in the central basin of the lake, off Stevenson Island, in an area with the deepest sounding of the lake, discovered just two years earlier in 1987 (Remsen et al. 1990; see also Kaplinski 1991). All of these locations were indicated to have sublacustrine geothermal activity, based upon the heat gradient data of Morgan et al. (1977; personal communications).

The Mary Bay sites, especially in a "deep hole" area (~50 m deep), have provided the greatest wealth of samples, including hydrothermal vent fluids (Table 2), fumarole gases, and samples of deep-living benthic communities. The most spectacular of these were the sponge communities colonizing rock and hard clay outcrops, microbial mat material, geological samples of fossil hydrothermal vent chimney or pipes, and other concretions. Within this "deep hole" or depression, the lake bottom is characterized by overhanging slopes of exposed lake sediments, slumps, hummock-like features, and amorphous concretions at scales ranging from 0.1 to 10 m (Klump et al. 1992).

First seen in 1987–1988, and then again in 1989 and in abundance in 1990 (as well as in the subsequent expedition years), were relatively flat sponges (Figure 7), each approximately 2–5 cm in diameter, found at a depth of 45–55 m in a region of high geothermal activity in Mary Bay. These sponges are usually identified by the silica "spicules" that are common to all sponges but are like fingerprints in that no two are alike. Henry M. Reiswig and Anthony Ricciatilis from the McGill University have identified sponges collected in Mary Bay from spicules and fragments as *Ephydatia fluviatilis* (Linnaeus, 1758). A specimen has been deposited in the Redpath Museum Invertebrate Collection as number 94-1-23.1. As mentioned, these sponges are usually (but not exclusively) found in the deeper waters of Mary Bay where the ambient temperature, warmed by geothermal heating deep within the sediments, remains a constant 14°C. This is very unusual, as most lake waters this deep are usually a constant 4°C. Swarms of zooplankton can be seen around the sponges. These sponges are also similar in appearance to ones that have been observed in Froelicka Bay, Lake Baikal, Siberia (Crane et al. 1991; K.H. Nelson, personal observations); however, that comparison is only tentative as actual samples have yet to be recovered from this area, which is approximately 1 km deep.

Our video footage reveals an extremely complex, convoluted, and rugged bot-

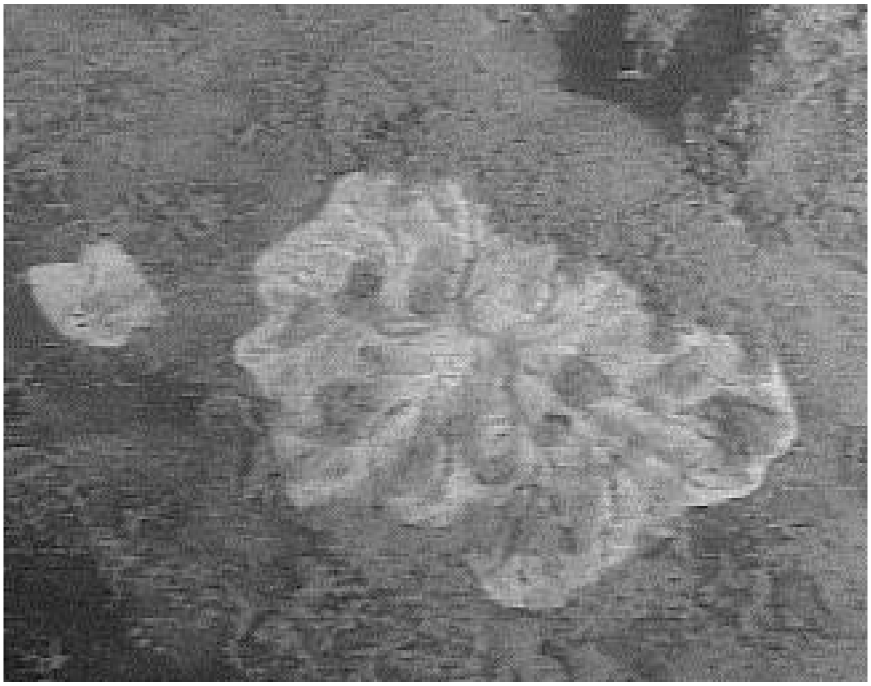

Figure 7. Close-up photograph, grabbed from video, of a "flat" sponge attached to a hard substrate (hydrothermal relict) at about 50 m in Mary Bay, Yellowstone Lake. Video by David Lovalvo, Eastern Oceanics, Inc.

tom topography unexpected in what, in a typical lake, would be the deep profundal basins of the system. For whatever reasons, seismic activity, venting, slumping, etc., these deep basins are not filled in with postglacial sediments, even though sedimentation in Yellowstone Lake is active and evident. Bottom sediments are deeply sculptured, most likely by periodic scouring by water forces that we have not yet observed (Klump et al. 1995).

Hot water vents are fairly common in these deeper parts of Mary Bay, and it is here that we discovered the freshwater equivalent of a "black smoker." On a routine dive in Mary Bay in 1995, after a relatively unsuccessful day, we came upon a vent that was obviously quite hot. The typical shimmering effect caused by hot vent water mixing with cold lake water was evident from quite some distance away, but what was most interesting was the fact that the hot-water plume had a dark color to it that clearly distinguished it from the water all around it. It was the closest we have come to a black smoker. When we measured the temperature, using an Onset recording thermistor, we found it to be approximately 115°C (Figure 8; Buchholz et al. 1995; Maki et al. 1995; Maki et al. 1996). Surrounding the vent were leeches. Some of them were feeding on the bacterial mat material that formed a halo around the vent and covered the vent opening like a flap; however, a number of them were dead, something we have since

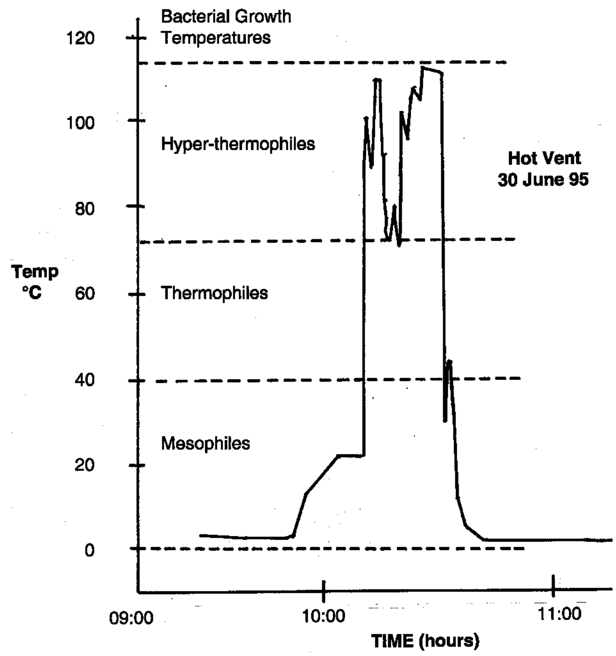

Figure 8. Temperature profile of a hot water vent in deep waters of Mary Bay (about 50 m), Yellowstone Lake. Manipulator arm of the ROV, with attached recording thermistor, was placed within the vent opening. Note that maximum temperatures of the vent water reached 115°C. The figure also indicates the temperature ranges for different classes of heat-tolerant to heat-loving microorganisms.

observed on numerous occasions. It would appear that these saprophytic leeches are attracted to these hot vents by the bacteria that grow nearby. These bacteria, usually sulfide-oxidizing, chemosynthetic bacteria, are utilizing the hydrogen sulfide in the hot water as an energy source and are thus able to grow and reproduce quite nicely. The leeches find them to be a tasty morsel and prey on them. Unfortunately for the leeches, however, many of these hot-water vents behave as geysers in that they have been seen to flow intermittently. Some leeches, eager to reach the bacteria on top of the vent, may periodically meet with very hot water suddenly erupting out of the vent. The result is boiled leeches. Through the eye of our ROV, these unfortunate victims, boiled white, stand out as beacons in its light.

In the deeper areas of the lake, off Stevenson Island for example, the features we observed most frequently were small depressions or openings in bottom sediments, 2.5–7.5 cm in diameter, from which an occasional gas bubble was emitted. Gas bubbles were not always seen, however, and we assumed that, based upon the loose, flocculent nature of these sediments, some relatively recent and persistent physical disturbance would be required to prevent the covering over and filling in of these depressions with sediment. Some of these small openings were also frequently surrounded, even covered, by a mat or film of stringy bacteria that fluttered and moved as warm or hot water flowed out of the vent, as well as white material that we assumed was elemental sulfur. In fact, after the first year or so, we used the white halo as a beacon indicating sulfide oxidation and the presence of bacteria.

Occasionally, warm or hot water was observed flowing from a fissure or openings in the bottom, creating a shimmering effect against a backdrop of cooler waters. The most dramatic example of this was observed at a depth of over 375 ft in a narrow depression in the main basin of the lake near Stevenson Island, where water in excess of 125°C was observed flowing from a small vent. This narrow, deep defile represented a sounding more than 14 m deeper than any before recorded in Yellowstone Lake. Sediments throughout this region were warmer than bottom waters by more that 5–7°C, and were even warmer still near presumed thermal features.

ROV observations of the bottom of the lake have revealed steep topography, sediment slumping, and "outcrops" of exposed sediment strata. If our estimates of deposition rates apply, these sediments are geologically quite young, no more than a few hundred to a couple of thousand of years old at most. They appear to be very well lithified, however, in contrast to sediments collected in other deep areas of the lake in cores nearly 3 ft in length. The sediments in Yellowstone Lake are a diatomaceous ooze consisting of up to 50-60% biogenic silica and having an organic carbon content of about 3%. It is possible that the exposed outcrops we see off Stevenson Island represent older sediments or that they have undergone accelerated lithification due to heating from below (Klump et al. 1995).

Among the more spectacular discoveries were the incredible cliffs in the deep canyons off Stevenson Island (Figure 9) in waters that reach 120 m or more. When we began to study the lake in detail, the recorded depth of Yellowstone

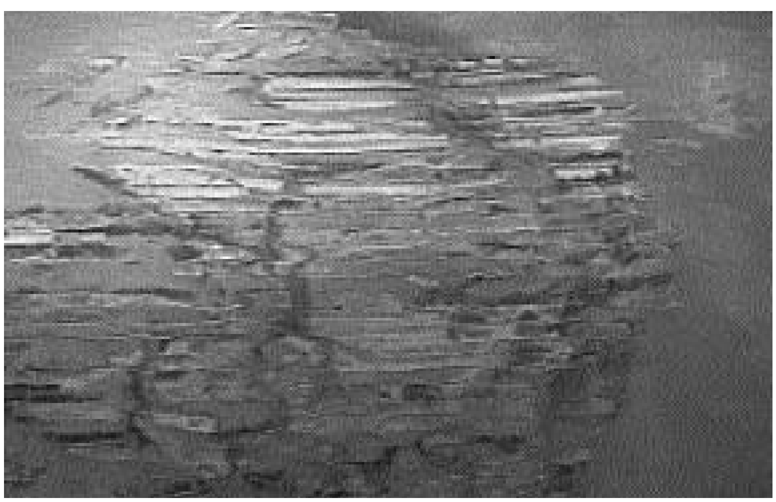

Figure 9. Photograph, grabbed from video, showing a panoramic view of spectacular cliffs in deep water (about 120 m) off Stevenson Island in Yellowstone Lake. Video by David Lovalvo, Eastern Oceanics, Inc.

Lake was 97.5 m. With our little robot submarine, however, we soon discovered that there were holes in the lake basin that went a great deal deeper. At the time we felt that there are areas of the lake that may well be deeper than 120 m, perhaps hiding more secrets that await discovery. In 1999, a side-scan sonar survey of the northern portion of Yellowstone Lake, conducted by the U.S. Geological Survey, Eastern Oceanics, Inc., and the University of Wisconsin–Milwaukee's WATER Institute, indicated depths off Stevenson Island reaching 137 m.

In 1987 and 1988 we conducted 12 dives off Stevenson Island in these deep and frigid waters. Incredible sights welcomed our eyes as we maneuvered our small robot down steep cliffs criss-crossed with cracks and fissures, and into narrow crevices and deep trenches. Cliffs of recently deposited and lithified sediment rose 50 to 75 ft and showed incredible structure. Rocky ledges that suddenly turned 90˚ with dramatic outcroppings were visible to us through the video eye of our small robot (Remsen et al. 1990). Occasionally, large, rounded hummocks of silty material appeared, on which were distributed, in a random fashion, stones or rocks of various sizes. These large, rounded hummock slopes often showed hot-water seeps or vents, identified by the presence of precipitated sulfur produced by the oxidation of sulfide by sulfide-oxidizing bacteria (Figure 10).

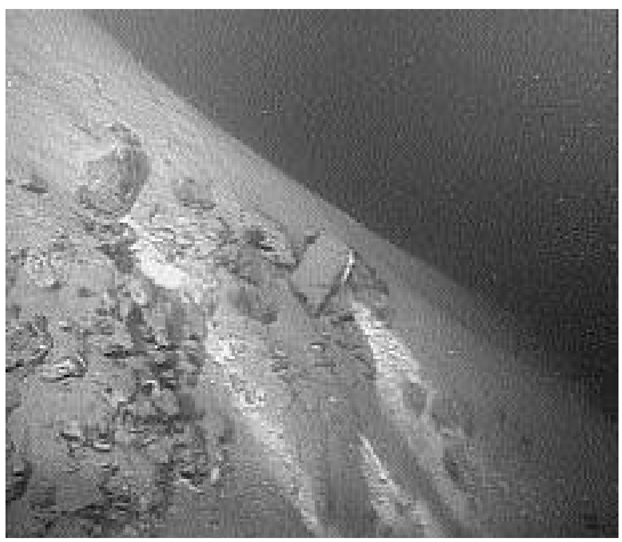

Figure 10. Photograph, grabbed from video, showing a panoramic view of a sediment slope, deep (about 100 m) in waters off Stevenson Island, Yellowstone Lake. Note the presence of hot water "seeps" or vents (arrow), identified by the presence of precipitated sulfur produced by the oxidation of sulfide by sulfide-oxidizing microorganisms. Video by David Lovalvo, Eastern Oceanics, Inc.

Hot water vents and fumaroles were almost always found at the base of these incredible cliffs in the waters off Stevenson Island (Figures 11 and 12). Sometimes they were hidden among the rocks and debris at the base of these

Figure 11. Photograph, grabbed from video, of a hot water vent in deep waters (about 135 m) off Stevenson Island, Yellowstone Lake. Again note the precipitated sulfur. Video by David Lovalvo, Eastern Oceanics, Inc.

Figure 12. Photograph, grabbed from video, of a hot water vent in deep waters off Stevenson Island, Yellowstone Lake. Note the accumulation of precipitated sulfur and sulfide-oxidizing microorganisms near the vent opening. Video by David Lovalvo, Eastern Oceanics, Inc.

underwater hills or mountains. These were often revealed by the white halo produced by sulfide-oxidizing bacteria living off of the hydrogen sulfide gas that was being emitted by the fumarole. Sometimes, however, they were simply identified by strange “caves” or “carvings” in the sediment cliffs. It became clear to us, after considerable thought and examining alternative explanations, that these features in the sediment were brought about by the action of hot water.

Finally, an intriguing discovery was made in 1992 while researching thermal areas in the West Thumb Basin, near the West Thumb thermal area. On advice from one of the local interpretive rangers, Jon Dahlheim, we began to search for—and found—what appeared to be an underwater geyser. With the ROV in position some 3 to 4.5 m down in a rocky, macrophyte-filled depression, a vent was discovered that periodically emitted large quantities of hot water. Initially erupting at approximately 20-minute intervals, a surprising observation was made: during each eruption, cutthroat trout appeared and actively swam into the roiling hot water, apparently feeding on particles of bacterial mat loosened by the action of the water. Further observations that year and in subsequent years confirmed our initial findings and the vent was dubbed the “Trout Jacuzzi.”

Evidence of Past Activity

Found on the bottom of the Mary Bay region, and serving as a surface for sponge colonization, were both small, hollow chimneys or pipe-like structures (Figure 13), about 12–25 cm in height and 4–7 cm in diameter, as well as larger irregular features. Preliminary X-ray diffraction studies and elemental analyses performed later in our laboratories at the University of Wisconsin–Milwaukee

Figure 13. Photograph, grabbed from video, of a hydrothermal relict pipe in bottom waters (about 50 m) of Mary Bay, Yellowstone Lake. Note attached sponge. Video by David Lovalvo, Eastern Oceanics, Inc.

indicated that these pipes consist of approximately 90% amorphous silica. Morphologically, and on a smaller scale, they resembled the carbonate (limestone) chimneys recovered from the outer continental shelf off northern Oregon (Kulm et al. 1988), and the so-called black smokers on the East Pacific Rise (Francheteau et al. 1979). We have hypothesized that these pipes are relict hydrothermal features that once served as conduits for hydrothermal fluids high in dissolved silica. Possibly formed below the sediment surface, the pipes may have become exposed following erosion of the surrounding (unconsolidated) sediment. Whether such hydrothermal plumbing exists under active vents has not yet been determined.

The pipes, or relict chimneys, that we discovered in the Mary Bay area seem to be more concentrated in the area we call the “Pipe Garden” (Remsen et al. 1990). For the most part, they are relatively small compared with the chimneys found in the marine environment.

The irregular features that have been seen range in size from rather small (5–8 cm in diameter) to quite large (up to 1 m in diameter). They usually are an amalgamation of connecting tubes molded together in a wide range of shapes. Others appear as if they were extruded from some strange mold and can be large mound-like structures, or thin, sheet-like structures sticking out of the side of a cliff or mound. In all cases, like the pipes, they consist almost entirely of amorphous silica. These concretions have not been observed outside of Mary Bay, certain areas off of Storm Point, and in the West Thumb area.

In 1996, thanks to some information provided by a NPS archeological survey team, transects were made over an area in Bridge Bay and the bottom was studied with a Furuno depth profiler (Figure 14). This work was rewarded with some spectacular sights: relict hydrothermal chimneys (Figure 15) that varied in height from 1.5 to 6 m and were covered with an incredible array of sponges, bryzoa,

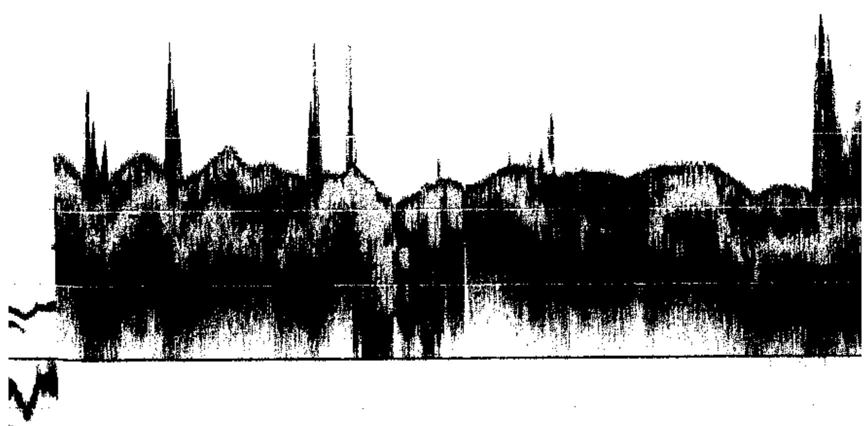

Figure 14. Sonar profile of an area of Bridge Bay, Yellowstone Lake. Note the spires (1 m to 10 m in height) rising from the bottom (about 20 m). These spires have been identified as relict hydrothermal chimneys.

and algae. These structures were analogous to the marine chimneys in their size and shape (Kulm et al. 1988), and, when active at some time in the past, must have been very similar to the hydrothermal chimneys that have been described in the marine environment.

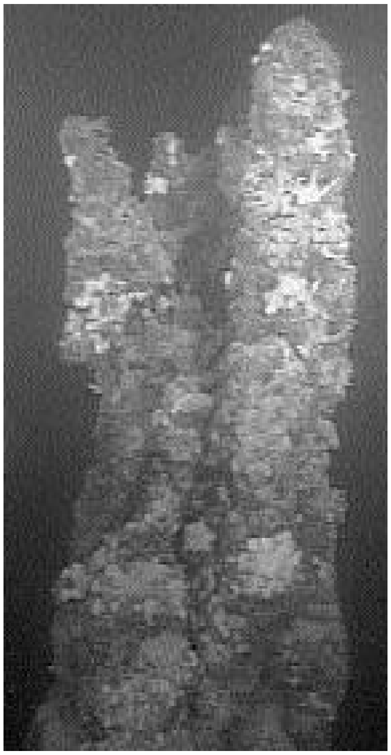

Figure 15. Photograph, grabbed from video, of a portion of a relict hydrothermal chimney in Bridge Bay, Yellowstone Lake. Note various sponges attached to the spire. Video by David Lovalvo, Eastern Oceanics, Inc.

General Conclusions

After a number of years of research on, and in, Yellowstone Lake involving SCUBA and ROV development, as well as sample collection and analysis, we are just now beginning to understand some of the dynamics at work, although the details are far from clear and will require continued research on our part. It is clear that the lake is richer than most high-altitude alpine lakes due to the nutrients that are introduced into it from the geothermal activity that we have just described. In addition, the microbial communities that exist in the lake as a result of this inorganic chemical input (chemosynthesis) contribute greatly to maintaining a thriving algal and zooplankton community. Furthermore, Yellowstone Lake may be subject to violent shifts in its underground plumbing caused by both minor and major earthquakes, and major sediment slumping events. These all have the potential to greatly influence the biology and chemistry of the lake.

In the deeper regions of the lake, off Stevenson Island for example, underwater hot springs and geysers are actively changing the landscape of the lake bottom by a variety of activities. On the one hand, constant streams of hot water carve out caverns in the sediment, exposing hard substrates through erosive power. In some areas, hot water simply oozes slowly out of a small vent, creating gradients of both nutrients and temperature that stimulate the growth of certain types of microorganisms. In other cases, chemicals in the hot water, such as methane or sulfur, can be used by these bacteria to produce new biomass or cell material—new biomass that is produced by chemosynthesis, not photosynthesis. As a result of these observations, we hypothesize that some of the sponges that we have observed in the deeper waters of Yellowstone Lake, as well as some of the plankton population that we find in swarms in deep waters, are sustained via a food chain driven by chemosynthesis. Thus in Yellowstone Lake, two life-driving forces—photosynthesis and chemosynthesis—are at work, as they are in the oceans where hydrothermal communities have been discovered.

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Prehistoric Land-Use Patterns within the Yellowstone Lake Basin and Hayden Valley Region, Yellowstone National Park, Wyoming

Paul H. Sanders

Abstract

Humans have inhabited the Yellowstone Lake area for at least the past 10,000 years. Archeological studies of the area are starting to provide a view of the prehistoric lifeways of these peoples. This paper summarizes the nature of this prehistoric use, including lithic raw material utilization, stone tool characterization, and food procurement practices. Changes in landform evolution during the late Pleistocene and early Holocene and their potential impact on prehistoric groups occupying the area are also discussed. Finally, the question of change versus stability is discussed in light of the prehistoric occupation of the area.

Introduction

This paper summarizes the archeological record of the Yellowstone Lake area; however, in order to place this record into its proper context, it is useful to provide some background information on the nature of Yellowstone archeology as a whole. Previous researchers have described the prehistoric occupation of Yellowstone National Park as poorly known (National Park Service 1993; Cannon, Crothers, and Pierce 1994; Cannon et al. 1997). This is partially true, as there are very few of the stratified, key "type" sites that are necessary for archeologists intent on building cultural chronologies or investigating changes in prehistoric life ways through time.

There are several reasons for this. First, the volcanic nature of much of Yellowstone has resulted in shallow, acidic soils. Both of these conditions adversely affect the preservation of prehistoric occupations. The acidic soils dissolve organic remains, which are most critical if one wants to know what animals prehistoric peoples were eating. This is particularly frustrating, because Yellowstone is the place people from across the world now come to view wildlife, and the archeological record is so poor in this respect.

The shallow soils that cover most of the Yellowstone Plateau are easily mixed by rodent burrowing, freeze–thaw cycles, and tree tip-ups, all of which disrupt the clarity of a buried prehistoric occupation. The volcanic rocks of Yellowstone and other geologic formations also lack the caves or rock shelters that provide the most ideal locations for the preservation of prehistoric artifacts and organic remains. More recently, the 125 or more years of artifact collecting by tourists and others has depleted the number of diagnostic artifacts that were once present. Wayne Replogle, a park naturalist who traced the Bannock Indian Trail through northern Yellowstone, noted in his 1956 publication on the trail (1956: 71) that he found comparatively few projectile points, but that old-timers said that they used to be quite common and were also a common souvenir in the early days of the park. This points to the diminishment of the archeological resource by the 1950s; so consider the state of affairs 50 years later, when annual park visitation is in the millions, despite the efforts of the National Park Service to discourage collecting.

Another factor is the virtual lack within Yellowstone of large-scale archeological excavations, which provide the most detailed information on prehistoric lifeways. Most of the archeological work in Yellowstone has been cultural resource inventories and small-scale test excavations. The inventories provide data on surface artifact assemblages and an assessment as to the site's potential for buried artifactual remains. The test excavations are generally designed for evaluative purposes and typically do not expose enough of a buried cultural level to provide much more than an inkling as to a site's actual contents. As a result of these factors, of the nearly 700 prehistoric sites that have been recorded thus far, most provide only a minimal glimpse of the prehistoric occupation of Yellowstone.

As a consequence, researchers have generally had to borrow cultural chronologies from regions that neighbor Yellowstone. The chronologies developed for the Northwestern Plains by William Mulloy (1958) and, later, George Frison (1978, 1991) are most often cited, although B.O.K. Reeves is currently developing a chronology for Yellowstone (see, e.g., Shortt 2001). Briefly, the chronological periods utilized in this paper follow Frison (1991) and are listed here in years before present (BP): Paleoindian period (ca. 11,500–8,000 BP), Early Archaic period (ca. 8,000–5,000 BP), Middle Archaic period (ca. 5,000–3,000 BP), Late Archaic period (ca. 3,000–1,500 BP), and Late Prehistoric period (ca.1,500–500 BP). Much of this chronology is developed around changes through time in the styles of projectile points, as well as past climatic conditions.

It should be noted that, in some ways, the borrowing of chronologies is somewhat appropriate, since it is likely that most if not all of the prehistoric inhabitants probably occupied Yellowstone only on a seasonal basis, moving to the lower elevations outside Yellowstone in the winter. As a result, some of the archeological remains in the valleys of southwestern Montana, northeastern Idaho, and northwestern Wyoming were likely created by the same peoples that spent the summer months in Yellowstone. Therefore, the styles and ages of the artifacts deposited in these neighboring areas should have relevance to Yellowstone.

Obsidian Utilization

The ability to determine the source of obsidian through x-ray fluorescence and similar techniques, and its prevalence within the Greater Yellowstone Ecosystem, is, perhaps, the one saving grace of Yellowstone archeology. Obsidian Cliff, located about 20 miles to the northwest of Yellowstone Lake, was a major source of obsidian throughout prehistory. Its occurrence within Hopewell sites in Ohio about 2,000 years ago is one of the more dramatic instances of artifact dispersal within North American prehistory.

Table 1 lists the results of the obsidian source analyses for the Yellowstone Lake area, while Figure 1 illustrates the locations of the various sources. All of the obsidian source analyses reported in this paper were conducted by Richard Hughes of Geochemical Research Laboratory. Two things are evident in Table 1. First, as to be expected, Obsidian Cliff is the dominant source. The popularity of the Obsidian Cliff source for tools is evident in the huge amounts of debris generated through its quarrying. The Hayden Valley–Yellowstone River area, just to the north of Yellowstone Lake, ranges from about 13–24 miles from Obsidian Cliff and, as expected, has the highest percentage (86.3%). However, the North Shore of Yellowstone Lake and West Thumb are both about 25–30 miles from Obsidian Cliff, but West Thumb has only 55.6% Obsidian Cliff obsidian compared with the 80.0% for the North Shore sites. This would suggest that the movement of peoples was along the Yellowstone River, through the Hayden Valley, and on toward Yellowstone Lake. The lower percentage of Obsidian Cliff obsidian at the West Thumb sites suggests that the movement of peoples from the Obsidian Cliff source area was more indirect.

Second, Bear Gulch obsidian is the next most common source, constituting, in the West Thumb sites, one-third of the obsidian for which a source could be determined. The Bear Gulch source area is in the Centennial Mountains along the Idaho–Montana border. From the West Thumb area, the Bear Gulch and Teton Pass (in Jackson Hole) sources are both about 60–65 miles away (Figure 1), yet Bear Gulch obsidian is much more common (Table 1). This pattern is duplicated in the Jackson Hole area, where Bear Gulch is also more prevalent than Obsidian Cliff obsidian (Reeve 1989; Schoen, Thompson, and Pastor 1995; Schoen 1997). This seems to suggest that there was some sort of boundary or obstacle that prevented people from accessing the Jackson Hole sources directly through southern Yellowstone. Based on the determination of obsidian sources, the pattern of movement appears to have been from Jackson Hole northwestward into northeastern Idaho, and then back east toward Yellowstone, probably following the Madison River. The other possibility is through Pacific Creek to the upper

Table 1. Summary of obsidian source analyses in the Yellowstone Lake Area.

	Obsidian Cliff, Yellowstone	Bear Gulch, Idaho	Teton Pass, Wyo.	Packsaddle Creek, Idaho	Park Point, Yellowstone	Cougar Creek, Yellowstone	Unknown	Total
Hayden Valley–Yellowstone Riv.	95 (86.3%)	7 (6.4%)	1 (0.9%)	1 (0.9%)	1 (0.9%)		5 (4.5%)	110
North Shore–Yellowstone Lake	132 (80.0%)	8 (4.9%)	1 (0.6%)			2 (1.2%)	22 (13.2%)	165
West Thumb	15 (55.6%)	9 (33.3%)	1 (3.7%)	2 (7.4%)				27

Sources:
Hayden Valley–Yellowstone River: Sanders (1999, Appendix 2); Sanders (2000, Appendix 1); Sanders (2001, Appendix 2); Shortt (1999a, Appendix 2)
North Shore–Yellowstone Lake: Cannon et al. (1997, Table 60)
West Thumb: Johnson (2001, Figure 1)

Yellowstone River and then along Yellowstone Lake (Wright 1975; Crockett 1999). Either route is indirect and would result in the gradual falling-off or discarding of lithic materials that occurs as distance from the source increases.

Another possibility is that the limited amount of Teton Pass or other Jackson Hole obsidians reflects a low prehistoric presence within this particular area. Except for Jackson Lake and a few other areas (Wright 1975; Connor 1998), previous inventories (e.g., Wright 1975; Waitkus, Rosenberg, and Wolf 1998; Sanders and Holtman 2001; Sanders, Waitkus, and Holtman 2001) have documented unusually low prehistoric-site densities over much of the open, lower elevations of Jackson Hole. Wright (1975: 44, 88) suggests that these areas of low site density may represent areas of low ecological productivity with regard to hunting and gathering potential, and also suggests that the game numbers in Jackson Hole were unpredictable and unreliable. Given the lower productivity of areas and carrying capacity within Jackson Hole, fewer people could have been supported, resulting in proportionally fewer people traveling out of Jackson Hole and, consequently, fewer instances of deposition of Jackson Hole lithic materials in Yellowstone. Conversely, there would be less motivation or attraction to trav-

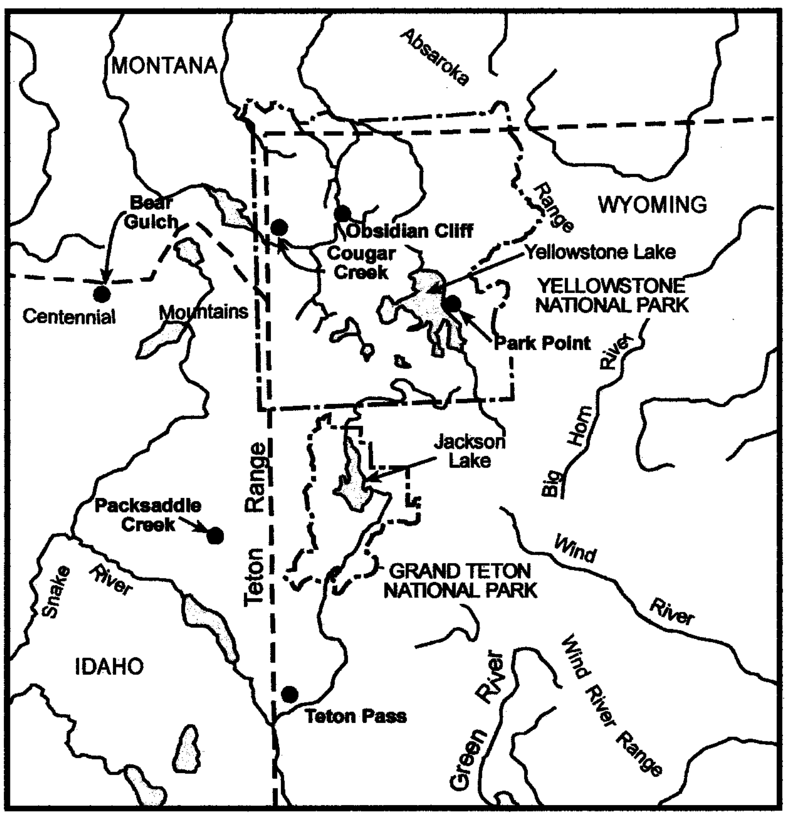

Figure 1. Map of obsidian source locations identified from archeological sites in the Yellowstone Lake area.

el into Jackson Hole, with fewer people depositing exotic lithic materials from outside areas (e.g., Yellowstone).

Subsistence Practices

Characterization of the foods eaten by prehistoric peoples is primarily based on inferences drawn from the recovery of faunal and floral remains from archeological sites. As noted previously, faunal remains are particularly scarce within Yellowstone. Within the Yellowstone Lake area, faunal remains have been recovered from only two sites, 48YE697, the Windy Bison site (Cannon et al. 1997) and 48YE545 (Sanders 2001; Table 2). Additional information has been gained from the analysis of blood residue on stone tools, which has identified a wider variety of animals that were likely hunted by prehistoric peoples. Curiously, no fish were identified, which would have been a rich resource. Although preservation of fish bones is a problem, fishing-related artifacts (e.g., net weights or sinker) have not been clearly identified (Taylor, Wood, and Hoffman 1964).

Bison were a primary food resource for Native Americans, as is evident by the number of bison kills that have been found throughout the Plains (see e.g., Frison 1991). No communal bison kill sites have been found within Yellowstone. The closest kill sites are north of Mammoth in Paradise Valley (Arthur 1966). The lack of communal kill sites is curious given the prevalence of bison within the park today, but, as noted earlier, the acidic soils are at least partially responsible. The excavations at the Windy Bison site indicated that only a single male bison had been killed and butchered. Cannon et al. (1997: 170) suggest that game animals were probably taken by small groups of hunters.

Besides faunal remains, inferences of hunting can be made because of the presence of projectile points. Test excavations of 20 sites in the Hayden

Table 2. Summary of prehistoric subsistence data in the Yellowstone Lake area.

	Species										
Area	Bovine	Bison	Elk	Bison/ Elk	Deer	Sheep	Bear	Felid/ Cat	Canid/ Dog	Rabbit	Vole
	Blood Residue[1]										
North Shore				1	6	1	1	2	2	4	
West Thumb	1					1				1	
	Faunal Remains										
North Shore[1]		58 (MNI = 1)	3 (MNI = 1?)			1 (MNI = 1)					1 (MNI = 1)
LeHardys Rapids to Fishing Bridge[2]	7 Medium Sized Mammal Bones (Deer/Sheep/Pronghorn)										

[1] Cannon, Pierce, Stromberg, and MacMillan (1997: Table 56).
[2] Sanders (2001: Table 27)
MNI = minimum number of individuals

Valley–Yellowstone River area recovered 40 projectile points, or an average of two points per site (Sanders 2000, 2001). Similar work in the Lamar Valley of northeastern Yellowstone found only six projectile points in eight prehistoric sites (Sanders, Wolf, and Rogers 1997), while excavations at sites along the Mammoth-to-Norris highway in northwestern Yellowstone found seven points from nine prehistoric sites (Sanders 1998)—both areas exhibiting less than one point per site. This suggests that hunting activities played a larger role within the Hayden Valley–Yellowstone River area than in these other two investigated areas of Yellowstone, despite the fact that the Lamar Valley, especially, also traditionally holds large numbers of potential game animals (National Park Service 1997).

Much of the prehistoric diet was composed of plants—usually the seeds, roots, or tubers. Archeologically, sites associated with the procurement and processing of plant resources are often identified by the presence of groundstone implements used to grind seeds and other plant remains. However, groundstone implements are uncommon in the park. Within the Yellowstone Lake area, the most prominent site with groundstone is 48YE701 (Cannon et al. 1997), located on the north shore near Steamboat Point, and which is also near the Windy Bison site. Limited groundstone suggests that processing of plant resources was similarly limited, or else utilized a different technology that is not presently showing up archeologically. Blood residue analysis of the groundstone from 48YE701 suggests that these types of implements could also be used to process animal remains, not plant remains (Cannon et al. 1997: 179).

The other line of archeological evidence for prehistoric use of plants is from fire hearths. These are usually about 1 m in diameter and 20–30 cm deep and often filled with burned rocks. Macrofloral analysis of the hearth fill can often reveal charred plant remains, most often chenopodium-amaranth seeds. However, such features are also uncommon within Yellowstone, and have generally yielded few charred plant remains. The lack of such features is unusual since their other function is to provide heat—essential for survival within Yellowstone's cool climate.

The limited number of identified hearths may be due to their low archeological visibility within Yellowstone. As noted above, burned rocks are commonly associated with hearth features; however, the local volcanic rocks do not change colors or fracture differently when heated in fires. In essence, culturally heated volcanic rocks do not look any different than the natural ones, which prevents archeologists from detecting the presence of fire hearths at an archeological site.

Geomorphological Factors

A factor concerning the locations and patterns of archeological sites is changes in the landform through time. Within the Yellowstone Lake area, Kenneth Pierce and others (e.g., Hamilton and Bailey 1990; Pierce, Cannon, and Meyer 2001) have documented changes in the level of Yellowstone Lake during the past 10,000–12,000 years. Obviously, this would have limited some of the areas available for occupation, especially during the Paleoindian period. Recent work within the Hayden Valley–Yellowstone River area (Sanders 1999, 2000, 2001) provides some additional details on the landform changes downstream from Yellowstone Lake.

In the late Pleistocene, after deglaciation, Alum Creek created a large outwash plain that was at least 5–10 m higher than the present level of the Yellowstone River. Alum Creek, and the Yellowstone River, started downcutting through the outwash plain sometime later. The starting date for this downcutting is not currently known, but was probably initiated by about 12,000 years ago, since a buried Paleoindian-age occupation was found in sediments overlying the outwash plains gravels at sites situated near the mouth of Alum Creek (Sanders 2000). Lower bracketing radiocarbon dates have been obtained from organic layers overlying fine alluvial sands, and indicate that 8,500 years ago in the Otter Creek area (a few miles north of the Hayden Valley), the Yellowstone River was approximately 1 m higher than it is at present, but had only cut down to within 2 m of the present river level in the Buffalo Ford area by 6,500 years ago (Sanders 2001: 159). Some of the reason for this may be due to the differential raising and lower of the Yellowstone caldera along a fault line that passes through LeHardy Rapids, just upstream from the Buffalo Ford area, as documented by Pierce, Cannon, and Meyer (2001).

The higher elevation of the Yellowstone River during the Paleoindian and Early Archaic periods indicates that such occupations should consequently be found on the higher terraces. Likewise, the lower terraces along the Yellowstone River would only have been available for occupation after the Early Archaic period. This appears to be the case in the Otter Creek–Chittenden Bridge area (just to the north of the Hayden Valley), where the first occupations at 48YE446 (Sanders 1999) and 48YE516 (Reeve 1984) are associated with the Middle

Table 3. Number of sites/components by area and period.

Chronological Period	Hayden Valley/ Yellowstone River	North Shore of Yellowstone Lake/ Pelican Creek	West Thumb	South Shore of Yellowstone Lake	Total
Paleoindian (ca. 11,500–8000 BP)	4 (23.5%)	7 (41.2%)	6 (35.3%)	0 (0%)	17
Early Archaic (ca. 8000–5000 BP)	2 (14.3%)	6 (42.9%)	5 (35.7%)	1 (7.1%)	14
Middle Archaic (ca. 5000–3000 BP)	8 (33.3%)	5 (20.8%)	9 (37.5%)	2 (8.3%)	24
Late Archaic (ca. 3000–1500 BP)	12 (38.7%)	10 (32.3%)	7 (22.6%)	2 (6.5%)	31
Late Prehistoric (ca. 1500–500 BP)	13 (41.9%)	9 (29.0%)	8 (25.8%)	1 (3.2%)	31
Multiple Components	10 (33.3%)	7 (23.3%)	10 (33.3%)	3 (10.0%)	30

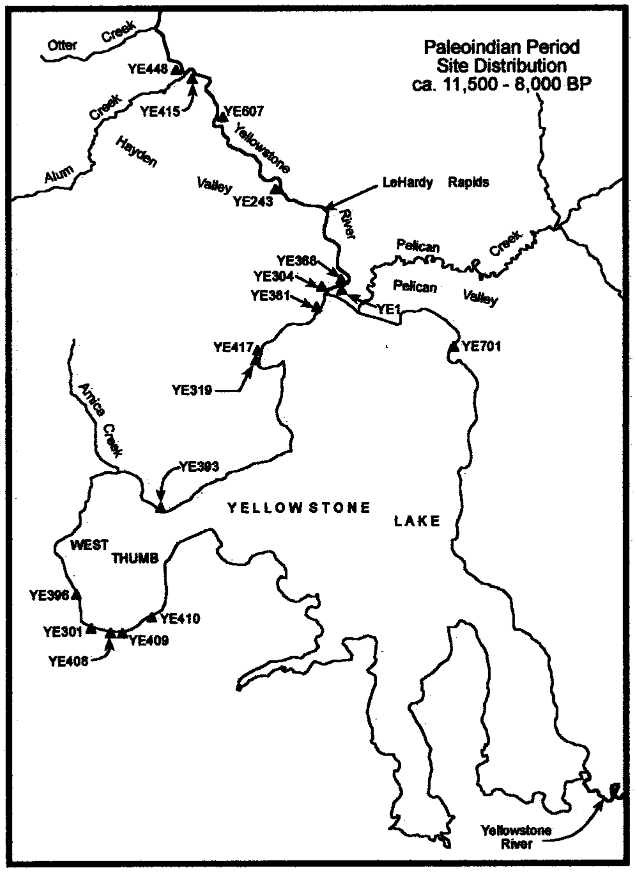

Figure 2. Paleoindian period site distribution in the Yellowstone Lake area.

Figure 3. Paleoindian artifacts from the Hayden Valley–Yellowstone River area. From left to right: fish-tailed point fragment from 48YE243, Scottsbluff point from 48YE448, and a spurred end scraper, also from 48YE448.

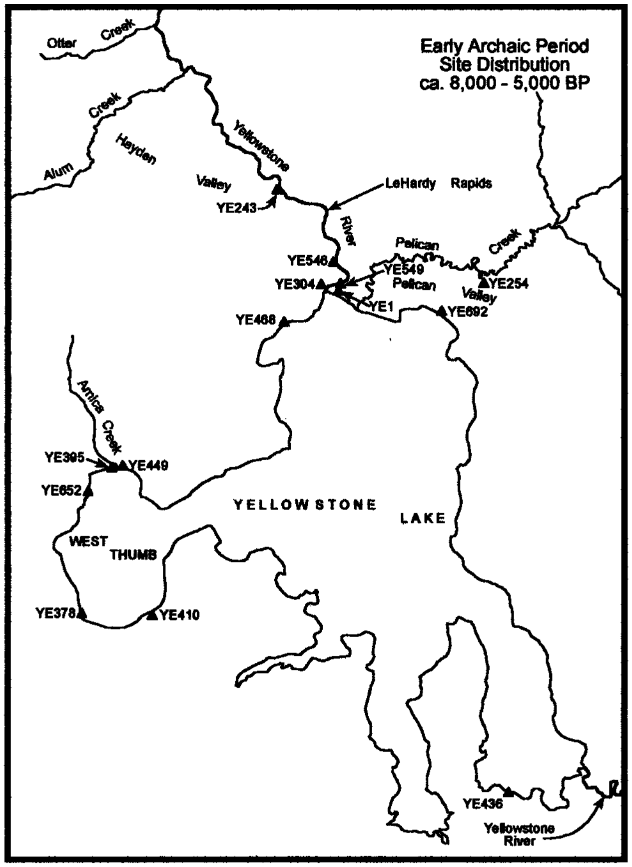

Figure 4. Early Archaic-period site distribution in the Yellowstone Lake area.

Archaic period (i.e., 5,000–3,000 years ago). The availability of the Yellowstone Lake shore for prehistoric occupation is much more complex (Pierce, Cannon, and Meyer 2001).

Prehistoric Land-Use Patterns

Investigations into the prehistoric use of the Yellowstone Lake area are based on the spatial distribution of those prehistoric sites containing chronologically diagnostic artifacts and/or radiocarbon dates. These data are summarized by area and chronological period in Table 3 from data presented in Table 4. The actual distribution of Paleoindian sites is presented in Figure 2. This figure shows that there are four sites in the Hayden Valley–Yellowstone River area, seven sites in the North Shore area (especially around the Fishing Bridge–Yellowstone Lake outlet), and six sites in the West Thumb area. Although it could be argued that some of this distribution may reflect areas that have received the most archeological investigations, it should be noted that most of these sites were initially

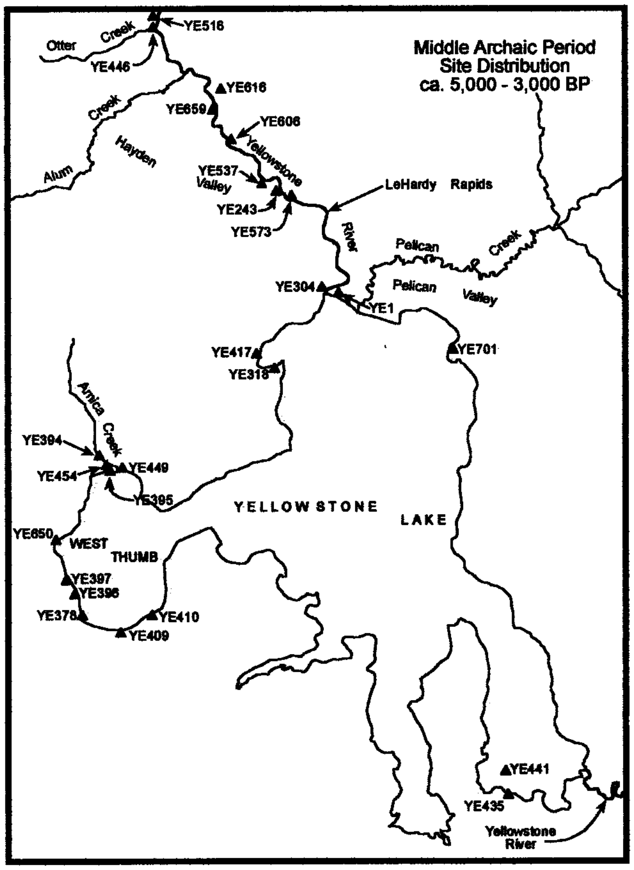

Figure 5. Middle Archaic-period site distribution in the Yellowstone Lake area.

recorded during first professional inventory of Yellowstone in 1958–1959.

One of the interesting aspects of the Paleoindian occupations is the presence of Cody Complex-style artifacts from this portion of Yellowstone, along with other stemmed or "fish-tailed" points (Figure 3). Cody knives and Scottsbluff points have been considered more "plains" adaptations, for example the Horner buffalo kill site near Cody, Wyoming, which incidentally contained the base of an obsidian Scottsbluff point thought to be from Yellowstone (Frison 1991: 66; Frison and Todd 1987: 275). The distinctive Cody Complex artifacts appear to illustrate the movement of peoples from plains or basins into mountainous areas, while the fish-tailed points appear to a part of a mountain–foothills-adapted complex that developed at around the same time.

The Early Archaic period shows a continuation of the use of the North Shore–Fishing Bridge and West Thumb areas (Figure 4). Within the West Thumb area, some of the focus has shifted to Arnica Creek, whose use may have been allowed due to a subsidence in lake levels. There appears to be less utilization of

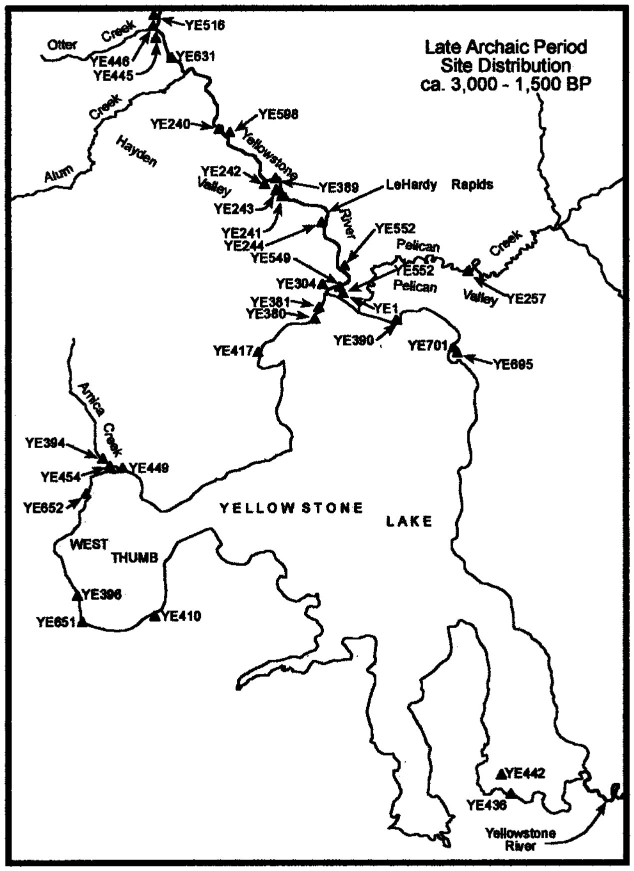

Figure 6. Late Archaic-period site distribution in the Yellowstone Lake area.

the Hayden Valley–Yellowstone River area during this period, but also the first apparent utilization of the South Shore of Yellowstone Lake.

The Middle Archaic period shows an overall increase in the number of components, with an apparent shift from the North Shore to both the West Thumb and Hayden Valley–Yellowstone River areas and additional components along the Southeast Arm of Yellowstone Lake (Figure 5). One of the latter occupations is located on the Molly Islands, indicating that the first use of watercraft occurred during this period. Within the Hayden Valley–Yellowstone River area, the increase in components may be partially due to the availability of new, lower landforms for occupation.

The Late Archaic period shows an increased use of the Hayden Valley–Yellowstone River and North Shore areas (Figure 6 and Table 3). The number of components slightly decreased in the West Thumb areas, while those along the South Shore remained the same. The Hayden Valley has the highest percentage (38.7%) of use (Table 3).

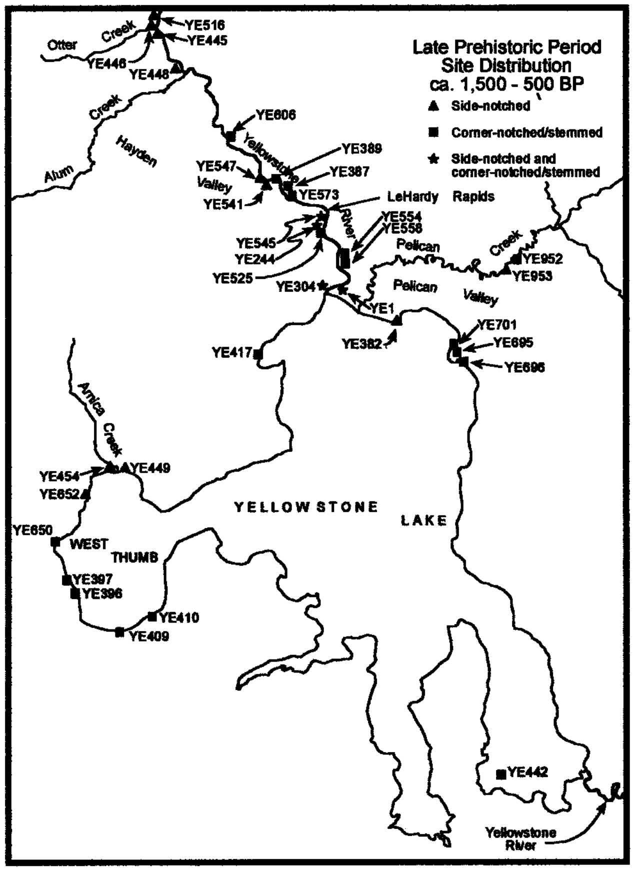

Figure 7. Late Prehistoric-period site distribution in the Yellowstone Lake area.

The Late Prehistoric period shows a slight increase in the use of the Hayden Valley–Yellowstone River and West Thumb, but slight decreases in the use of the North and South shores of Yellowstone Lake (Figure 7 and Table 3). One of the sites at Arnica Creek (48YE449) contained pottery, the only instance within Yellowstone (Taylor, Wood, and Hoffman 1964). Figure 6 also shows the distribution of two styles of Late Prehistoric-period projectile points: side-notched and corner-notched/stemmed points. The latter may be associated with the early portion of the Late Prehistoric period (i.e., Reeves' Tower Junction subphase). These sites appear to be more prevalent within the southern portion of the Hayden Valley area and throughout the shorelines of Yellowstone Lake. The side-notched points are more limited in distribution, although they co-occur at sites in the Fishing Bridge to LeHardys Rapids area along the Yellowstone River, and at Arnica Creek on the north side of West Thumb.

The shifts in occupations are summarized in Table 3, where it is evident that the North Shore has the highest percentages for the Paleoindian and Early

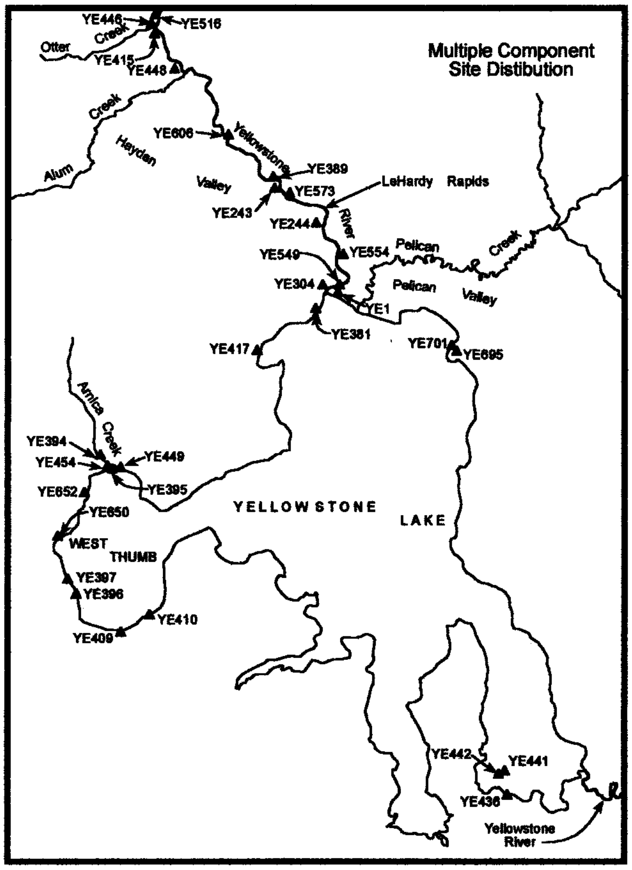

Figure 8. Multicomponent site distribution in the Yellowstone Lake area.

Archaic periods, while the Hayden Valley–Yellowstone River area has the highest percentage during the Late Archaic and Late Prehistoric periods. The pattern of use of the West Thumb also shows high percentages during the Paleoindian through the Middle Archaic periods, the latter exhibiting the highest percentage. The highest percentage for the South Shore area is also during the Middle Archaic period. However, the patterns exhibited in this latter area are based only upon sites recorded during 1958–1959. Additional inventories in this area would likely reveal additional prehistoric occupations, especially considering that the upper Yellowstone River Valley has been posited as a probable access route from Jackson Hole (Wright 1975; Crockett 1999)—as has the upper Wind River Valley.

Finally, the overall pattern in the use of the Yellowstone Lake area is depicted through the distribution of sites containing multiple components (Figure 8). Figure 8 shows that the multicomponent sites are concentrated in a small area of the South Shore of Yellowstone Lake, the west half of West Thumb, the North

Table 4. List of prehistoric sites and their general location and chronological periods.

Site	Area	Paleoindian	Early Archaic	Middle Archaic	Late Archaic	Late Prehistoric Side-notched	Late Prehistoric Corner-notched stemmed	References
48YE240	Hayden Valley/ Yellowstone River				X			Sanders 2000
48YE241	Hayden Valley/ Yellowstone River				X			Sanders 2001
47YE242	Hayden Valley/ Yellowstone River				X			Sanders 2000
48YE243	Hayden Valley/ Yellowstone River	X	X	X	X	X		Sanders 2000
48YE244	Hayden Valley/ Yellowstone River				X	X	X	Sanders 2000
48YE387	Hayden Valley/ Yellowstone River						X	Mitchell 2001
48YE389	Hayden Valley/ Yellowstone River				X		X	Shortt 1999a
48YE415	Hayden Valley/ Yellowstone River	X						Sanders 2000
48YE445	Hayden Valley/ Yellowstone River				X	X		Sanders 2001 Shortt 1999a
48YE446	Hayden Valley/ Yellowstone River			X	X	X		Sanders 1999
48YE448	Hayden Valley/ Yellowstone River	X				X		Sanders 2000
48YE516	Hayden Valley/ Yellowstone River			X	X	X		Sanders 2000
48YE525	Hayden Valley/ Yellowstone River						X	Sanders 2001
48YE537	Hayden Valley/ Yellowstone River			X				Sanders 2000
48YE545	Hayden Valley/ Yellowstone River					X	X	Sanders 2001
48YE546	Hayden Valley/ Yellowstone River		X					Sanders 2001
48YE547	Hayden Valley/ Yellowstone River					X		Sanders 2000
48YE552	Hayden Valley/ Yellowstone River				X			Mitchell 2001
48YE554	Hayden Valley/ Yellowstone River						X	Mitchell 2001
48YE558	Hayden Valley/ Yellowstone River						X	Mitchell 2001
48YE573	Hayden Valley/ Yellowstone River			X			X	Mitchell 2001
48YE598	Hayden Valley/ Yellowstone River				X			Mitchell 2001
48YE606	Hayden Valley/ Yellowstone River			X		X		Mitchell 2001
48YE607	Hayden Valley/ Yellowstone River	X						Mitchell 2001

Table 4. Continued.

Site	Area	Paleoindian	Early Archaic	Middle Archaic	Late Archaic	Late Prehistoric Side-notched	Late Prehistoric Corner-notched stemmed	References
48YE616	Hayden Valley/ Yellowstone River			X				Mitchell 2001
48YE631	Hayden Valley/ Yellowstone River				X			Mitchell 2001
48YE659	Hayden Valley/ Yellowstone River			X				Sanders 2000
48YE1	North Shore	X	X	X	X	X	X	Taylor et al. 1964 Reeve 1989 Cannon et al. 1997
48YE304	North Shore	X	X	X	X	X	X	Taylor et al. 1964 Reeve 1989 Cannon et al. 1997
48YE318	North Shore			X				Taylor et al. 1964
48YE319	North Shore	X						Taylor et al. 1964
48YE368	North Shore	X						Taylor et al. 1964
48YE380	North Shore				X			Cannon et al. 1997
48YE381	North Shore	X			X			Taylor et al. 1964
48YE382	North Shore					X		Cannon et al. 1997
48YE390	North Shore				X			Taylor et al. 1964
48YE417	North Shore	X		X	X		X	Taylor et al. 1964 Sanders and Wedel 1997
48YE468	North Shore		X					Sanders and Wedel 1997
48YE549	North Shore		X		X			Mitchell 2001
48YE692	North Shore		X					Cannon et al. 1997
48YE695	North Shore				X		X	Cannon et al. 1997
48YE696	North Shore						X	Cannon et al. 1997
48YE701	North Shore	X		X	X		X	Cannon et al. 1997
48YE952	Pelican Valley						X	Shortt 2000
48YE953	Pelican Valley					X		Shortt 2000
48YE254	Pelican Valley		X					Shortt 1999b
48YE257	Pelican Valley				X			Shortt 1999b
48YE436	South Shore		X	X	X			Taylor et al. 1964
48YE441	South Shore			X				Taylor et al. 1964
48YE442	South Shore				X		X	Taylor et al. 1964
48YE301	West Thumb	X						Taylor et al. 1964
48YE378	West Thumb		X					Taylor et al. 1964
48YE393	West Thumb	X						Taylor et al. 1964 Cannon et al. 1996
48YE394	West Thumb			X	X			Cannon et al. 1996
48YE395	West Thumb		X	X				Taylor et al. 1964 Cannon et al. 1996

Table 4. Continued.

Site	Area	Paleoindian	Early Archaic	Middle Archaic	Late Archaic	Late Prehistoric Side-notched	Late Prehistoric Corner-notched stemmed	References
48YE305	West Thumb		X	X				Taylor et al. 1964 Cannon et al. 1996
48YE396	West Thumb	X		X	X		X	Taylor et al. 1964 Samuelsen 1983
48YE397	West Thumb			X			X	Samuelsen 1983 Cannon et al. 1996
48YE408	West Thumb	X						Cannon et al. 1996
48YE409	West Thumb	X		X			X	Taylor et al. 1964 Cannon et al. 1996
48YE410	West Thumb	X	X	X	X	X		Taylor et al. 1964 Cannon et al. 1996
48YE449/457	West Thumb		X	X	X	X		Taylor et al. 1964 Cannon et al. 1996
48YE454	West Thumb			X	X	X		Cannon et al. 1996
48YE650	West Thumb			X			X	Samuelsen 1983
48YE651	West Thumb				X			Samuelsen 1983
48YE652	West Thumb		X		X	X		Cannon et al. 1996

Cannon et al. 1997 = Cannon, Pierce, Stormberg, and MacMillian 1997; Taylor et al. 1964 = Taylor, Wood, and Hoffman 1964; Cannon et al. 1996 = Cannon, Crothers, and Pierce 1996

Shore (especially around Fishing Bridge), and spread out along the Yellowstone River. Within the latter area, most of the sites border the Hayden Valley, with only one multicomponent site situated within it. This would suggest that the use of the Hayden Valley may have been as an extractive locale, where resources may have been procured and subsequently brought to campsites located at the valley margins.

The last question concerns evidence for stability versus change in the prehistoric use of the Yellowstone Lake area. Generally, there are few differences between the sites in this area, as they mostly consist of scatters of flakes and chipped stone tools, most of which were made from obsidian, primarily from the Obsidian Cliff source. These sites also contain relatively few fire hearths, groundstone implements, or floral or faunal remains. Although there appears to be some differences in the distribution of sites through time, the reasons for this remain elusive. However, most of the Paleoindian sites (*n*=10, 58.8%; Table 4) were reoccupied by later groups, suggesting that the characteristics that made these particular locales attractive for extractive activities and habitation during the Paleoindian period continued to be attractive in the later periods as well. At this time, it would appear that the limited variability in the archeological remains suggests that prehistoric use of the Yellowstone Lake area has been one of consistency (i.e., stability).

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The Osprey Beach Locality: A Cody Complex Occupation on the South Shore of West Thumb

Mack William Shortt

In early August 2000, a group of Wichita State archeology students under the direction of Donald Blakeslee recovered four diagnostic stone tools from a beach on the shore of West Thumb. While the entire area yielded a variety of artifacts, these particular specimens were typical of an Early Precontact-period (Paleoindian) archeological unit known as the Cody Complex. Of particular interest was the knowledge that Cody components at archeological sites elsewhere have provided radiocarbon dates of ca. 10,000 and 8,000 radiocarbon years before the present (RCYBP) (Stanford 1999: 321, Table 7). Clearly, these artifacts were much older than the other archeological materials found by Blakeslee's crew at the time. The portion of the beach where the specimens were found was ultimately named the Osprey Beach Locality. To date, Osprey Beach is the oldest, best-preserved Precontact site in Yellowstone National Park. As such, its study will provide an excellent opportunity to gather information about the lifeways of Yellowstone's early human occupants.

The Cody Complex was first defined in 1951 at the Horner site, a bison kill located to the east of Yellowstone National Park near Cody, Wyoming (e.g., Frison and Todd 1987; Frison 1991). Horner subsequently became the type site for the Cody Complex because of the occurrence of diagnostic Eden and Scottsbluff projectile points and specialized, bifacially flaked tools referred to as Cody knives. Radiocarbon dates from Horner range from approximately 9,300 to 8,700 RCYBP (Frison and Todd 1987: 98; Frison and Bonnichsen 1996: 313). Since then, the Cody Complex has become a relatively well documented cultural entity identified on the Northwestern Plains and in adjacent Central and Northern Rocky Mountain basins (e.g., Stanford 1999: 321, Figure 34). The typical Cody site consists of Scottsbluff and/or Eden projectile points and Cody knives, with radiocarbon dates approximating 9,000 RCYBP.

In the archeological literature, Cody represents "classic" Early Native American plains bison hunters, who were different from contemporaneous peoples who inhabited the foothills and mountains. This impression is, for the most part, founded upon a focus on the excavation of Cody bison kill sites and their associated processing and campsite areas. Indeed, sites such as Finley in the Green River basin (Moss et al. 1953; Haspel and Frison 1987), Carter/Kerr-McGee in the Powder River basin (Frison 1984), and the Frasca (Fulgham and Stanford 1982) and Jurgens (Wheat 1979) sites in northeastern Colorado are all interpreted as large-scale bison procurement operations.

Other sites with Cody components include, as examples, Hell Gap in eastern Wyoming (Irwin-Williams et al. 1973), Medicine Lodge Creek in northern

Wyoming (Frison 1991), and Claypool (Dick and Mountain 1960; Stanford and Albanese 1975) in eastern Colorado. The MacHaffie site (Forbis and Sperry 1952; Knudson 1983) and Mammoth Meadow (Bonnichsen et al. 1992) in southwestern Montana are examples of Cody lithic workshops or areas where stone tools were manufactured. In the current study area around Yellowstone Lake, Cody artifacts have been found at Fishing Bridge (Cannon et al. 1997: 345, Table 65) and near the mouth of Solution Creek on the shore of West Thumb (Cannon, Crothers, and Pierce 1996).

After the initial recovery of Cody artifacts by the Wichita State crew, a field crew from the Museum of the Rockies returned to Osprey Beach to further site investigations. Initially, we wished to relocate the exact positions of the Wichita State surface artifacts. Then, we wanted to address questions pertaining to the geologic associations of the materials and erosional processes that had exposed the artifacts on the beach surface. In addition, it was anticipated that a small assessment-oriented excavation would result in the recovery of artifacts similar to those recovered from the beach.

The initial field program, conducted during mid-August 2000 (after the departure of the Wichita State crew), involved a pedestrian reconnaissance of the entire beach area in the vicinity of the Wichita State finds. In this undertaking, the Museum crew recovered a number of Precontact lithic artifacts, including a third Cody knife. Like the specimens collected by the Wichita State crew, this artifact was not in situ, but instead had been eroded out of its primary context onto the beach below the bluffs.

At the terminus of the surface survey, the Museum crew then established a series of 1 x 1-m test excavation units on the heavily eroded edge of the bluff top directly above the Cody knife findspot. This particular portion of the shore of West Thumb is characterized by a high bluff that today rises 6.75 m above the datum at Bridge Bay which, in 1985, was 2,356 m (7,731 ft) above sea level.

The field testing program at Osprey Beach resulted in the completion of 8.5 contiguous 1 x 1-m units excavated to an average depth of 85 cm below the surface. In profile, the test excavations revealed a simple stratigraphic sequence consisting of a surficial dark brown sandy silt overlying a thick deposit of gray–brown sand, the latter of which persisted to an average depth of about 70 cm below the surface. The basal deposits reached by excavation consisted of coarse gray–brown sandy pea gravel.

With regard to cultural stratigraphy, Precontact archeological materials were recovered from almost all levels in the excavation, although there was a general tendency for artifacts to occur from 30 to 70 cm below the surface in the thick deposit of gray–brown silty sand. Artifact types included a limited quantity of lithic debris and a variety of stone tools. Of 62 waste flakes recovered, nearly one-half (n = 28) were small obsidian waste flakes that had resulted from manufacturing tools. Other lithic material types represented in the sample of debris included opalized wood, volcanic tuff, various colors and grades of chert, and a single piece of Knife River flint, the sources of which are located in western North Dakota. Unfortunately, zooarcheological (animal bone) specimens that might provide direct evidence of food consumption were not recovered.

Tool types recovered from the excavation included three biface fragments, one fragmentary Cody knife, one sandstone shaft abrader, one pumice hide abrader, and a single projectile point. All were recovered in direct spatial association with quantities of stone flakes 30 to 60 cm below the ground surface.

The Cody knives found both on the beach surface below the test units and during excavation represent two lithic material types: vitreous dark green (Absaroka volcanic?) chert (Figure 1) and obsidian (Figure 2). The source of the obsidian specimens was determined to be the Obsidian Cliff Plateau, which is located in north-central Yellowstone National Park. Generally, the finely made dark green chert specimens are, in subjective terms, in better condition than their obsidian counterparts. One obsidian specimen had been snapped during use and the other appears to have been resharpened so often that the artifact had nearly lost its asymmetric form. It seems that the inhabitants of the site were less concerned with curating obsidian knives than with maintaining the integrity of the green chert specimens. This phenomenon is undoubtedly related to unlimited quantities of readily available Obsidian Cliff Plateau volcanic glass (see Davis, Aaberg, and Johnson 1992; Davis, Aaberg, and Schmitt 1995) versus more "exotic" green chert likely derived from sources to the east of Yellowstone National Park. The Cody knives from Osprey Beach are similar to specimens recovered at Horner (Frison and Todd 1987: 221, Figure 6.15) and other sites (Stanford 1999: 320, Figure 33).

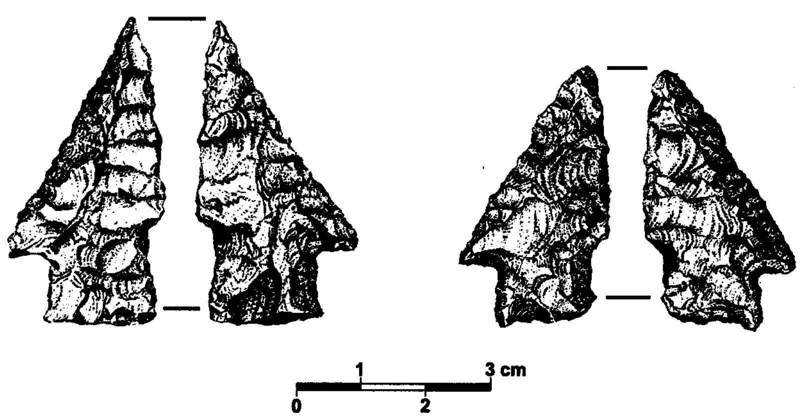

Figure 1. Osprey Beach Locality chert Cody knives.

The sandstone shaft abrader found at Osprey Beach is significant in light of the fact that similar artifacts are rare at other Cody Complex sites. Other shaft abraders of similar age have been recovered only at the MacHaffie site near Helena, Montana, at the Claypool site, and at the Jurgens site. In overall form, the Osprey Beach specimen is roughly rectangular, with a broad U-shaped transverse cross-section that continues over the length of the artifact (Figure 3). The main tool face exhibits a wide, relatively deep groove caused by the grinding and

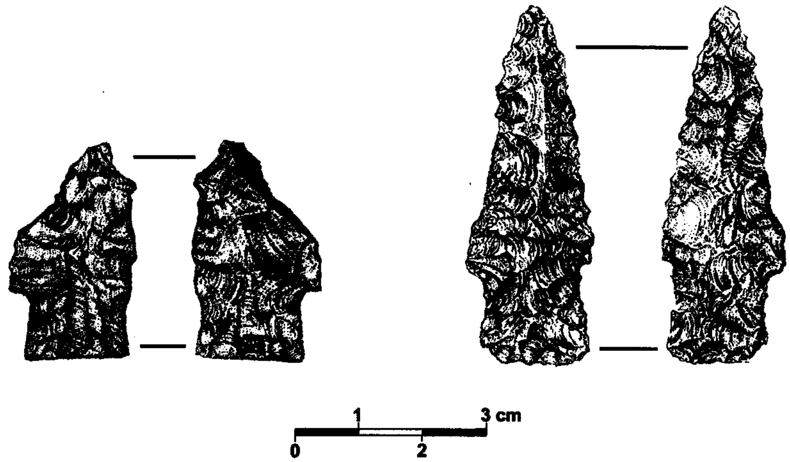

Figure 2. Osprey Beach Locality obsidian Cody knives.

smoothing of what were likely wooden shafts to which the stone artifacts were attached. Indeed, it was this heavy use that resulted in the U-shape. Close examination of the U-shaped interior, however, revealed narrower, incised grooves probably related to the actual abrading or sharpening of pointed shafts. The reverse face, rather than exhibiting a wide U-shape, exhibits four relatively narrow grooves that do not extend over the entire length of the artifact. These features are interpreted as the result of sharpening the pointed ends of shafts rather than the actual grinding of the main shaft itself.

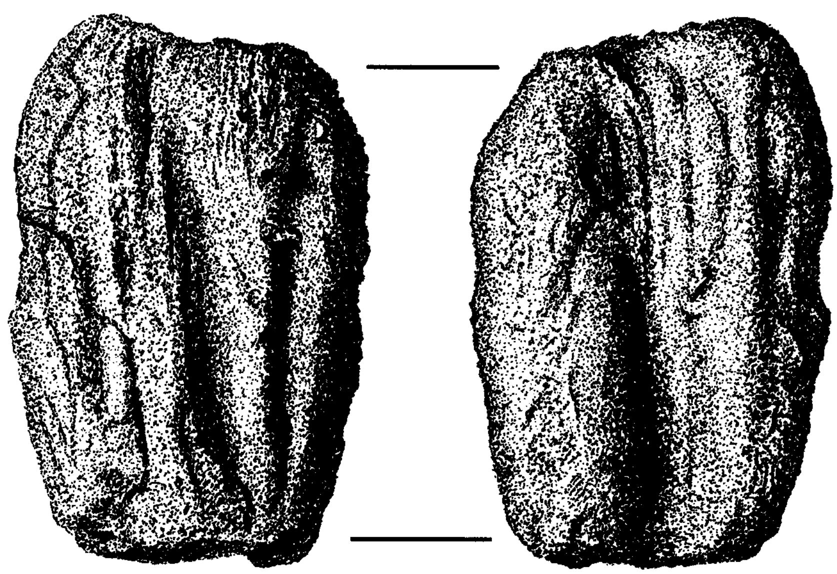

Figure 3. Osprey Beach Locality sandstone shaft abrader.

The test excavation program at Osprey Beach also resulted in the recovery of a split pumice cobble, 7.8 cm long, that had likely been utilized as an abrading type of implement (Figure 4). One aspect is relatively flat with rough, unmodified surfaces, while the opposite exhibits an undulating surface with smoothed, polished facets. Portions of the artifact's lateral margins also appear to have been worn smooth. While additional microscopic analyses are needed to verify the use-wear pattern on this specimen, it is clear that the cobble was transported into the site by Precontact native people. References to the use of such artifacts occur in the ethnographic literature. Denig, for example, in reference to the Assiniboine in 1854, describes rubbing a heated hide "with a pumice stone or porous bone..." (Dyck 1977: 159).

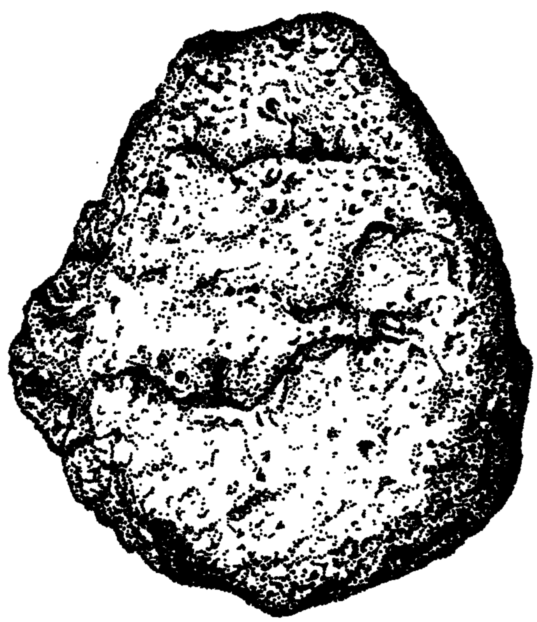

Figure 4. Osprey Beach Locality pumice hide abrader.

The projectile points recovered by Donald Blakeslee and the Museum of the Rockies are, for the most part, consistent with styles recovered at other Cody sites (e.g., Frison 1991; Stanford 1999). The beach finds included the midsection of an Eden point and the base of what appears to be a Scottsbluff point. Both styles conform to specimens in Cody assemblages at, for example, the Horner, Carter/Kerr-McGee, and Finley sites.

The projectile point recovered during excavation, however, differs morphologically from Scottsbluff and Eden, the hallmarks of the Cody Complex. Instead, this artifact is characterized by a convex base, excurvate lateral margins, a slightly narrowing stem, incipient shoulders, and a parallel-oblique flaking pattern typical of post-Cody Complex projectiles (Figure 5). The Osprey Beach-excavated specimen closely resembles forms from the Lookingbill site in northwestern Wyoming (Frison 1991: 75, Figure 2.37). While most parallel-oblique lanceolate projectiles succeed the Cody Complex in later assemblages (ca. 9,000 to 8,500 RCYBP; e.g., Frison 1991), archeological research at Barton Gulch (Alder Complex) in southwestern Montana (Davis et al. 1989: 7-8) and Medicine Lodge Creek in the Bighorn Basin (Frison 1997: 93), for example, demonstrated that lanceolate projectiles, often exhibiting parallel-oblique flaking, occur in assemblages that are roughly contemporaneous with or older than Cody. As such, we suggest that the projectile point data from Osprey Beach indicate a mixture of peoples or members of different cultural groups probably coalescing seasonally.

When were Precontact Native American people at Osprey Beach and what activities took place there? What was the local landscape like? Ken Pierce of the U.S. Geological Survey, during a visit to the site in the summer of 2000, recovered a piece of charcoal for radiocarbon analysis from a locality several meters east of the Museum of the Rockies test excavation units. It was recovered from the lowest part of the artifact-bearing stratum, slightly lower than the main Cody Complex. A conventional radiocarbon age of 9,360 ± 60 years before present was subsequently obtained (Beta-148567). Given the relative stratigraphic position of the charcoal, one can surmise that occupation of the site by Cody peoples may have been slightly later. However, tree tip-ups, rodent burrowing, and other natural site formation processes had likely, to some extent, mixed the archeological deposits in the past.

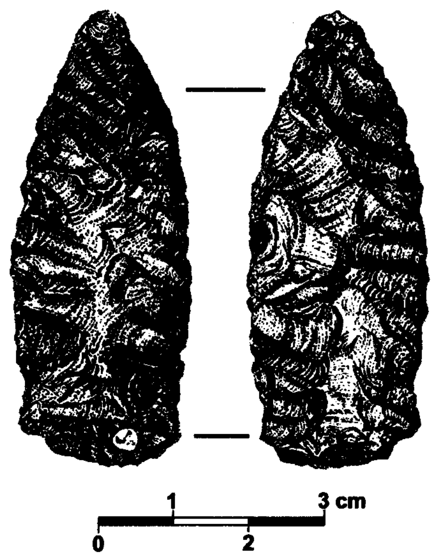

Figure 5. Osprey Beach Locality projectile point.

In terms of geomorphologic history, Pierce has suggested that, after the formation of a paleo-shoreline which is dated to ca. 10,500 years ago, the level of Yellowstone Lake lowered and retreated to the north. A shoreline of similar age was identified on the Fishing Bridge peninsula (Cannon et al. 1997: 357, Figure 8) where Cody artifacts were also found. Immediately following the lake recession, Precontact Native American peoples occupied the bench adjacent to the lake at Osprey Beach (the level of which was several meters higher than today), eventually abandoning some artifacts. Pierce suggests that, after site abandonment, aeolian sands blew into the area and eventually buried the archeological deposits.

Upon completion of the field program during the summer of 2000, eight of the Cody tools were submitted for blood residue analysis, a test that seeks to identify species of origin for blood proteins extant on some artifacts. The results, derived through crossover immunoelectrophoresis analyses, were surprising. The stem of one of the green chert Cody knives provided a positive reaction to rabbit antiserum. Whether this is related to the consumption of rabbit by site inhabitants or to the use of rabbit tissue for hafting is unknown, although both are strong possibilities. Second, the blade of the broken obsidian Cody knife yielded a positive reaction to dog antiserum. As such, any canid could be represented. The third test, undertaken on the parallel-obliquely flaked projectile point, provided a positive reaction to deer antiserum.

Finally, and perhaps what is the most interesting, the Cody knife collected from the surface of the beach below our excavation units provided two positive test results: rabbit on the stem and Rocky Mountain bighorn sheep on the blade. It is interesting to note that bison, the hallmark of the Cody Complex (e.g., Frison 1991), was conspicuously absent in the small sample of artifacts tested from Osprey Beach. As an aside, however, a Cody knife previously recovered from a site located near Solution Creek had tested positive to bison antiserum (Cannon, Crothers, and Pierce 1996: 149, Table 25). In addition, a Cody stemmed projectile point collected from Fishing Bridge in 1992 tested positive to rabbit antiserum (Cannon, Crothers, and Pierce 1994: 359, Figure 56e).

Some archeologists have suggested that, about 10,000 years ago, an ecological boundary separated plains-oriented, bison-hunting cultural groups from other contemporaneous Precontact cultural groups that occupied adjacent foothill and mountain regions. It is suggested that cultural groups in the latter were adapted to hunting and gathering in environs where more diverse faunal and floral species could be exploited (e.g., Frison 1992: 337; Frison 1997: 99). It is further suggested that, by Cody Complex times, the dichotomy between the ecological zones was breaking down (Frison 1992: 339; Frison and Bonnichsen 1996: 314; Frison 1997: 100).

The variety of mammalian species represented by blood residues on Osprey Beach artifacts indicate that a more diverse economy typified the Cody Complex adaptation around Yellowstone Lake than on the plains and intermountain basins to the east and southeast. Indeed, the Osprey Beach data suggest that the foothills-mountain/plains cultural dichotomy suggested by some researchers was in fact breaking down by the time of the Osprey Beach occupation. That Osprey Beach yielded relatively large numbers of Cody Complex artifacts suggests that Cody peoples were adapted to not only the plains and intermountain basins as bison hunters, but also to upland and mountain environs around Yellowstone Lake where a more diverse faunal resource base was exploited.

In sum, the archeological program at Osprey Beach has demonstrated that, by at least 9,360 ± 60 RCYBP, Precontact Native American peoples were traveling into the heart of Yellowstone country to exploit local game populations. While in the area around the lake, people utilized obsidian from the Obsidian Cliff Plateau to manufacture projectile points and specialized bifaces. Other non-local cherts were also used by Osprey Beach peoples.

With regard to daily activities at Osprey Beach, the tool types collected by the Museum of the Rockies are suggestive of a variety of tasks, from projectile point and biface manufacture to the production of wooden shafts and, possibly, the preparation of animal hides. The use of the area was likely seasonal and limited to the spring to fall time of the year. The projectile point sample represents not only Cody peoples, but also other contemporaneous groups traveling from the plains and intermountain basins and foothills to Yellowstone—a seasonal subsistence and settlement pattern that continued throughout the Precontact Period.

Finally, plans for future research at the Osprey Beach locality include additional evaluative excavation to determine the horizontal extent of the site and to mitigate the negative effects of continual landform erosion. Not only will an additional field program stabilize this ancient and highly significant site, but it will also contribute to a better understanding of Yellowstone's distant cultural past. This, we believe, can only enhance the Yellowstone National Park experience for its employees and visitors.

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Yellowstone Lake as Seen by Artists

Eugene Lee Silliman

Abstract

The title of the Sixth Biennial Scientific Conference on the Greater Yellowstone Ecosystem rhetorically asks, "Yellowstone Lake: Hotbed of Chaos or Reservoir of Resilience?" Although geologists know that Yellowstone Lake was the focal point of an ancient cataclysmic volcanic eruption, the subsequent evolution of the caldera into a landscape of quiescent sublimity is the immediate reality apparent to human visitors. The igneous prehistory of the lake region, coupled with its guardian cordon of volcanic peaks even older, set the stage for a revelation. For here, out of nearly unimaginable chaos, nature has reconfigured itself into a land of resplendent harmony. From lake's verge the human eye is allowed to encompass an inland sea set upon the apex of an immense plateau, and the universal response is a declaration of transformative beauty. Artists have long sought to distill the ethereal essence of Yellowstone Lake, and thereby have played a role in establishing it as one of the brighter jewels in the crown called Yellowstone.

This paper shall attempt to analyze the historical role played by key visual artists of Yellowstone Lake in the development of the park. Specifically, what influence was wielded by Yellowstone's first two prominent artists, Thomas Moran and William Henry Jackson, in the park's formative years? Secondly, a brief examination of the written record left by park visitors will demonstrate that their characteristic emotional response to the lake was the template for artists. As a species, we share in common a reverence for the grand vista of earth, water, and sky made so accessible from the environs of Yellowstone Lake. Lastly, this paper will record the personal impressions made by Yellowstone Lake upon this author during his numerous photographic forays about the periphery of this noble body of water. That Yellowstone Lake has always becalmed its viewers with the vast scale of its geographical expanse and frequently excited them with its intriguing interplay of water against land along its endless shoreline, are propositions that appear well-founded. That this array of natural forces should beckon and challenge the visual artist seems self-evident.

Influence of Moran, Jackson, and Other Artists

Thomas Moran. Yellowstone Lake, being the largest single feature on the plateau, was well known to the fur trappers and gold prospectors who penetrated this wilderness highland prior to the discovery expeditions which commenced in 1869. Since artistic talent was not a prerequisite for trapping and prospecting, however, these men left no artwork commemorating their peregrinations. The first attempts by Euroamericans to delineate artistic impressions of Yellowstone onto paper were executed by Private Charles Moore and Henry Trumbull—military and civilian members, respectively, of the 1870 Washburn Expedition. Their primitive pencil sketches, while lacking textural finesse and depth perception, remain valuable primary documentation. Unfortunately, none of the extant Moore or Trumbull sketches housed in the Yellowstone National Park archives depict Yellowstone Lake. This gap in the pictorial record is as notable as it is regrettable, for surely these two men made sketches of the lake during their twelve-day near-circumlocution of it. Three diaries in the party lauded the beauty of the lake and noted that all members of the party were enthralled by the force of its character.

The first published image of Yellowstone Lake was, nonetheless, a derivative of the 1870 Washburn Expedition. A member of this party, Nathaniel P. Langford, wrote the first major article on Yellowstone to receive national distribution. Entitled "The Wonders of Yellowstone," it was published in the May and June, 1871, issues of *Scribner's Monthly.* Being an important illustrated periodical of its day, the magazine's editors charged Thomas Moran, a talented and well-trained artist on their staff, to rework the Moore and Trumbull sketches into higher-quality images. Moran rendered the original pencil drawings into black and white washes on paper, and then skilled engravers transposed Moran's pictures into reproducible engravings. Thus, the American public was given "On Guard on Yellowstone Lake," a 7 x 9-cm image of a man on night guard reposing on the bank of Yellowstone Lake with a poorly constructed log raft plus sail in the background. Although this engraving does not bear Thomas Moran's "T.M." signature and does bear the engraver's initials "F.S.," circumstantial evidence points to the hand of Moran. While the title of this image bears the lake's name, its subjugation to the background hardly does justice to the lake's manifest importance. The world would have to wait eight months.

The task of improving upon the Moore and Trumbull Yellowstone sketches must have stimulated Moran, for a year later he readily accepted an invitation to accompany Ferdinand Hayden's 1871 government-sponsored survey of Yellowstone as a guest artist; the official survey artist was Henry Wood Elliott. Moran's expenses were paid by the railroad financier Jay Cooke in the form of a $500 loan—to be paid black by Yellowstone artwork. Also accompanying the entourage was the survey's official photographer, William Henry Jackson, a man whose medium and mentality were sufficiently compatible with those of Moran's to make them mutually supportive artists. Their collaborative efforts in Yellowstone were symbiotic. Moran, using his well-honed sense of composition, assisted Jackson in the selection of camera positions. In return, Jackson gave Moran photographs that would serve as vital field sketches for later studio paintings (augmenting the painter's own fieldwork). Indeed, Moran recounts in his diary that when the expedition was encamped upon Yellowstone Lake, he "sketched but little but worked hard with the photographer selecting points to be taken etc." This professional and personal affinity between Yellowstone's two primary artists was forged upon their coincidental union in 1871 and lasted until Moran's death in 1926. Each benefited, as did the nation.

When Hayden returned to Washington, D.C., in the autumn of 1871, he petitioned Congress to pass a bill establishing the Yellowstone region as America's first national park. Not only did Hayden employ the oral and written word in this campaign, he adduced the powerful visual testimony of Moran's watercolors and Jackson's photographs as proof of Yellowstone's astounding reality. Enough circumstantial evidence exists to ascertain that the public presentation of Yellowstone art, as rendered by Moran and Jackson, was an important factor in the founding and early promotion of Yellowstone National Park, although modern scholars deplore the paucity of documentation for this assertion. Since the scope of this paper is limited to the art of Yellowstone Lake, scrutiny will be focused upon the images of the lake by Moran and Jackson.

Because the background appearance of Yellowstone Lake in Moran's 1871 engraving "On Guard on Yellowstone Lake" is so inconsequential and is an injustice to the lake's undeniable glory, the honor of the first published artworks to fairly portray Yellowstone Lake for a national audience belongs to the two Moran engravings in Ferdinand Hayden's article "The Wonders of the West II, More About the Yellowstone," which appeared in the February 1872 issue of *Scribner's Monthly* on pages 392 and 394. The first image, measuring 6x6 cm and entitled "The First Boat on Yellowstone Lake," depicts the Anna, a 12-ft dinghy which transported Elliot, the survey's official artist, to the newly christened Stevenson Island. The second image, measuring an elongated 5x12 cm and entitled "Yellowstone Lake," depicts a handsome view of the lake from a northerly shoreline toward the mountains which ring it to the south and east (Figure 1). Moran's mastery of compositional complexity, tonal contrast, and visual drama are amply displayed in all eleven expertly printed images in Hayden's article. This panoramic lake engraving begins with foreground vegetation, follows mounted riders down to an extending sand spit, conveys the viewer to an island, extends one's eye to distant mountain serrations, and concludes with a sunset sky punc-

*Figure 1. This engraving by Thomas Moran was the first published image (*Scribner's Monthly, *February, 1872) to fairly depict Yellowstone Lake.*

tuated by a formation of migrating waterfowl.

At last the public had an image to match Hayden's words, which he published soon thereafter in his 1872 *Preliminary Report of the United States Geological Survey of Montana and Adjacent Territories:*

> On the 28th of July we arrived at the lake, and pitched our camp on the northwest shore, in a beautiful grassy meadow or opening among the dense pines. The lake lay before us, a vast sheet of quiet water, of a most delicate ultramarine hue, one of the most beautiful scenes I have ever beheld. The entire party were filled with enthusiasm. The great object of all our labors had been reached, and we were amply paid for all our toils. Such a vision is worth a lifetime, and only one of such marvelous beauty will ever greet human eyes.

The same two Moran engravings were reproduced in Hayden's 1872 report at a lesser technical quality and size.

Moran's talents for rendering Yellowstone Lake were again pressed into service for the art journal *Aldine,* a large folio magazine (29 x 42 cm) which was published between 1869 and 1879. The journal took pride in producing the finest wood engravings of the day, including a total of thirty-nine by Moran, and fervently stoked American enthusiasm for western landscape imagery. The April 1873 issue presented a laudatory piece entitle "The Yellowstone Region," and was illustrated with five outstanding Moran engravings. The author of the article states, "But we must not forget the brightest jewel of this wonderful park—the Yellowstone Lake," and praises Moran's illustrations for their ability to "open to us a world as wild as the one we see in dreams,—a strange and beautiful wonderland." The second view in the article, "Yellowstone Lake," is a masterful panorama measuring 9 x 23 cm; it improves upon his *Scribner's* image by being larger and with more contrast, including a forest fire plume "moved" to the Promontory for heightened dramatic effect (Figure 2). This latter stratagem illustrates Moran's admitted use of artistic license: he often united in one picture disparate but realistic elements not conjoined in nature.

Figure 2. Thomas Moran idealized and rearranged nature (like moving a forest fire to the lake's edge) in order to delineate greater truths about Yellowstone. Engraving appeared in Aldine*, April, 1873.*

A year after he returned from the 1871 Hayden expedition, Moran agreed to execute a series of sixteen watercolors for the British industrialist William Blackmoore, who had accompanied Hayden in 1872 on his second surveying expedition to Yellowstone. Among the set, now owned by the Thomas Gilcrease Institute of Tulsa, Oklahoma, is "Yellowstone Lake with Hot Springs." This panoramic-proportioned watercolor primarily focuses upon the prismatic thermal features of Thumb Geyser Basin. The serene lake and the stately Absaroka Mountains which rim it are coolly rendered in sunset purple and mauve as an attractive complement to the brilliant yellows, whites, and oranges of the thermal formations. To those evening loiterers on the western shore of Yellowstone Lake, this sunset coloration upon the waters and peaks will ring true. These watercolors were displayed at Goupil's Gallery in New York before their shipment to England.

For Moran's finest delineation of Yellowstone Lake, however, we must turn to a tripartite project by Hayden, Louis Prang, and the artist himself. Within one year of Moran's return to the East Coast, he accepted a commission to paint a set of watercolors for vibrant chromolithographic reproduction by Prang, America's most skilled lithographer. In today's world, saturated with color reproduction, it is hard to contemplate the enormous cultural change set loose in mid-nineteenth century by this technology that made color imagery available for wide audiences. Hayden was enlisted to write the supportive text. *The Yellowstone National Park, and the Mountain Regions of Portions of Idaho, Nevada, Colorado and Utah* (1876) presented fifteen vividly colored images of the American West. One thousand copies of the edition were produced, selling for $60.00 each. At last a general audience could appreciate the artistic wonders of the Yellowstone region inclusive of its most crucial parameter—color. As Hayden opined in his preface:

> All representations of landscape scenery must necessarily lose the greater part of their charm when deprived of color; but of any representation in black and white of the scenery of the Yellowstone it may truly be said that it is like Hamlet with the part of Hamlet omitted, for the wealth of color in which nature has clothed the mountains and the springs of that region constitute one of the most wonderful elements of their beauty.

The fifth plate of the Prang chromolithographs is entitled "Yellowstone Lake, Yellowstone National Park" (Figure 3). Into it Moran poured all of his classical, thematic artifices: depth perception by near, intermediate, and distant subject matter; opulent color contrast between ochre highlights and marine blue and burnt umber darks; a Turneresque atmosphere convulsed by a thunderstorm whose virga intersects an arching rainbow; and the animation of flocks of birds on near waters and in distant sky. As a statement of Edenic wildness and spacious reach to near-infinity, this view looking far into the Southeast Arm of Yellowstone Lake could hardly be surpassed.

The foregoing chromolithograph of Yellowstone Lake illustrates Moran's standard artistic practices. During his 1871 journey through Yellowstone, he executed quick watercolor field sketches, first employing pencil to establish con-

Figure 3. Perhaps the finest artistic depiction of Yellowstone Lake is this 1876, full-color chromolithograph by Thomas Moran.

tours, and then overlaying these outlines with broad, brilliant washes to record coloristic effects. Back in his studio in Newark, New Jersey, he would refer to Jackson's photographs for accuracy of detail when composing a more refined and elegant artwork. Moran, under the strong influence of the English critic John Ruskin and the famous British painter J.M.W. Turner, sought not an exact replication of the thing in nature, but a conveyance of its mood and impression upon the human spirit. Moran praised Turner when he wrote that Turner "sacrificed the literal truth of the parts to the higher truth of the whole." Speaking of himself, Moran wrote:

> I place no value upon literal transcriptions of Nature. My general scope is not realistic; all my tendencies are toward idealization. Of course, all art must come through Nature: I do not mean to depreciate nature or naturalism, but I believe that a place as a place, has no value itself for the artist only so far as it furnished the material from which to construct a picture. Topography in art is valueless.…[W]hile I desire to tell truly of Nature, I did not wish to realize the scene literally, but to preserve and to convey its true impression.

In Moran's lake painting the view seems to be from the northeast shore looking southward up the Southeast Arm, with Colter Peak in the left background, while incorporating foreground elements from a Jackson photograph. Yet, the Absaroka Mountains, which lie to the south of the lake in Moran's picture, actually reside to the east; nor can one look south and see a rainbow (because the sun must be at a low altitude behind the observer to the north, which does not happen in Yellowstone). Yet these are quibbles, for all adventurers familiar with Yellowstone Lake will recognize these natural elements, and accept with full consent their synthesis by Moran into an organic, idealized whole.

William Henry Jackson. At Moran's side on the 1871 Hayden survey was the preeminent frontier photographer William Henry Jackson. As previously mentioned, these two men forged an informal partnership that abetted their goal of visually recording the Yellowstone region, each in his own medium. The Hayden party's route, encircling Yellowstone Lake counterclockwise from Thumb to the outlet, gave Jackson ample opportunity to photograph the lake from numerous points.

Unlike that which is produced with facile modern cameras, photography with the nineteenth-century view camera was a cumbersome and complex process. The bulk and weight of a wooden camera, a portable darkroom with chemicals, and fragile glass negative plates, required the services of a trusty mule (disposition not always guaranteed). After unpacking, the photographer would first erect his camera upon a tripod. The task of carefully focusing the inverted image upon the ground glass at the rear of the camera, while the operator hovered under a hot, opaque darkcloth as he wrestled with the upside-down image, was laborious. Because wet-plate technology was yet to be invented—and then superseded by dry-plate technology (not to mention flexible and unbreakable celluloid film)—the photographer had to set up a darkroom tent, prepare the chemicals, coat the glass plate, and then quickly repair to the camera before the plate dried. Furthermore, film speed was so slow—on the order of many seconds—that the motion of water, steam, smoke and animals would be registered as a blur. After exposure, the glass negative had to be developed in the portable darkroom, and thereafter carefully transported hundreds of miles back to a studio for the production of a positive print. A final impediment was the orthochromatic sensitivity of film emulsion in the 1870s, which caused atmospheric blue to overexpose and hence yield a blank white sky devoid of the fascinating interplay of cloud against sky so often visible above Yellowstone Lake. When the plethora of technical challenges are considered, Jackson's trove of three hundred images from the 1871 Yellowstone expedition is rightly seen as a monumental achievement.

This discussion of Jackson's photographs of Yellowstone Lake will be restricted to those readily available to the public. In Aubrey L. Haines' tome *The Yellowstone Story*, Volume 1 (1977), three 1871 Jackson photographs are reproduced on pages 143 and 147. The first, "A Camp of the Hayden Survey Party on Yellowstone Lake, 1871," is a well-composed view of their camp on the east side of the lake. Next, "The Anna, First Boat on Yellowstone Lake, 1871," is the source of the wood engraving of the same in *Scribner's Monthly*, February 1872. Lastly, "The Hayden Survey Camp on Mary Bay, August 19, 1871," is an artful overview of what they called "earthquake camp" in remembrance of a tremor that perceptibly shook them the night of August 22, 1871 (Figure 4). All these images typified the artistic convention of placing human beings in the scene to establish scale in an alien landscape, and to perhaps suggest that the human presence in this Eden was the natural progression of our destiny.

Other 1871 Jackson images of the lake country worthy of note include "Peale

Figure 4. This 1871 panoramic view of "Earthquake Camp" on Mary Bay is a fine example of photographer William Henry Jackson's sense of composition.

Overlooking Yellowstone Lake and Promontory Point," which is reproduced in *Yellowstone and the Great West*, edited by Marlene D. Merrill, 1999, page 160. "Yellowstone Lake, Looking South from Where the River Leaves It," reproduced in *William Henry Jackson and the Transformation of the American West* by Peter B. Hales, 1988, page 107, is a panoramic view looking southeastward, with a conspicuously blank white sky. "Mary Bay, Yellowstone Lake," reproduced in *Yellowstone Science*, Volume 8, Number 1, Winter 2000, page 8, presents the chastely beautiful, elongated curve of this northern indent. Lastly, a person may view, at the Horace Albright Visitor Center at Mammoth, Yellowstone National Park, an original 1871 Jackson albumen print of Yellowstone Lake form the northeast shore looking southward—which was Moran's inspiration for his grand chromolithograph of the lake. Jackson's albumen print amply demonstrates that a vintage print created by the hand of the photographer is immeasurably superior to a modern book reproduction—especially when the former is matted and framed. These Jackson photographs, while unquestionably imbued with a documentary component, may be classified as works of art when seen in the original. Jackson exhibited great skill in selecting views with compositional merit and textural detail, and demonstrated complete mastery of the technical aspects of his medium. Indeed, scores of Jackson images were copied by engravers of the 1870s and 1880s for wide distribution in popular magazines, illustrated newspapers, and scientific reports. For two decades significant numbers of mass-circulated Yellowstone images were derivatives of his outstanding photographs.

The paintings of Moran and the photographs of Jackson set the standard for all artists to follow. The work of each artist complemented the other, with the former emphasizing the resplendent colorations and mythic views to be found throughout Yellowstone, while the latter utilized the pencil-sharp eye of the camera to etch a crystalline record of Yellowstone's truth that none could dispute. They each saw the lake and sought to return to civilization with their proof of what nature had wrought—one of the most sublime spectacles in the American West. Moran and Jackson would agree, however, that the reality always remained beyond transcription, and must be experienced for the fullest realization.

Other artists. As noted above, Henry Wood Elliott, a contemporary of Moran and Jackson, was the official artist of the 1871 Hayden Survey. This was Elliott's third summer as Hayden's paid artist, and his benefactor complimented him in his 1870 report: "[T]he artist, Elliott, worked with untiring zeal, and his sketches and sections have never been surpassed for clearness or beauty." Elliott made numerous pen-and-ink sketches, plus pencil sections, of the Yellowstone scenery through which the party traversed and many of these informative, if crude, sketches illustrated Hayden's 1871 report. Hayden informs us in his "Letter to the Secretary" that "Messrs. Elliott and [Campbell] Carrington surveyed and sketched its [Yellowstone Lake's] shore-lines from the water in a boat." However, when Hayden presented his report to the public, Moran's two engravings—not Elliott's—comprised the Yellowstone Lake illustrations. This subtle elbowing of Elliott to the side by the publication of Moran's lake images suggest that Hayden felt the latter's artwork was superior.

One fine watercolor image of the lake by Elliott has survived: "Yellowstone Lake," 25 x 50 cm, completed in 1871; it is reproduced in *The Rocky Mountains: A Vision for Artists in the Nineteenth Century* by Patricia Trenton and Peter Hassrick, 1983, p. 188. This finely detailed watercolor is claimed by Trenton and Hassrick to have been painted on the spot, but that is unlikely because of the exigencies of survey work. A more plausible scenario is that Elliott painted it later, with a copy of Jackson's photograph no. 268—which it closely resembles—and his own geographical sketches close at hand. One manipulation in this picture bears mentioning: the clouds are backwards. Because the Absaroka peaks, Southeast Arm, Flat Mountain, and Mount Sheridan are correctly rendered on the distant horizon, there is no doubt that the view is southward. Yet, the high-altitude cirrus "mares'tales" are drifting from the southeast, a full ninety degrees off their obligatory course from the southwest. If Moran can move rainbows, can Elliott move clouds? Elliott's lake painting is the quintessential classical view of untrammeled nature awaiting the appreciation of Western Man. This well-executed image of Yellowstone Lake demonstrates Elliott's finer talent, and contrasts markedly with the draughtsman style that he utilized when rendering topographic and geologic scenes.

Four other photographers of Yellowstone Lake deserve to be mentioned. The first one is actually a null set, for August F. Thrasher, a contemporary of Jackson, regrettably left no extant images. He actually photographed the lake in 1871, while participating in the first tourist excursion of Yellowstone. His cohort Rossiter Raymond recalled in his 1880 autobiography *Camp and Cabin* that "Thrasher was wild with enthusiasm about the views to be obtained from every point around the lake; and it took the whole company to tear him away from each successive promontory. By judiciously indulging him on occasions of peculiar importance, however, we succeeded in bringing him to the outlet…"

The second and third photographers, the father and son dynasty of F. Jay Haynes and Jack E. Haynes, probably sold more images of Yellowstone Lake than anyone because of their long tenure as owners of the most popular photo concession in the park. They mass-marketed a number of lake images as color postcards, such as "Yellowstone Lake and Mt. Sheridan," and "Yellowstone Lake and Colter Peak" (Figure 5), as well as larger, framable reproductions of the same. Not surprisingly, these views are "picture postcard perfect." Is it too unkind to say that the artistic quality of their lake views bears no relationship to the number sold? The fourth artist worthy of mention is America's foremost black-and-white landscape photographer, Ansel Adams. In 1941 and 1942 Adams was employed by the U.S. Department of Interior to photograph the western national parks for a mural project at the department's new museum in Washington, D. C. His three Yellowstone Lake images, first reproduced in *The Mural Project* by Peter Wright and John Armor (1989), are the epic land, water, and sky photographs for which he is justly famous. Adams' photograph "The Fishing Cone, Yellowstone Lake" illustrates a photographer's need to incorporate other objects in a lake view (Figure 6).

Figure 5. "Yellowstone Lake and Colter Peak" was a 1934 black-and-white image by Jack E. Haynes that was colorized and reproduced endlessly as a postcard.

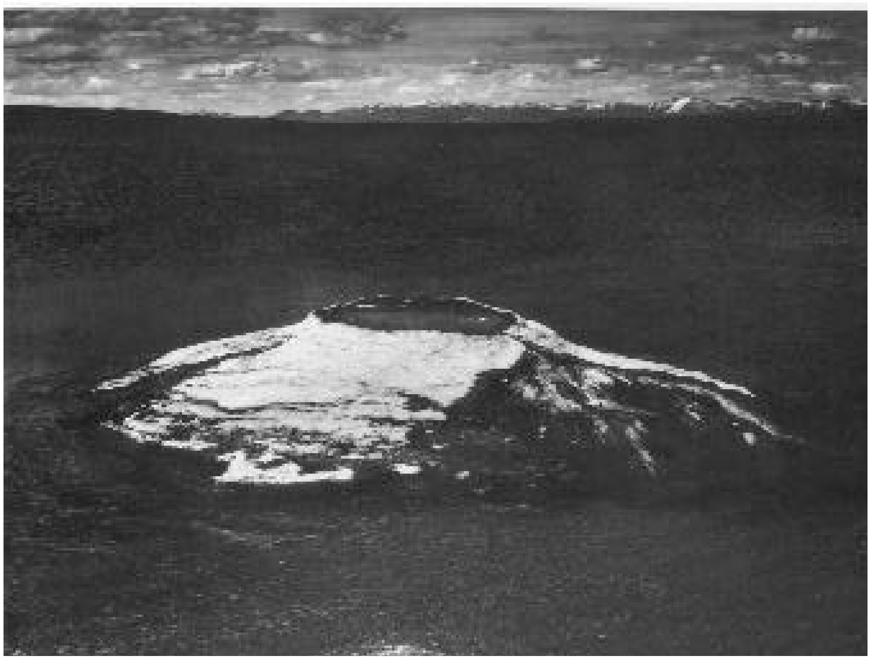

Figure 6. Ansel Adam's 1941 "The Fishing Cone, Yellowstone Lake" illustrates a photographer's need to incorporate other objects into the monotony of vast water scene.

Common Emotional Response

Artists who portray Yellowstone Lake in their chosen medium are responding to emotional tides which pull at the psyche of all human beings when confronted with sizeable bodies of water. Who among us is immune to wonder when first embracing the expansive view of an inland sea surrounded by soaring mountain peaks—especially after traversing a forest? Who among us cannot be mesmerized by the unceasing play of wave against sandy beach or rocky point? Who among us can ignore the intricately patterned and ever-changing motion of cloud against sky when the heavenly vault is presented so fully above water's horizon? Who among us is not enthralled when strong winds pour forth from unobstructed miles to whip water into frenzied, frightening motion? And who among us is incurious at the detritus, organic or inorganic, found afoot when walking along a shoreline? These emotional drivers common to all humanity are the motive forces to which artists respond, and not unreasonably so—for water is our lifeblood. If talent could be purchased for a halfpence, would not we all be artists of Yellowstone Lake?

Essayist Loren Eiseley once observed, "If there is magic on this planet, it is contained in water." Surely the waters of Yellowstone Lake possess this magic, for almost every diarist and travel writer who has submitted himself to the pleasures and vagaries of this inland sea speaks of its power in superlatives. The lake's allure draws visitors to its shores with irresistible magnetic force. Its many facets elicit imaginative comparisons and analogies, in order to give those who have not experienced it some relative semblance of its character. Words dissolve into word paintings as writers tax their vocabulary. Yellowstone Lake becomes the largest, highest, most sublime mountain lake in America, with jeweled shores rimmed by gloried, snow-clad mountains, and beset by magnificent storms. With utmost regret pleasure seekers leave this locale, remember it dearly, and perhaps find it eclipsed only by the incomparable Grand Canyon of the Yellowstone. Indeed, tour operators during the first half-century of the park's existence carefully orchestrated the route of their clients from the geyser basins to the lake, and thence to the denouement, the Grand Canyon.

The enumeration and quotation of the many well-written and heartfelt descriptions of Yellowstone Lake penned by its legion of lovers would be too lengthy for this paper. Various authors have adulated Yellowstone Lake as "a great sapphire," "a lake among lakes," "a scene of transcendent beauty," "the glory of the Park," and "without doubt the most wonderful and beautiful body of water in the world," to excerpt but a few of their key phrases. The one deemed this author's favorite will be reproduced, realizing that its grandiloquent literary style is out of vogue. Yet, its power of suasion remains. Wrote Calvin C. Clawson in his newspaper *The New North-West* on 27 January 1872:

> Thus for the greater part of two days we watched anxiously from every point and through every opening for the first glimpse of the great and wonderful lake. We were at last rewarded for all the troubles and dangers of the journey, when, from a high hill, on which was an open space in the timber, we looked down upon and out over the grand and beautiful water, clear as glass of finest finish, lying calm and still as death in the evening sun. The like of
>
> YELLOWSTONE LAKE
>
> has not yet come under the eye or within the knowledge of civilized man. The curious and marvelous sights that encircle it; the wondrous beauty of the mighty peaks that overshadow it as they stand arrayed in gorgeously painted garments of red and purple and yellow, like gigantic sentinels guarding the precious treasure entrusted to their care and keeping; its romantic shores, fringed with forests of richest green, which the frosts of winter or the heats of summer cannot fade; the unequaled beauty of its outline—all unite to enveil it in an unnatural, indescribable appearance; unlike any other spot or place seen or heard of—as if not of this world—something spiritual, beyond the reach of pen or tongue. The eye must behold the glory thereof to believe;
>
> And even then,
> Doubting, looks again.

Personal Observations on Photographing the Lake

I have been photographing Yellowstone National Park with an 8 x 10-inch field view camera since 1990, exposing over 3,000 images. On numerous occasions, including a five-day circumnavigation by canoe of the Southeast Arm, I have brought my equipment and energies to bear upon the task of recording the multifaceted aspects of Yellowstone Lake.

With Yellowstone Lake's undeniable beauty apparent from every vantage point, one would think that successful photography of the lake's charms would be an easy process. However, the achievement of a high-quality, fine-art, black-and-white photograph remains an elusive goal, one whose attainment requires substantial labor, constant experimentation, and a measure of luck. That rare print of brilliant excellence sits atop a pyramid of massive effort and countless failures of vision. Every image focused upon the ground glass contains the potential of being that great picture, yet victory is seldom attained.

What are the challenges that face a large-format photographer as he stalks the lake? Weather is one crucial and contentious factor which aids and bedevils the view camera photographer, whose craft requires a substantial investment of time for set-up, focusing, exposure, record-keeping, and packing up. Special qualities of light and cloud may vanish in the twenty-minute period needed to prepare the camera for the click of the shutter. Thus, optimum conditions must either be anticipated, or, more usually, waited for patiently. Clouds, shadows, and sunbeams are vital ingredients in a waterscape, but they are most capricious and uncontrollable. Furthermore, the atmospheric effects of violent rain storms over the lake are fascinating to witness, but a positive hindrance to the view camera operator, for wind shakes the camera unacceptably and blows dust into the film holders, while rain ruins sheet film and cannot be allowed to soak the camera's wooden body or leather bellows.

Another challenge facing the black-and-white landscape photographer as he or she contemplates the lake is the need for contrast. Since the vastness of water is often a featureless monotone, the photographer searches for tonal contrast by including textured clouds, pebbly beaches, rocky points, arching shorelines, contorted driftwood, treed headlands, and breaking waves. The skillful photographer attempts to unite some of these elements into a dynamic whole.

Because the lake is a panoramic phenomenon, the photographer is tempted to retreat from its shoreline to gain a broader perspective. As the photographer recedes from the lake to nearby elevated buttes or mountains (such as Lake Butte, Elephant Back Mountain, Jones Pass, Langford Cairn, or the Promontory), a greater breadth of view is obtained, but at a price. Such panoramic vistas excite the eye and mind, and are truly memorable, but attendant atmospheric haze borne of moisture or particulate matter can degrade the picture's detail and contrast. This attenuation can lead to unattractive muddy gray tones, as distant islands, shores, and ridges fade into semi-obscurity. The high and grand view challenges the photographer's skill and medium.

This photographer has engaged Yellowstone Lake at four locales: Pumice Point, Storm Point, the mouth of Cub Creek, and the Southeast Arm. Pumice Point (a road stop) was photographed on a chill, autumnal day, and remains vivid for its austere and dark ambience. Storm Point (a short day hike) is a dramatic lunge of rock against water, where the full force of southwesterly gales is spent. From its eminence I was able to photograph the white volcanic strata that wave action has so masterfully sculpted along Yellowstone Lake's north shore (Figure 7). Incidentally, the embankment of rocks shown in the background of this scene is marbled with the most striking swirls of blue, indigo, maroon, and violet colors I have ever witnessed in nature. At the mouth of Cub Creek (a short day hike), nature has strewn about a speckled, pebbly beach the refuse of its never-ceasing

Figure 7. Storm Point and the northeast shoreline offer needed contrast to the lake's transparent waters in this 1996 view camera photograph by the author.

war against the east bank—undercut and toppled trees, bleached driftwood, and detached boulders of all dimensions. Close-up views of this debris can be most artistic. Lastly, the Southeast Arm (a multi-day canoe adventure) afforded this photographer a lengthy opportunity to experience and record the lake in its many wilderness moods. Morning calms, afternoon thunderstorms, high-elevation overviews from Langford Cairn and the Promontory are a few of the photogenic scenes witnessed. Every place and every hour on Yellowstone Lake was a unique glimpse into a grand beauty and fierce power on a scale seldom realized in our mundane lives. Recording these images in my mind was easy; upon my film, harder.

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Yellowstone Sand Verbena (Abronia ammophila): A Yellowstone Lake Endemic

Jennifer J. Whipple

Abstract

Yellowstone sand verbena, *Abronia ammophila* Greene, is restricted to stabilized sand sites that principally lie just above the maximum splash zone along the shoreline of Yellowstone Lake. A 1998 survey of the entire population found little more than 8,000 plants, most of which were seedlings. A summation of current knowledge regarding the life history of the species is presented, though many aspects still require further elucidation. Historical collections suggest that this species was more widely distributed around the lake in the early years after the park's establishment. The high level of human activity on the beaches, especially along the northern shoreline of the lake, may have resulted in the extirpation of the sand verbena from significant portions of its original range. The long-term survival of Yellowstone sand verbena is in doubt if the remaining sites are adversely affected. Strategies will be presented to help insure the continued survival of this unique endemic.

Introduction

Yellowstone National Park is known for the spectacular abundance of geysers and other geothermal phenomena and also as one of the premier places to see wildlife in the temperate zone. An overlooked and underappreciated component of the ecosystem on the Yellowstone Plateau is an endemic wildflower, Yellowstone sand verbena, *Abronia ammophila* Greene (Figure 1). According to park records, prior to this study the sand verbena was known to occur only along the northern shoreline of Yellowstone Lake. Yellowstone sand verbena is restricted to stabilized sandy sites that lie primarily just above the maximum splash zone along the shoreline of the lake.

Frank Tweedy in 1885 was the first Euroamerican to collect the sand verbena, at the mouth of Pelican Creek along the north shoreline of Yellowstone Lake. This specimen was originally identified as *Abronia villosa* (Tweedy 1886), a common purple-flowered species of the American southwest. Subsequently, Per Axel Rydberg looked at Tweedy's specimen and decided that the material from Yellowstone was sufficiently different to justify recognition as a unique species (Rydberg 1900) and named it *Abronia arenaria*. Archibald Menzies, though, had previously used this name for one of the maritime sand verbenas that occurs in sand dunes along the west coast of North America. E.L. Greene resolved the resulting problem by proposing the name *Abronia ammophila* (Greene 1900) for the Yellowstone species.

Figure 1. Abronia ammophila *in bloom.*

Treatments of the Yellowstone flora in the first half of the twentieth century continued to recognize the sand verbena as *A. ammophila* (Coulter and Nelson 1909; Conard 1928; McDougall and Baggley 1936, 1956). More recently, Yellowstone sand verbena was included within the widespread western species *A. fragrans* Nutt. ex Hook. by C. Leo Hitchcock and Arthur Cronquist in Vascular Plants of the Pacific Northwest (Hitchcock et al. 1964), which Despain then followed (Despain 1975). The monograph on *Abronia* by Galloway (Galloway 1975) reevaluated the Yellowstone material and resurrected *A. ammophila* as a unique species. Galloway included within his interpretation of *A. ammophila* material from Yellowstone National Park and also from sandy hills near Big Piney, Sublette County, Wyoming. Subsequent investigations have revealed that the specimens reported from Sublette County are now believed to be *A. mellifera* (Marriott 1993; Fertig et al. 1995; L.A. Galloway, personal communication). *A. ammophila* is now recognized to be a highly restricted endemic of Yellowstone National Park.

Even though Yellowstone sand verbena was described as an annual in the only recent monograph of the genus (Galloway 1975), the plants are clearly perennial, with a substantial taproot that can be more than 0.5 m in length in large individuals. The taproot is often vertically oriented and not highly branched. The prostrate plants are spread on the sand, rarely rising more than a couple of inches from the surface. Sticky glands are present everywhere on the plants except on parts of the corolla, causing the plants to be covered in sand. The white flowers are in head-like arrangements of up to 20 separate flowers subtended by membranous bracts. During the bright sun of mid-day the flowers usually close, reopening again in the evening. Examination of the plants during the early 1990s revealed that flowering begins by the middle of June, and the plants continue blooming well into September until a killing frost occurs. The flowers may be sensitive to light levels, opening when light levels decrease, such as under heavy thunderclouds and in the evening, but the controlling mechanisms appear to be more complex since observations are confusing. Possible different hypotheses include responses to temperature or temperature change, wind speed, time of day, cloud cover, or a complex interaction of several factors.

Apparently the plants are pollinated by insects. Moths have been observed visiting flowers, but whether pollination is occurring is unknown. Observations of the plants revealed that fruits were first observed on 15 July in 1998. However, unlike many of its associated native species, *Abronia* continues to flower vigorously long after setting fruit. Seed set is sporadic, with many flowers not developing mature seeds. The flowers of several *Abronia* species do not appear to self-pollinate (Tillett 1967; L.A. Galloway, personal communication). Perhaps the extended blooming season for Yellowstone sand verbena is in part due to the very erratic presence of pollinators.

Seed dispersal may be facilitated by the sticky surface of the anthocarps. Some fruits accumulate in depressions in the sand where the wind has deposited them. The widely dispersed locations occupied by the sand verbena suggest that there is some effective method of seed dispersal, perhaps on the feet of gulls or waterfowl. Seed longevity in the seed bank is unknown.

One of the continual difficulties in determining the distribution of an unusual plant such as *A. ammophila* is the dilemma inherent in trying to determine the original distribution of the species. The most valuable records are old herbarium sheets that can be examined and found to be the species in question. Yellowstone National Park was the scene of a phenomenal amount of collecting during the last part of the nineteenth century as botanists flocked to see the new national park and the wonders that were being preserved. As a result, herbariums literally all over the world have material from Yellowstone National Park. The advent of the Worldwide Web and the efforts to make specimen data available in computer databases will eventually make it possible to search for *A. ammophila* specimens at many institutions. Meanwhile, locating specimens is difficult due to the time and expense involved with searching widespread collections.

The historical distribution of *A. ammophila* is uncertain, but clearly the species was more widely distributed in the past along the shoreline of Yellowstone Lake. Apparently, plants were present in the vicinity of the Fishing Bridge Museum in the 1920s. H.S. Conard made a collection of Yellowstone sand verbena on 23 June 1926 from "near Fishing Bridge Camp; Lake." The Fishing Bridge campground was located at that time in the vicinity of what is now the current parking area near the Fishing Bridge Museum (Haynes 1928; Figure 2). Conard also mentions the habitat as being sandy dune. There are sandy dune deposits stretching from near the outlet of the Yellowstone River to the mouth of Pelican Creek. Aven Nelson collected extensively in 1899 throughout Yellowstone National Park, including near the Lake Hotel on Yellowstone Lake. On 23 August, he collected Yellowstone sand verbena from “[o]n the sandy banks, near lake Hotel” (Nelson 1899). The closest extensive sand banks to the Lake Hotel would be the shoreline in the vicinity of the current Fishing Bridge development. Leo A. Galloway visited the west side of the mouth of Pelican Creek on 28 August 1968. In his field notes, he states that he was a quarter of a mile west of the mouth of Pelican Creek, where there were numerous small plants in the vicinity (L.A. Galloway, personal communication).

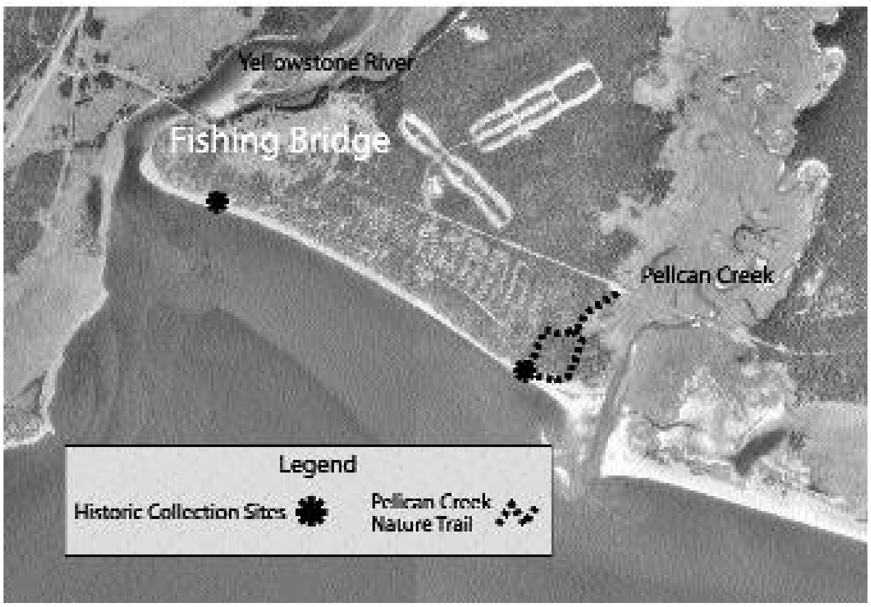

Figure 2. Map of known historical locations of Yellowstone sand verbena along the north shore of Yellowstone Lake.

Surveys during the early 1990s along the north shoreline of Yellowstone Lake revealed that there are no plants present from the mouth of Pelican Creek west to the outlet of the Yellowstone River. This area appears to represent good habitat for Yellowstone sand verbena, as documented by the historic collections of Nelson and Conard. Further east, Mary Bay may also at one time have supported a population of *A. ammophila*. No herbarium collections are known from this stretch of beach, but the habitat appears to be very similar to the occupied area from Storm Point to the east side of the mouth of Pelican Creek. Currently, the east entrance road is directly on top of the area that would be occupied by the sand verbena if it were present in the area. The construction of the road in the 1930s may have extirpated plants.

The Wyoming Natural Diversity Database maintains a list of plant species of special concern for the state (Fertig and Beauvais 1999). *A. ammophila* is listed as a state endemic with a high conservation priority. The global and state ranks of the plant are G1/S1. This rank means that Yellowstone sand verbena is "critically imperiled," either because of "extreme rarity," which is defined as being known "from 5 or fewer extant occurrences or very few remaining individuals," or because "some factor of [the] species' life history makes it vulnerable to extinction" (Fertig and Beauvais 1999).

Yellowstone sand verbena was classified as a category 2 candidate for listing under the Endangered Species Act in the 30 September 1993 notice of review (U.S. Fish and Wildlife Service 1993). Category 2 includes those taxa for which information now in the possession of the U.S. Fish and Wildlife Service indicates that proposing to list as endangered or threatened is possibly appropriate, but for which sufficient data on biological vulnerability and threat are not currently available to support such a listing (U.S. Fish and Wildlife Service 1993). This category was eliminated by the U.S. Fish and Wildlife Service in 1996.

Yellowstone sand verbena does not have any official status under the Endangered Species Act at this time. Nonetheless, this endemic restricted to the shoreline of Yellowstone Lake certainly qualifies as a rare species that must be carefully managed. The limited distribution and relatively small number of plants increases the danger that the species could undergo a significant decline that could lead to its global imperilment, and necessitate its listing as either endangered or threatened under the Endangered Species Act.

With increasing evidence suggesting that at least part of the habitat had been adversely impacted, and the realization that *A. ammophila* was a highly restricted endemic within Yellowstone National Park, it became apparent that more information about the current status and distribution of the species was needed. A study was therefore initiated in 1998 to (1) survey all of the likely habitat along the shorelines of the major lakes within Yellowstone National Park for additional populations, (2) establish a permanent grid system at all known locations, and (3) count all individuals present.

Methods

Survey. Yellowstone Lake, as the site of the only known population, was the primary focus for the shoreline survey. All of the lake's 144 miles of shoreline, including Stevenson, Dot, Frank, and Peale islands, the two Molly Islands, and the unnamed island in the southwest corner of the South Arm, were systematically searched by foot, power boat, and canoe for *A. ammophila*. All locations where sand occurs were carefully investigated for the presence of sand verbena. The shorelines of Heart, Delusion, Duck, Riddle, Lewis, and Shoshone lakes were also searched by foot, canoe, or both. In total, 200 miles of shoreline were surveyed. Additional backcountry areas have been investigated opportunistically at scattered locations around Yellowstone Park.

The Shoshone Lake shoreline was surveyed by foot and canoe in July 1995. Yellowstone Lake and its islands, and Lewis, Delusion, Duck, and Riddle lakes were searched from mid-June to mid-September 1998. Several promising areas of habitat on Yellowstone Lake were rechecked later in that summer, in case plants were late in emerging from the sand. The Heart Lake survey was conducted in August 1999. *Abronia*-occupied sites and areas of potential habitat were marked on U.S. Geological Survey 7.5-minute topographic quad maps. These sites were then mapped, using a Trimble Pro-XR global positioning system (GPS) unit that had meter to submeter accuracy with differential correction, and entered into the Yellowstone National Park Geographic Information System (GIS) database.

Census. Fieldwork for the census data was conducted during July and August 1998. A baseline of permanent points was established at all the sand verbena sites, with additional reference points placed outside of the baseline to aid in relocating the baseline if any points are lost through time (Whipple 1999). A list of all permanent reference points placed at the occupied sites, each point's UTM (Universal Transverse Mercator coordinate) as determined by GPS, bearings ahead (to the next point on the baseline), bearings to landmarks, and physical location description were documented. All permanent reference points were mapped using a Trimble Pro-XR GPS unit.

A grid of 1-m^2 cells was used to census the areas occupied by *Abronia*. A meter-tape was stretched between baseline points and a series of 1-m-wide rows perpendicular to the baseline was created with another meter-tape and string attached to survey stakes. A 1-m^2 quadrat was placed in a row and moved down a meter at a time, counting *Abronia* plants within each 1-m^2 plot. Each plot was denoted by its position in meters along the baseline and the number of meters north or south of the baseline. The position north or south of the baseline was denoted by letters. Areas between major groups of *Abronia* were subdivided into rows perpendicular to the baseline and several meters wide. The sections were searched and any isolated plants found were given a plot designation, using their distance along and from the baseline. The tape and string row boundaries were leapfrogged over each other so there were no gaps in coverage. Sites with only a few Yellowstone sand verbena plants were censused in a similar manner, though the orientation of the baseline could differ.

All rows and plots containing *Abronia* were photographed using 35-mm cameras with both color slide (Kodachrome 64) and black-and-white film. Horizontal format was used for individual plot photos and vertical format for rows. All photos were taken facing south, except that long rows were photographed from both the north and south ends. Photographs were taken from a position 1 to 2 m beyond the near edge of the subject plot or row, which was centered in the frame.

Yellowstone sand verbena plants were censused with four size/demography classes that were selected and defined on the basis of field observations. The classes are: recruit (<5 cm diameter, basal leaves only, no stem branching, no flowering); medium (<5 cm diameter, branching present, flowering or not); large (>5 cm but <30 cm diameter); and very large (>30 cm diameter).

Some of the larger plants have a mat-like morphology. Examination of *A. ammophila* exposed in a wave-cut slope found that stem branches can spread at least a decimeter in different directions from the top of the root, which may be buried several decimeters deep in the sand. Since excavating most or all of a plant was not appropriate, determination of an individual was not always possible because impacts to the plants needed to be kept to a minimum. When determination of an individual was problematic, the most likely number of plants in a mat or clump was recorded followed by the maximum possible number, e.g., a plant that appeared to be one but could have been as many as three was recorded as 1(3). Final tallies therefore include a "most probable" total and a "maximum possible" total.

Plants were tallied in the plot in which they were rooted. Few plants fell directly on plot boundaries, but those that did were counted in the plot closest to the beginning (point 0) of the baseline. Dead plants were also tallied. A few *Abronia* were nearly dead and desiccated with a tiny amount of green tissue remaining; these were tallied as "dying."

Results

Survey. The field survey found three previously unknown *A. ammophila* sites on the shoreline of Yellowstone Lake: at Rock Point; at the unmarked fishing access near Pumice Point; and one isolated plant on the east shore of the South Arm of Yellowstone Lake (Figure 3). No *Abronia* was found on any of the islands in Yellowstone Lake or at any of the other large lakes. The four known Yellowstone sand verbena sites are all located on loose, unconsolidated sand with minimal fines, gravel, and organic matter. Three of the four sites are on beach sand, just outside the maximum wave zone. The exception is the Pumice Point site, which is located on black sand that is significantly above the current lake level. This sand may have weathered in situ from rhyolite, but probably represents a residual sand accumulation from a former lake level. Several of the occupied areas, notably Rock Point, Storm Point, and a small group on the north shore, occur in horseshoe-shaped, sandy depressions that are slightly bowl-like in cross-section.

A. ammophila is found as high as approximately 10 m elevation above the high-water line and as far inland as roughly 60 m, although it mostly occurs within 40 m of the shoreline. The species generally occurs above the high-water mark, but in the north shore site some plants were found on and below a sand slope cut by the unusually high water level of Yellowstone Lake of 1997. No plants were found in any location that appears to be regularly inundated.

Yellowstone sand verbena favors open, sunny sites with widely spaced vegetation. Common associates include *Phacelia hastata* Dougl. ex Lehm., *Rumex venosus* Pursh, *Polemonium pulcherrimum* Hook., and *Lupinus argenteus* Pursh. Other species that often occur in the vicinity include *Haplopappus macronema* Gray var. *linearis* (Rydb.) Dorn, *Aster integrifolius* Nutt., *Chaenactis douglasii* (Hook.) H. & A., and *Polygonum douglasii* Greene.

Census. In all, 8,326 *Abronia* plants (a maximum of 9,680, if some mats are greater than one plant) were found among all the sites. In addition, 41 dying and 68 dead plants were also counted. A total of 7,978 live plants (9,316 maximum) were found at the north shore site; 325 live plants (339 maximum) at the Rock

Figure 3. Map of Yellowstone Lake showing the location of all current Yellowstone sand verbena sites.

Point site; 22 plants (24 maximum) at the Pumice Point site; and one plant along the shore of the South Arm (Table 1).

The north shore population was 18% recruit size, 27% medium, 45% large, and 10% very large. Percentages are based on the "most probable" totals. The recruitment class made up a disproportionate share of most of the small, isolated subpopulations within the north shore population: 33% of the 166 plants near 400 m on the baseline, and 79% of the 82 plants near 575 m. Some of the seedlings seen were tiny, with only one or two leaves and less than 1 mm diameter. It is possible that the field personnel overlooked some seedlings and that the recruit class may have constituted a larger proportion of the north shore population than indicated.

Rock Point had the same percentage of plants in the recruit category, 18%, but the other size classes differed from the north shore site, with 49% of plants in the medium class, 29% in the large, and 3% in the very large. Many of the medium-

Table 1. Yellowstone sand verbena population count for all sites with the number of individuals followed by the maximum possible number if a large mat is composed of more than one individual. The four size classes are: recruit (<5 cm diameter, basal leaves only, no stem branching, no flowering); medium (<5 cm diameter, branching present, flowering or not); large (>5 cm but <30 cm diameter); and very large (>30 cm diameter).

	Recruit	Medium	Large	Very Large	Total
North Shore	1,448	2,183	3,573	774	7,978
		(2,287)	(4,329)	(1,252)	(9,316)
Rock Point	59	161	96	9	325
		(168)	(103)	(9)	(339)
Pumice Point	3	4	14	1	22
			(16)	(1)	(24)
South Arm	0	0	1	0	1
			(1)		(1)
Total	1,510	2,348	3,684	784	8,326
		(2,459)	(4,449)	(1,262)	(9,680)

sized Rock Point plants appeared later in the summer in an area that had been devoid of *Abronia* when first visited in June. The small number of plants at Pumice Point yielded 14% in the recruitment class, 18% in the medium, 64% in the large, and 5% in the very large. The lone plant along the shore of the South Arm was in the large size class.

In 1998, the total population of Yellowstone sand verbena was composed of 18% recruitment size, 28% medium, 44% large, and 9% very large. Percentages are based on the "most probable" totals. Fifteen percent of the north shore plants, mostly large and very large but also a few mediums, were recorded as possibly more than one plant. If "maximum possible" totals are used, the percentages in the large and very large size classes increase slightly and those in the recruit and medium classes decrease slightly. No assumption of age of the individuals can be made at this time, except for the recruitment class, which apparently were all first-year seedlings.

The north shore site had less than 1% dead or dying plants. No dead or dying plants were found at Pumice Point or the South Arm. Notably, the Rock Point site had 12% dead and 31% dying *Abronia*, apparently due at least in part to a herd of elk trampling the area.

Discussion

A casual survey of the north shore population in 1994 yielded a population estimate of approximately 1,000 individuals. At that time there were relatively few plants that were small, with most forming obvious mats, though no attempt was made to count different size classes. No young seedlings were observed. In contrast, by 1997 it was obvious that there were many more plants along the north shore, with young plants forming a conspicuous component. Apparently, the conditions during the intervening time had been highly conducive for new plant establishment. The size classes of the plants censused in 1998 reflect the large recruitment event that had recently occurred. Most of the plants present in the early 1990s were apparently in the largest size class, which in 1998 numbered approximately 784 individuals, with a maximum of 1,252 individuals (Table 1). Since the census in 1998, the summers have been relatively dry, with drought conditions occurring during 2000 and 2001. The total number of extant sand verbena individuals can be presumed to have dropped significantly, and many of the plants in the recruit and medium size classes have probably died from water stress. Possibly, the number of plants present on the lakeshore at this time could more closely resemble the number present in the early 1990s than in the complete count of the population in 1998.

The restriction of the sand verbena at all sites to a zone of relatively open vegetation suggests that this species may not be capable of competing adequately in areas that are more highly vegetated. This tendency is obvious when one examines the distribution of plants around the lakeshore. Typically, the plants occur in a relatively constrained zone between the area influenced by wave action and the densely vegetated region inland. Some natural disturbance may be necessary to prevent the establishment of dense vegetation that would then preclude sand verbena.

The record high lake levels of 1996 and 1997 (Farnes 2000) eroded the southern edge of the stabilized sand along the north shore, washing out part of the occupied habitat. Perhaps dynamic changes in lake levels, such as occurred with these high levels and the correspondingly low levels observed in 2001, may be important to the persistence of the sand verbena since the increase in erosion and fluctuation in water level reopens or creates new habitat. Since the lake level has varied tremendously during the last several thousand years (Meyer and Locke 1986; Cannon, Pierce, and Crothers 1995), Yellowstone sand verbena must be capable of moving with the changing lake levels to be able to persist along the lakeshore. Global warming may cause a change in the climate of the Greater Yellowstone area, thereby affecting the lake levels in the future, so the plant's ability to respond to change will continue to be important.

Another component that affects *A. ammophila* is the presence of thermal activity in the immediate vicinity of some of the plants along the north shore. The largest subpopulation on the north shore is adjacent to a small thermal barren. The center of the thermal area is unvegetated, but a sandy mound to the northwest hosts the most dense concentration of Yellowstone sand verbena known to exist, as well as some of the largest individuals. Many of the plants in this area are on ground with a slight thermal influence. Most of the associated species drop out as the ground temperature becomes hotter, leading to an area where the sand verbenas dominate the vegetation. The possibility exists that the warmth associated with thermal sites along the lakeshore has enabled sand verbena to persist during periods when the climate was perhaps not as conducive for the survival of this species, or that the thermal habitat provided sites where sand verbena was at a competitive advantage over other species that thrive on cooler sand.

Elucidating questions about the evolution and current population biology of *A. ammophila* requires further investigation of many facets of the plants. The relationship of Yellowstone sand verbena to other sand verbenas is unknown. DNA analysis is needed to ascertain relationships among the sand verbenas of the northern Rockies. This information might clarify whether the sand verbena is a recent immigrant into the park, and thus closely related to other taxa or perhaps not actually distinct, or whether the sand verbena has been evolving in Yellowstone for an extended period of time.

Yellowstone sand verbena appears to have a relatively poor seed set (L.A. Galloway, personal communication). Investigation into who are the pollinators and what other constraints are affecting the pollination ecology of this species is needed. Corollary questions involving population dynamics that warrant further investigation include what conditions are advantageous to recruitment, the longevity of plants, and the presence and effects of herbivory.

In order to maintain a healthy population of Yellowstone sand verbena, the park must protect all known sites. The South Arm site and the Rock Point site are easily accessible only by boat and due to low levels of boating use on Yellowstone Lake do not need any special management attention at this time. There is the possibility that the single individual present at the South Arm site represents the lone survivor of a more extensive group of individuals that was washed out during the high lake levels of 1996 and 1997. The relatively dry summer weather in the succeeding years may be preventing new seedling establishment. An alternative hypothesis is that one individual grew from a single dispersed seed and is persisting, but due to a lack of pollinators there has been no viable seed production so the population is not increasing.

The Rock Point site, which prior to 1998 was unknown to the National Park Service, was perhaps first located by Loran C. Anderson, who visited Sand Point on 30 June 1958 and collected *Abronia ammophila* (Allyson Davis, collection manager, Intermountain Herbarium, personal communication). The information on specimen #1241 (UTC #95348) reads: “Frequent in moist sand of Sand point, southeast neck of the West Thumb of Yellowstone Lake, Yellowstone National Park.” There was no Yellowstone sand verbena at Sand Point in 1998, but it is possible that the collector was actually at Rock Point and only had available a park brochure or other map that didn’t include both names. An alternative hypothesis is that the sand verbena formerly did occur on Sand Point, since the area appears able to support the taxon but was flooded and eroded out during 1996 and 1997. Under the later scenario, Yellowstone sand verbena would be expected to eventually recolonize Sand Point if lake levels remain low.

The Pumice Point fishing access should continue to be left unmarked by signs in order to keep the visitation and use of the picnic tables at current levels. This subpopulation is currently declining, with only one plant visible in 2001, in contrast to 22 in 1998. The sand at this site is elevated above the shoreline, with rocky substrate preventing the roots of the plants from intercepting the water table associated with the lake level. The decline appears to be natural, caused by the drought conditions during the summers of 2000 and 2001. This site may be ephemeral and an artifact of the wet years in the mid-1990s.

Currently, there is a low level of visitor use within the area occupied by the north shore population. It may become necessary to place signs at the east end of this site adjacent to Storm Point asking people to stay on the Storm Point trail. At this time there is no need to close the area as long as visitor use within the area stays low, though this action should be considered if use and corresponding plant loss increase on the east end of the occupied habitat on the north shore.

The lakeshore from the outlet of the Yellowstone River to the mouth of Pelican Creek was formerly occupied by *A. ammophila*. Due to the high levels of visitor use in the area near the Fishing Bridge development, it is not practical to attempt reintroduction in that area. As late as 1968, sand verbena was still present a quarter of a mile west of Pelican Creek in the vicinity of the Pelican Creek Nature Trail (L.A. Galloway, personal communication). The presence of this nature trail has probably contributed significantly to, if not caused, the extirpation of sand verbena from this portion of the shoreline. Since the closure of the Fishing Bridge Campground in 1989, there has presumably been a decrease in visitor use on the eastern portion of the beach away from the Fishing Bridge Visitor Center. If the Pelican Creek Nature Trail was removed, it is very likely that Yellowstone sand verbena might be able to re-establish near Pelican Creek. Without removal of the trail, the disturbance of the sand is expected to continue at a level that would preclude the possibility of natural reestablishment or successful reintroduction of sand verbena. Currently, the Pelican Creek Nature Trail is in need of some repair. Consideration should be given to removing or relocating the trail to another area that is less sensitive environmentally, rather than repairing it. Of the areas that were historically occupied by Yellowstone sand verbena, this is the only place where recolonization or reintroduction is likely to succeed, especially if the beach is closed to public access.

Yellowstone sand verbena has been extirpated from a significant portion of its original range along the shoreline of the lake due largely to human influences. The north shore site is the key to the survival of this Yellowstone endemic, as it is the location of 96% of the species' entire population. The presence of three additional sites is interesting, but doesn't change the reality that the continued survival of *A. ammophila* is coupled to the survival of the plants on the north shore.

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Native Americans, the Earliest Interpreters: What is Known About Their Legends and Stories of Yellowstone National Park and the Complexities of Interpreting Them

Lee H. Whittlesey

The thermal wonders of the Park did not frighten the native peoples of the region. Euro-Americans originated this idea and it must be dispelled before we can understand the true nature of Yellowstone's human past.
—Joseph Weixelman, "The Power to Evoke Wonder" (1992)

What did the Indians say about Yellowstone? They must have told stories about its strange wonders, but what were those stories? Historians have long wondered. Answers have been slow to appear.

Native Americans probably had many more tales, legends, and myths about the Yellowstone country than the few we currently know of, but thanks to Peter Nabokov and Larry Loendorf, we now know more than ever before about some of those early Yellowstone stories. Prior to the emergence of their manuscript "American Indians and Yellowstone National Park: A Documentary Overview," historians trusted only one Indian legend relating to Yellowstone; that is, they knew of only one that appeared to be genuinely Indian rather than "white" (the Ralph Dixey story discussed below). Moreover, before the Nabokov book appeared, only small, unsatisfying tidbits of Yellowstone information were known to us in general about the Sheepeaters, Shoshones, Crows, Bannocks, Blackfeet, Flatheads, Kiowas, Arapahoes, Nez Perce, Assinboines, Northern Cheyennes, Gros Ventres, Sioux, and other tribes who inhabited the upper Yellowstone country and its edges at various times prior to 1870. But now, because of that book, we know more than ever before about how these tribes related to Yellowstone.

There seems to have been an effort by early whites in Yellowstone National Park to make the place "safe" for park visitors, not only by physically removing Indians from the park and circulating the rumor that "Indians feared the geyser regions," but also by attempting to completely segregate the place in culture from its former Indian inhabitants, including their legends and myths. If historians cannot conclusively prove that whites conspired to do this, many of us who have spent years studying Yellowstone's literature certainly cannot escape the overarching feeling that something like that happened. Superintendent P.W. Norris's 1870s statements that "these primitive savages" feared the geyser regions are well known. Even as early as 1895, historian Hiram Chittenden could not find much about what Indians thought about Yellowstone nor about what they told whites of it. “It is a singular fact in the history of the Yellowstone National Park,” wrote Chittenden, “that no knowledge of that country seems to have been derived from the Indians.…Their deep silence concerning it is therefore no less remarkable than mysterious” (Chittenden 1895: 8, 99).

One wonders whether Chittenden (like so many later writers) simply could not find information about Yellowstone Indians, or whether the Indians would not talk to him because of religion (we know that many tribes considered Yellowstone sacred) or because of other reasons (see the following paragraph), or whether he purposely fostered this thinking for motives of his own. At this late date it is difficult to point fingers at our “white” forebears and accuse them of such conspiracies, but that belief must figure at least a modicum into the fact that until American Indians and Yellowstone was written, we knew less about Indians in Yellowstone than about Indians anywhere else in the American West.

It now turns out that there may be a fascinating reason after all for Chittenden’s comment concerning Indians’ “deep silence” about Yellowstone. I searched for this information for nearly thirty years and only recently found it in a rare book that came to the park via the massive collections of Jack and Susan Davis of Bozeman, Montana. The source is a man named John Hamilcar Hollister who visited Yellowstone in 1883 with the well-known Rufus Hatch party. Hollister published an account of that trip in 1912, and in it he told the now disreputable story of Indians fearing the park’s geyser regions. But following that story, Hollister stated that his attempts to find Indian legends about Yellowstone had been unsuccessful. He, like me many years later, wondered why he could not find such Indian legends of Yellowstone. He then made the following statement that appears in no other known place in Yellowstone literature:

> …there are but few [published] Indian legends which refer to this purposely [!] unknown land. Of these I have found but one [other than for the Indians-fearing-the-geysers story], and that is this—that no white man should ever be told of this inferno, lest he should enter that [Yellowstone] region and form a league with the devils, and by their aid come forth and destroy all Indians. Hence the trappers, who were the first white men to enter these western lands, learned little or nothing [about Yellowstone] from that source [Indians] (Hollister 1912: 145).

This is a fascinating assertion that we can prove neither absolutely true nor absolutely false. Hollister does not tell us whence he obtained this supposed legend of Yellowstone, but the fact that he apparently heard it in 1883, very early in the park’s history when hundreds of pre-1872 Indians were still living, gives me great pause. I believe that we must consider this story as possibly true until such time that we get good information debunking it. In light of all that we know about how fervently some Indian tribes believed in the park as a sacred place, the idea of not revealing it to whites makes total sense. Of course we have no idea exactly which tribes Hollister referred to, and, again, we do not know whence he obtained the legend. If true, the Hollister rendering of this Native American story represents a very large and possibly final piece of a long, incomplete puzzle relating to Yellowstone, i.e., the fact that some tribes may have kept the place a secret and why they did it.

The idea that at least some Indians (we do not yet know which tribes might have had such a policy or how many such tribes there were) might have kept the existence of Yellowstone a secret for religious reasons squares well with both known native proclivities for not telling certain things to white men and with Chittenden's 1895 perception of a deep Indian silence about Yellowstone. It also begins to explain why historians Nabokov and Loendorf, Aubrey Haines, Joseph Weixelman, I, and others have all had a fair amount of difficulty finding good numbers of literature connections between Indians and Yellowstone. Finally, it explains why we have so few known Indian legends about a place that must have generated dozens or hundreds of such legends among ancient natives. Thus, we now must, in my opinion, begin asking our Native American friends whether there is anything in their oral traditions to confirm this, and hope that one or more of them will tell us whether they indeed kept the place secret on purpose. Considering how we white people have spoken "with forked tongue" in the past, I certainly would not blame them if they would not tell us.

One final point with regard to Hollister. A critic has suggested that Hollister's use of the word "devils" here might somehow negate his statement because it might show that the Indian(s) he talked to were "Christianized." Here is why I believe Hollister's statement is not negated by that.

Christianization and the accompanying linguistic translations about it back and forth from Indians to whites and vice versa were (and are) very complicated things. And white men were notoriously poor at understanding Indian religion, whether it had been "Christianized" or not. Note that historian Colin Calloway says many white men tended to dismiss Indian religion as "devil worship" (Calloway 1997: 68). Thus, just because Hollister used the term "devil" does not mean we should jump to conclusions about what he meant or what the Indian(s) he spoke to meant. For all we know, Hollister simply mistranslated what the Indian(s) told him into "white-man vernacular."

Secondly, Indians did not always "buy into" Christianization. In this case, if they did not buy into it, then their comments to Hollister were probably still based upon their intact native religion. Even if their buy-in to Christianity was partly complete, they still might have been using a religion that involved pieces of their original religion and hence their statement on the taboo might still have made it through Hollister to us as a true statement.

Indians' buy-in to Christianity ran the gamut from "not at all" to "partly" to "completely." That is a point Calloway makes over and over again in his chapter on religion entitled "A World of Dreams and Bibles." His chapter discusses the complex interplay between Indian religion and Christian religion in the new world. Calloway mentions instance after instance wherein Indians simply played along with white Friars and Fathers (merely mouthing their words and phrases in order to placate them, or remaining silent, which the Fathers often incorrectly took to mean tacit agreement) before returning to their old ways of religion. In many other cases, Indians simply took pieces of the white man's religion and incorporated them into an already-established native religion. That often meant that the native religion was essentially left intact with only a few baubles-and-bangles-and-crucifixes thrown into the mix. A few attempts by whites at Christianization undoubtedly worked, wherein Indians were mostly or totally converted, but we cannot assume that this was the general rule, as many white people have assumed.

We now move to other known Indian legends about Yellowstone. For many years, Yellowstone historian emeritus Aubrey Haines believed that only one Indian legend relating to Yellowstone was genuine. It is a tale of the origin of the Snake and Yellowstone rivers, apparently truly handed down in Shoshone and Bannock families and published in Ella Clark's *Indian Legends of the Northern Rockies* (Haines 1982; Clark 1966: 174–177). Other than for this story, there was, until the production of American Indians and Yellowstone, little reliable information or documentation on legends, myths, or other folklore that may have been communicated by Indians about the present Yellowstone National Park. Even after the emergence of the Nabokov and Loendorf's book, the "Coyote" Yellowstone stories that have been bandied about by both Indian and popular "white" writers remain controversial in that historians disagree as to which are genuine and which are made up by whites.

And, too, we now know that there are a great number of other so-called Indian stories that can be totally dismissed as tales made up by whites to explain what Indians "should have thought" about Yellowstone. Again, the most common example of such misinformation is that Indians "feared the geyser regions as inhabited by evil spirits." Virtually all of the stories included in Mary Earle Hardy's *Little Ta-Wish: Indian Legends from Geyserland* (1913) and La Verne Fitzgerald's *Blackfeather: Trapper Jim's Fables of Sheepeater Indians in Yellowstone* (1937) are, in the opinion of this historian, "white baloney," that is, faked Indian tales. At the least, if they are real, there is no documentation to prove it.

With all of that as background, we now begin looking at Indian legends in the Yellowstone country by examining the known Indian names for the place. Nabokov and Loendorf, after years of looking at the ethnological, anthropological, archeological, and historical literature and interviewing dozens of tribal members, have concluded that certain Indian tribes did have names for the upper Yellowstone country. Most of those names referred to the park's hot springs and geysers. The Crow Indians called Yellowstone "land of the burning ground" or "land of vapors" while the Blackfeet called it "many smoke." The Flatheads called it "smoke from the ground." The Kiowas called it "the place of hot water." Only the Bannocks had a name that did not call to mind the park's thermal regions: "buffalo country." Additionally, the Crows specifically called the Yellowstone geysers "Bide-Mahpe," meaning "sacred or powerful water."

As for the stories themselves that might have been told about Yellowstone by the Indians, the Ralph Dixey story is thought to be genuine. It is a tale concerning the origin of the Snake and Yellowstone rivers and long known to have been handed down in the Shoshone tribe (both Ralph Dixey and his Bannock wife stated that this story was handed down in both of their families). The story begins with "long ago there was no river in this part of the country. No Snake River ran through the land." A man came from the south who was always sticking his nose into everything. He traveled north past the Tetons and went up onto a mountain in what is now called Yellowstone. There he found an old lady with a basket of fish. Hungry, he asked her to boil some fish for him. She offered to make him food but warned him not to bother her basket. He did not listen, stepped on the edge of the basket, and spilled its water and fish. The water spread all over. The man ran fast, ahead of the water, trying to stop it. He piled up rocks to hold the water back, but the water broke his dam and rushed on. That is where the Upper Falls is today. The man ran on ahead of the water and again built a dam of rocks, but it did not hold the water back either. That is where the Lower Falls is today. The water kept on rushing and formed the Yellowstone River. The man then ran to the opposite side of the fish basket and followed its waters downstream, building several dams of rocks, but the water would not be stopped. Those broken dams are the site of American Falls and Shoshone Falls today on the Snake River. The big fish basket that the man tipped over is Yellowstone Lake while the old woman with the fish was Mother Earth. The man himself was Ezeppa or Coyote (Clark 1966: 191–193).

Until recently this Dixey story was arguably the only known, genuine (truly known to have been told by Indians) Native American story about Yellowstone National Park. But there is now new evidence (per Nabokov and Loendorf) not only as to the fact that Indians told stories about Yellowstone but also as to what some of those stories were. In particular we now have several "new" (actually old) stories known to have been told by the Crow tribe.

A Crow narrative from a man named Sharp Horn, who passed it down to his son who passed it to his grandsons, concerns the mythic deeds of a character named "Old Woman's Grandchild" and how at least two of Yellowstone's geysers were supposedly created. This Crow said that in one of the thermal regions of the park, Old Woman's Grandchild fought many beasts and turned them into mountains and hills after he killed them. A large buffalo bull that he killed was turned into a geyser formation that continued to blow out hot air. Near it he placed a mountain lion, also a geyser formation blowing hot air, in order to keep the buffalo bull from coming back to life (Nabokov and Loendorf 1999: 107).

Another mythic tale, told by the Crow and associated with the park, concerns Yellowstone Lake and what happened to the dinosaurs. A thunderbird grabbed a Crow Indian by his hair and took him to "Overlook Mountain," on the southeast side of Yellowstone Lake, and placed him in a nest there. The thunderbird told the Crow that he wanted him to help him fight the giant water beast that lived in Yellowstone Lake and which ate the thunderbird's young. The Crow built a large fire and heated many rocks and boiled much water. When the beast came out of the lake and climbed up the mountainside, the Indian pitched hot rocks and hot water into its mouth. Steam came out of the monster's mouth and it tumbled down the mountainside and into the lake. Supposedly this was the last "dinosaur," and steam vents around Yellowstone Lake may be remnants of this event, a myth from Crow history (Nabokov and Loendorf 1999: 107–109).

Of course, as Paul Schullery pointed out to me when we discussed this subject, the very idea of dinosaurs and Indian tales generates numerous immediate questions. Is this tale perhaps younger than other such Indian tales? Is it only as aged as the old nineteenth-century white guys who first discovered dinosaur fossils? Or did Indians themselves find dinosaur fossils and generate stories about them long before the nineteenth-century white guys found the "terrible lizards"? Did Indians perhaps have contact with the nineteenth-century white-guy dinosaur hunters and merely generate the story after talking to them? Or is this story just pure "Native American baloney," a faked Indian tale? There are no easy answers to these questions.

From Hunts-to-Die, a Crow Indian born about 1838, we have it that his tribe believed there were spirits in Yellowstone geyser areas who were benevolent and helpful rather than malevolent and dangerous. This tends to correct what is perhaps the worst piece of supposed Indian information about Yellowstone—-the long-surviving but incorrect notion that Indians feared the geyser regions. Even though this piece of white baloney has been thoroughly discredited by Weixelman, Haines, and Nabokov and Loendorf, we can look for it to continue to appear in the shallow, unresearched, and thoughtless writings of popular journalists for years to come. It belongs in the same class of malarkey as the notion that "Yellowstone Park was once called Colter's Hell" (Nabokov and Loendorf 1999: 83; Mattes 1949).

The incorrect notion that Indians feared the geyser regions seems to have originated in Euroamerican literature from a note that William Clark added to his notes after 1809 when he returned to St. Louis. It is not known whence Clark obtained this information, but here is the relevant quote (complete with misspellings and incorrect syntax and punctuation):

> At the head of this [Yellowstone] river the nativs give an account that there is frequently herd a loud noise, like Thunder, which makes the earth Tremble, they State that they seldom go there because their children Cannot sleep—-and Conceive it possessed of spirits, who were averse that men Should be near them (Haines, 1974: 4).

Unexpectedly, the Kiowa tribe is now known to have oral traditions associated with the upper Yellowstone country. The Kiowas, who eventually settled in western Oklahoma, were earlier located in the present Crow country near the headwaters of the Yellowstone River. Lewis and Clark found them below there in 1805 "in seventy tents," somewhat near the Yellowstone Valley. One of their descendants, N. Scott Momaday, has written that around the time of the Revolutionary War the Kiowas migrated from a place near the "headwaters of the Yellowstone River." In this earlier history they were friends and trading partners with the Crows, but nevertheless it was an unexpected surprise for Nabokov and Loendorf to find that the Kiowas had traditions associated with present Yellowstone National Park (Nabokov and Loendorf 1999: 93–96).

Nabokov and Loendorf found what so far may be the most important piece of

Indian "interpretation" associated with present Yellowstone National Park. It is the legend told by the Kiowas about their origins in the present park. It concerns a man whose name no Kiowa remembers but who "was one of the greatest Kiowas who ever lived." The Kiowa informant called him "Kahn Hayn" for the purposes of the story. He said that when Doh Ki, the Kiowa equivalent of the Great Spirit, put people on earth he had no homeland for Kiowas, so he promised them a homeland if they could make the difficult sojourn through a barren and desolate volcanic land where clouds of steam shot from holes and fissures in the ground. Doh Ki called all of the Kiowas around one particularly disturbing steaming pool, a deep caldron of boiling water that surged and smashed against jagged rock walls and made fearsome sounds as if a great beast were just below the surface. Most of the Kiowas ran away, but a few remained, including Kahn Hayn. Doh Ki then pointed to the fearsome pool and said that the land there would belong to the tribe of any man who would dive down into it. While some of the Kiowas did not want this hot land, Kahn Hayn knew that Doh Ki was a benevolent spirit whose rewards were always good and lasting, so he decided to take Doh Ki's test. He dove into the boiling pool and was immediately panic-stricken. He burned and ached and thrashed and lost consciousness. Suddenly he felt himself being lifted from the water by the hands of many Kiowas who were yelling excited, victory cries. As he looked about he saw that Doh Ki had vanished and that the landscape was no longer barren and desolate. Instead it was covered with rich forests, lush meadows, cascading streams, and large animals. This spot in the present Yellowstone National Park was now the most beautiful and abundant of all places on the earth, and it became the homeland of the Kiowas.

The Kiowas today have a name for the place where these mythic events supposedly occurred. It is at the Dragon's Mouth Spring near Mud Volcano in the park, and the Kiowas call it "Tung Sa'u Dah" which means "the place of hot water" (Nabokov and Loendorf 1999: 97–100).

Historians have long argued about whether Ella Clark's tales of Yellowstone in her book *Indian Legends of the Northern Rockies* (1966) are genuine tales passed down by Native Americans or whether Clark made them up herself, either partially or fully, by being careless in how she translated the stories, by failing to tell us enough about who her Indian sources were, or both. Haines and I take the side that we should not always trust Clark, an English teacher with little or no training in history or anthropology. We believe that she was primarily interested in the stories themselves and not in whether they were truly Indian rather than made up by whites, in whether they had been genuinely passed down orally through Indian history, or in how carefully she translated them.

On the other hand, Nabokov and Loendorf take a more charitable view of Clark's book. As anthropologists, they see in her stories a thread of consistency to other parts of Native American folklore (especially, they say, that of the Blackfeet and Flathead) and they tout that connection as evidence that Clark's stories may be genuine Indian tales (Nabokov and Loendorf 1999: 129–132).

But of course one can argue that anyone who has spent a small amount of time reading Indian legends and myths can easily make up new ones in the same vein as the genuine ones that they have just read. I could certainly do it easily, and, in my opinion, this would be the very type of thing an English teacher or journalist might be tempted to do in "doctoring" Indian stories that did not otherwise quite "work" for them. Because Clark talked to a lot of Indians and produced three books on Indian legends in the Northwest, I have no doubt that some if not many of her stories are indeed genuine. But she did such a poor job of telling us where they came from that I remain suspicious of some of them.

As it turns out, however, probably the best known of Clark's Yellowstone legends may well be a genuine Flathead tale. It is the one that she calls "Coyote's prophesy concerning Yellowstone Park," and according to her, it goes like this:

> In generations to come this place around here will be a treasure of the people. They will be proud of it and of all the curious things in it—-flint rocks, hot springs, and cold springs. People will be proud of this spot. Springs will bubble out, and steam will shoot out. Hot springs and cold springs will be side by side. Hot water will fly into the air, in this place and that place. No one knows how long this will continue. And voices will be heard here, in different languages, in the generations to come (Clark 1966: 103).

As one might expect, less-discerning writers, especially journalists, have glommed onto this story like flies to a carcass. They have not been able to resist it, in the apparent belief that surely the story contains some kind of ancient Indian wisdom about Yellowstone that accords with the later "good" judgments of whites about the place, and which must thus somehow give dramatic credence to those judgments. I remain suspicious of the story, because it sounds fake and because Clark did such a poor job of documenting it. It is exactly the type of contrived-sounding piece that white writers would make up as a faked Indian legend. It is written too slickly and has too much perfectly balanced drama in it to ring true as a real Indian legend (which generally are neither slick nor perfectly balanced). The prediction about the pride of future generations sounds European. The business about future voices in different languages seems beyond the reach of the normal Indian legend.

But, again, the story may well be genuine. Clark claims (1966: 79) that most of her Flathead stories came from Pierre Pichette or Bon Whealdon. Pichette was a completely trustworthy source, because he was a blind Indian who spent at least fifty years of his life becoming an authority on the traditions and culture of his people. Clark would have us believe either that Pichette told this story to her from one handed down to him by elders in the summer of 1953 (the year before he died), or else that Bon Whealdon told it to her. Whealdon came to Montana's Flathead reservation in 1907, and he too spent many years gathering information on the Flathead culture. Unfortunately, Clark not only does not tell us exactly from where she got the story or when, but her citation (1966: 366, 376) lists only an article by herself, "How Coyote Became a Sachem," as the source. Worse, the story does not appear in a pamphlet by Pichette found and cited by Nabokov and

Loendorf. Thus, while I am suspicious of this Yellowstone legend, if it truly came from Pichette or Whealdon, it must be a genuine Flathead story rather than a piece of white baloney.

Another of Clark's stories, "Defiance at Yellowstone Falls" (1966: 361–362), is a fascinating mystery. It is the supposed Crow legend of thirteen Crow braves and five Crow women taking a raft over Lower Falls to their deaths in a suicide story that Clark says originated because the Crows wanted to escape the U.S. Army. She attributes it to Charles M. Skinner's *Myths and Legends of Our Lands* (1896), and indeed a look at that book reveals that Clark merely rewrote Skinner's "A Yellowstone Tragedy" (Skinner 1903: 204–206).

We do not know whence Skinner got the story, but he may have gotten it from Charles Sunderlee. Sunderlee's version appeared many years earlier in a purported news story in a Helena, Montana, newspaper *(Helena Daily Herald,* May 18, 1870) under the headline "A Thrilling Event on the Yellowstone" (Kearns 1940). There, Sunderlee listed the five members of his party and claims that they witnessed the event above Lower Falls on April 2, 1870. Suspiciously, none of the five men he mentioned appeared in the 1870 Montana census. Haines dismissed the Sunderlee story as fiction inspired by Clark's Crow Indian legend (Haines 1974: 40–41; 1977: 339n49).

At first I thought that Sunderlee's newspaper story might have inspired a fake (white) Indian legend that Skinner and Clark passed on. After all, there is no hint of U.S. Army soldiers chasing Crows in the upper Yellowstone country in 1870, as Skinner and Clark say, and in fact Sunderlee says nothing about soldiers being present. And, too, Sunderlee's story is 26 years older than the first known appearance of the legend (some of its details seem at least partially convincing as a news story). But later I found that it was not that simple.

Two present-day Crow experts know nothing about this supposed legend. When I ran the story past Burton Pretty-on-Top, the current chairperson for the Crow Tribal Cultural Committee at Hardin, Montana, he told me that it sounded like "hogwash" to him. "Crow people do not kill themselves," he said to me. He also stated that he knew of no Crow historians nor "tribal elders" that had ever passed this story on in oral history as a Crow legend, at least to him. While he was not familiar with Clark's book, he stated that he had read numerous comparable works by white authors, and he stated that all too often he would have to "put these books down without finishing them" because they were filled with so much bad information. I also spoke to Tim McCleary, head of General Studies at Little Bighorn College, Hardin, Montana, and a Crow expert. He too was suspicious of the Clark "legend," but cautioned me about how easy it was to be wrong about such things, regardless of which side one is on. He had read the Clark version of the legend but had never heard it in any other form (meaning from Crow elders or otherwise in Crow oral history). He agreed with Pretty-on-Top's assessment of Crows generally not committing suicide, and expanded on that, saying that those beliefs were based in Crow religion. McCleary says that the Crow belief was and is that if one commits suicide, one's spirit will remain on earth rather than ascending to some promised land, so they do not generally commit suicide. McCleary was also suspicious of the idea of Crow Indians being on rafts or boats, because “they tend to avoid boats and water and getting onto water” (Pretty-on-Top 2000; McCleary 2000)

But even with all of this evidence for the proposition that Clark’s “Defiance” legend is false, Haines points out that Clark got a number of her Indian stories from military man Lt. James A. Bradley. A look at Bradley’s long Crow discussions makes it clear that Bradley did get a lot of stories, legends, and general information during the period 1871–1877 from Little Face and numerous other Crows (Haines 2000; Bradley 1917: 197–250). If Clark truly got the story from Bradley (and one of his stories bears some resemblance to it) rather than pirating it strictly from Skinner, then perhaps the Crows do (or did) have such a suicide legend even though certain Crow experts have never heard it. All in all, I do not know what to think about this convoluted mess.

These problems with both Clark’s “Defiance at Yellowstone Falls” and her “Coyote’s prophesy concerning Yellowstone Park” point up the difficulty of determining whether or not some reputed Indian legends are truly Indian. They also point up how easy it is for any of us to get confused when white baloney, known or suspected, enters the picture. For those of us who do not always trust the vagaries of oral tradition (was the story passed down correctly by one person and was it remembered/retrieved correctly by another, especially over many generations?), having to worry about white baloney adds one more complex and troubling wrinkle to the equation.

And these problems also point up the reasons why all researchers, including those who talk to Indians simply to write down their stories, must be meticulous in documenting their sources. We must be certain that we ask the tribal person conveying the story to us (1) from whom he heard the story and (2) whether others in his tribe have also heard it. These two questions are important because they give us clues as to both the antiquity of the story and how widespread it is (or was) within the tribe. For example, I am a lot more willing to believe Joe Medicine Crow’s story if he tells me that he heard it from his 100-year-old grandmother than if he tells me he isn’t quite certain from whom he heard it but only that he remembers hearing it. And, too, I am a lot more willing to believe that the story is truly established within the tribe if I also hear from several other tribal members that they heard it from their forebears.

Finally, we should end by making one thing perfectly clear even if some of this is murky. While Indians appear not to have feared the Yellowstone geyser regions, we know that many tribes revered them. Revere and fear are two different things, reverence referring to beliefs in something sacred. There is much evidence put forth by Weixelman, Haines, and Nabokov and Loendorf that a number of tribes considered the Yellowstone country sacred and used it as a vision-questing, prayer-making, and gift-bequeathing place, and there is much other material in their writings that disproves the theory that Indians feared Yellowstone.

These few known Indian stories then, and probably dozens or even hundreds of others that are now lost to us or perhaps still in the oral traditions, were among the first known attempts to interpret the strange Wonderland country at the head of the Yellowstone River.

[Ed. note: This paper represents the first chapter, with title and text somewhat modified, from the author's upcoming book *Yellowstone's Horse-and-Buggy Tour Guides: Interpreting the Grand Old Park, 1872–1920,* which is as yet unpublished.]

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Conservationists and the Battles to Keep Dams Out of Yellowstone: Hetch Hetchy Overturned

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Abstract

Between 1919 and 1938 irrigation interests in Idaho, Montana, and Wyoming repeatedly tried to construct reservoirs in Yellowstone National Park by damming several large park lakes and Bechler Meadows. Conservationists of the time joined forces with Horace Albright and Steven Mather of the National Park Service to oppose the dams. Ultimately successful in all their efforts, their key victory came in 1923 when they defeated an attempt to dam Yellowstone Lake. This victory reversed the loss of protected status for national parks that had occurred just ten years earlier at Hetch Hetchy Valley in Yosemite National Park. By chronicling the protracted conflict over dams in Yellowstone, I illustrate that the conservationists (including Mather and Albright) reestablished the fundamental preservation policy of the national parks and empowered the newly created National Park Service to carry out its mission of park protection. This effort was the key battle in proving national parks and wilderness to be inviolate to industrial, exploitive uses. Conservationists both defined and tested the inviolate policy in Yellowstone; their battles in Dinosaur National Monument and the Grand Canyon cemented it into place.

Introduction

Far off, there lies a lovely lake
Which rests in beauty, there to take
Swift pictures of the changing sky,
Ethereal blues, and clouds piled high.

When black the sky, when fall the rains,
When blow fierce winds, her face remains
Still beautiful, but agitate,
Nor mirrors back their troubled state.

Within a park this treasure lies, —
Such region ne'er did man devise —
The hand of Mighty God, alone,
Could form the Park of Yellowstone.

Deep gashes score its rugged face,
Where mighty rivers fall and race,

Where upflung pinnacles stand high,
With aeries crowned, whence eagles fly.

From some deep caldron, does it seem,
Come boiling springs that hiss and steam,
And Sullen mouths pit bubbling mud
Like o'erfed cattle retching cud.

There splendid geysers fling in air
Their plumes of mist — a sight most rare —
And terraced springs lip o'er the rocks
Enrobing them with crystal frocks.

Forever thus inviolate
May this our heritage of State
Untroubled lie, our Country's trust,
Protected from men's greed and lust,

Lest they the lesson fail to learn,
That though they struggle, pray and yearn,
God's wasted gifts come not again;
Men's follies — these, alas, remain!

Remain to rob the future ones
Who follow us, our daughters, sons.
They share with us, not ours alone,
Is beautiful Lake Yellowstone.

Molest it not, nor seek to bind
Its water, lest we find
'Tis not the Lake, alone, that can
Be dammed, — but soul of ruthless Man!

—Anna Elizabeth Phelps, "Yellowstone Lake" (1938)

Yellowstone's southwest corner is called "Cascade Corner" because it contains twenty-five well-known and seventy-two lesser-known waterfalls (Rubinstein, Whittlesey, and Stevens 2000). It was highly contested terrain in the 1920s and 1930s. Irrigators from Idaho, to which state the local rivers drain, attempted to dam the Bechler River and its tributaries at several different times in order to store water for summer irrigation. Not to miss having its piece of the pie, Montana irrigators proposed the same thing on Yellowstone Lake. Both groups tried numerous times and in different ways to accomplish their goals, but neither group ever succeeded. Park administrators and conservationists nationwide rose to the defense of the park, defeating the irrigators time and again.

The battle pitted farmers struggling for economic survival against conservationists attempting to uphold the integrity of national parks. Local agricultural interests took on powerful national preservation interests. Gifford Pinchot's utilitarian conservation dominated public lands policy during this era, but in this case the preservationists won out and Yellowstone's waters were not impounded.

Coming hard on the heels of the Hetch Hetchy controversy in California (see Cohen 1988), many conservationists grasped the parallel in this battle. Unlike Hetch Hetchy, however, the park protectors won, establishing the policy that national parks were and are inviolate to industrial, exploitive uses. This policy, as with most such policies, would be tested time and again, both in Yellowstone and in other parks, such as Dinosaur National Monument in Utah in the 1950s. While the policy continues to be tested today, it was the dam battle of Yellowstone that reversed the Hetch Hetchy precedent, thereby illustrating that parks are to be preserved inviolate.

This story will relate the conflict between reclamationists and conservationists over dams in Yellowstone from 1915 to 1938. I will examine the motives of both sides and the methods they used to further their ends. Finally, I will conclude with a discussion of the significance of this "battle" in national park conservation history. Because the conservationist victory was so important in national park history, I will focus primarily on their efforts to prevent the dams, while attempting to present the irrigators' perspective.

The First Round of Dam Proposals: "Hands Off the National Parks!"

Background. In much of Idaho and western Montana, geography challenges agriculture. Areas that receive adequate annual precipitation for agriculture are generally too high and cold to support it, while areas warm enough for agriculture do not generally receive sufficient rainfall. Farmers have typically solved this problem by irrigating their cropland with water from the moist mountains. In the early part of the twentieth century, natural river flows provided enough irrigation water during most summer seasons, but in extreme droughts even large rivers such as the Snake were completely dewatered by irrigators (Fiege 1999). At such times, the irrigation channels ran dry, leading to the failure of the farmers' crops. The summer of 1919 was one such summer; farmers in Idaho lost over $10 million in failed crops.

To solve such problems, irrigators throughout the West began damming the region's rivers in the early 1900s to store the excess spring runoff for later summer use. In this way, they provided themselves with a form of natural insurance against the inevitable drought. Drawn upon in all years, the reservoirs were especially important during times of drought. Reservoirs such as the Jackson Lake Reservoir in Wyoming (upstream on the Snake River) were built during this period.

Beginning in 1915, farmers in eastern Idaho's Fremont and Madison counties began to search for a reservoir site to provide themselves with more reliable irrigation. They formed the North Fork Reservoir Company to pursue the reservoir, and focused on a potential dam site on the Falls River in Yellowstone's Cascade

Corner (Berlin 1915; Colonel of Cavalry 1915; Hillman 1916; Martin 1917; Albright 1985; Bartlett 1985; Fiege 1999). The U.S. Geological Survey had identified this potential site in its planning for the Jackson Lake Reservoir in 1902-1903 (U.S. Geological Survey 1904: Plate 34). When the drought of 1919 struck, the farmers increased their agitation for the reservoir. In their favor was the political climate of the era, which favored reclamation, and the Hetch Hetchy precedent, which made damming in national parks possible. Against them, however, were zealous leaders of the recently established National Park Service (NPS) and its growing group of supporters in the conservation community. The stage was set for controversy.

The battle: three major threats. Under the auspices of the Fremont–Madison Reservoir Company (evidently descended from the North Fork Reservoir Company), the farmers approached Secretary of the Interior Franklin K. Lane to receive permission to build two dams in the Bechler region (the second dam on Mountain Ash Creek, a tributary to the Falls River). They also persuaded Senator John Frost Nugent and Representative Addison Smith of Idaho to introduce bills into Congress in early 1920 enabling the Bechler dams. On 6 April, the Senate passed Nugent's bill, S. 3895, with little opposition, but the House version (H.R. 12466) stalled (Lovin 2000). The farmers also proposed damming Yellowstone Lake and diverting its waters under the Continental Divide via a tunnel they would construct, but this proposal was never introduced into Congress *(Livingston* [Montana] *Enterprise,* 7 December 1919; McMillen 1920).

With missionary zeal the farmers promoted the Falls River project. They were Pinchot's yeoman farmer, extending American society throughout the interior West. They noted that

> Idaho is dependent entirely on the development of its agricultural resources by irrigation for further growth and prosperity. This development can only progress by the conservation of our water resources through the construction of storage reservoirs....[The Falls River reservoir] will be entirely devoted to the creation of happy farm life and prosperity....At a time when the world is largely filled with unrest, due to Bolsheviki activities in Russia and elsewhere,…it is well to remember that the owners of farm property and the people who are tilling their own soil are not Bolsheviki but really constitute our most loyal and patriotic American citizens (Fremont-Madison Reservoir Company 1920).

Agriculture, and thus reclamation, were the cornerstones of the great society all Americans wanted.

The Falls River project was only the first of three substantial reclamation threats to the integrity of Yellowstone that surfaced in 1920, as farmers throughout the region attempted to conserve the region's water with dams in Yellowstone. The second major threat arose from the discussions of a Livingston, Montana, group called the "Yellowstone Irrigation Association." This group formed in December 1919 to promote the construction of a dam at Fishing Bridge, the outlet of Yellowstone Lake. The stored water could then be sent down the Yellowstone River to irrigate farmland in the lower Yellowstone valley. Senator Tom Walsh of Montana formalized this proposal with a bill he introduced on 7 December 1920 *(Livingston Enterprise,* 7 December 1919). This group later tried to unite Idaho, Oregon, Washington, Montana, Wyoming, and Utah in a collective reclamation raid on the national parks ([Mather] 1920; *Northern Wyoming Herald,* 28 July 1920; Ise 1979). The interstate coalition, however, was weak at best, and so the Irrigation Association focused its efforts on the Yellowstone Lake dam.

Like the Idaho farmers, the Montana irrigators envisioned a better society in the Yellowstone Valley if the Yellowstone Lake dam were built. They felt it would both reduce the damaging floods wrought by the Yellowstone River and also provide enough water to irrigate up to a million acres. Promoters believed the dam and consequent agricultural development would thereby stimulate development of the region's cities; the population of Livingston, for example, was forecast to reach 50,000 *(Livingston Enterprise,* 19 March 1920). Utilitarian conservation ideas are evident in their rhetoric:

> The volume of flow in the Yellowstone river is twenty-six times as much during the flood period in the spring as it is during the irrigation season in the late summer.…The river becomes a veritable torrent. This enormous volume of water runs to waste. Not only is there a waste of water and energy but the raging torrent does a damage that runs into the hundreds of thousands, even millions of dollars (Yellowstone Irrigation Association 1921).

The third significant threat came from Congress' passage of the Water Power Act on 10 June 1920. This act created the Federal Water Power Commission, which promoted irrigation and hydroelectric development on federal lands, *including the national parks.* While not as immediate a threat to Yellowstone's integrity, the act posed a broader threat to the National Park System in general, because it gave this commission blanket authority to impound waters in the parks without congressional approval. Reclamationists saw the act in another light, as one would expect: they believed that "the greatest beauty in the world is the beauty of use;" and "[i]f the United States is to compete with Europe in foreign trade it must at least have cheap power for industrial use" *(Electrical World* 1920).

By the end of 1920, Yellowstone was facing a three-pronged attack on its integrity. Should any of the three proposals pass, Yellowstone would cease to exist as a pristine national park. Because Yellowstone was the gem in the crown of the National Park System, a weakening of its protection would probably lead to the fall of the entire system. What happened in Yellowstone, then, was key to the future of wilderness preservation in the United States. The reclamation threat, while supported by well-meaning people, did indeed have far-reaching implications.

Conservationist response. NPS and its conservationist supporters, then, were faced with an attack that threatened to make Hetch Hetchy commonplace throughout the National Park System. Park supporters responded in 1919 and

1920 with an aggressive campaign to protect national park integrity. They began with immediate action to stymie dam surveying efforts in the parks, then followed that by publicizing the threats to the parks in the popular and conservation press and urging readers to write in defense of the parks. Political and civic actions rounded out their repertoire of defensive actions. The odds were long, though, given the reclamation fervor of the day. Still, if they could not defend Yellowstone's integrity, what would remain of the national parks?

Secretary of the Interior Lane favored reclamation, and was thus sympathetic to the proposal of the Fremont–Madison Reservoir Company. He ordered NPS Director Stephen Mather not only to allow a reclamation survey of the area but also to follow that with a report *favoring* the project. There is evidence to suggest that Mather did not originally oppose the dams. In a letter to him, J. Horace McFarland of the American Civic Association stated: "I view with deep regret and great alarm the fact that you have formally consented to the passage of the bill,…and have apparently advised the Secretary of the Interior to interpose no objection to it" (McFarland 1920b; *Livingston Enterprise*, 28 May 1920). Regardless of whether this is true, it is clear from his following actions that Mather strenuously opposed the dams. As director of the country's newest public conservation agency, he was not about to endorse another such Hetch Hetchy degradation of the National Park System. So, he initially dragged his feet on the report, then lost the order directing him to do it, then determined to resign if he indeed had to submit it (Bartlett 1985). The report he finally did submit was adverse to reclamation, stating:

> I can not submit at this time anything but an adverse report on this project, and urge upon you as strongly as I can the necessity for taking no favorable action upon it. Should I take any other view, as I see it, I would be violating the obligations imposed upon me as Director of the National Park Service, which is to so administer Yellowstone Park that it be preserved in its natural state unimpaired for future generations (Mather 1920b).

Lane was intent upon surveying Yellowstone's reclamation possibilities, however. On 28 July 1919, he directed that a permit be given to I.B. Perrine of Twin Falls, Idaho, to make a preliminary reclamation survey of the Falls River Basin and all four of the park's large lakes. Acting NPS Director Arno Cammerer telegrammed this information to Horace Albright, the superintendent of Yellowstone, who responded in a telegram:

> Any or all of these projects will ruin absolutely Yellowstone Park for public use. Hetch Hetchy project in Yosemite [is] insignificant in comparison. Public condemnation of these projects will be a thousand times more vitriolic.…Fall River Basin might well be surveyed but am sure construction [of] dam will cause wiping out our biggest moose herd (Cammerer 1919; see also Albright 1919).

A few days later, Lane carried through with his directions, granting the permit to Perrine, who was thus headed to Yellowstone for his survey. To warn Albright, J.J. Cotter of the Interior Department sent an encoded telegram stating:

"Unvouched seamanship sardachate toponym to perrine to subacute preliminary venge in fistful." Decoded, the message meant, "Secretary of the Interior has given authority [to Perrine] to make preliminary surveys in Yellowstone Park" (Cotter 1919). Alerted by the telegram, Albright scrambled to stymie Perrine. Because it was late in the tourist season, he sent the horses that Perrine would need for his survey to winter pasture early, and directed the boat company to put up its boats for winter storage (Albright 1985; Bartlett 1985). These actions kept Perrine from fully surveying the park, but he was still able to survey the Falls River Basin and Yellowstone Lake, and recommended both for impoundment (Bickel [n.d.]). Even though Albright was able to partially deflect the irrigators' onslaught, they had obtained enough information for their needs, and the threat persisted.

To help protect the parks against such threats, Mather had helped form the National Parks Association (NPA; today's National Parks Conservation Association) in 1919. Led by Robert Sterling Yard, the young organization jumped into the dam fray the following year. Yard editorialized against the dams in his organization's journal and issued a special magazine whose lead article was entitled "Hands Off the National Parks" ([Yard] 1920a). He consistently urged association members and the public "to the defense" ([Yard] 1920b). Realizing that his small circulation was inadequate for the size of this challenge, he pulled together a network of "more than 12,000 clubs and associations throughout the United States, representing paid memberships of nearly four million people in opposition to the dams" (Yard 1922a). The Appalachian Mountain Club, Sierra Club, Mazamas, and Mountaineers assisted him in setting up regional organizations to address the issue in Boston, Chicago, San Francisco, Portland, and Seattle. Yard's network of groups was impressive and diverse:

> By Christmas [1920], the organizations actively at work included business associations of various kinds, chambers of commerce, teachers'clubs and federations, shooting and fishing clubs, manufacturers' associations, patriotic leagues, automobile associations, travel and outing clubs, universities, bar associations, nature study clubs, political clubs and all the greater scientific associations in the land (Yard 1922a).

Yard also networked with the country's women's organizations, specifically thanking them twice in the *National Parks Bulletin* for their strong stance against the dams ([Yard] 1920c; [Yard] 1921a; see also McMillen 1920). The number of cooperating associations bears witness to the gravity of this threat upon the idea of the national park.

Some of Yard's most active allies were the conservation groups in existence at the time. For example, the Audubon Societies of America sent out 25,000 circulars calling for letters in opposition to the dams and soliciting donations, which they used as a "National Parks Defense Fund" *(Bird Lore* 1921b). Yard was successful in uniting virtually all the country's conservation groups in opposition to the dams, including the Sierra Club (Sierra Club 1920), Boone and Crockett Club *(Livingston Enterprise,* 12 December 1920), and National Geographic Society

([Yard] 1921a). Of all the groups, though, his, the NPA, was most consistent in its defense of Yellowstone and was arguably the leader of the conservationist battle against the dams (Miles 1995).

Yard and Mather knew that the national parks were David battling the reclamation Goliath. They had to reach as wide an audience as possible, so they also published defenses of Yellowstone in popular or civic magazines. Both men were well connected with the leading conservationists of the day, such as George Bird Grinnell, Emerson Hough, McFarland, and the editor of *The Outlook,* a popular magazine similar in style to *The Nation* or *The Independent.* The editor (who remains unidentified, his or her name not being given on the masthead) closely supported Yard in opposing the dams and was clearly the opposition leader in the popular press.

Together, the American conservationists worked against the dams throughout 1920 and 1921. They frequently reported on the congressional progress of the dams and urged readers to write their representatives in opposition (see *National Parks Association Bulletin,* no. 10, 25 June 1920; no. 11, 30 September 1920; no. 13, 20 November 1920; no. 14, 22 December 1920; no. 15, 10 February 1921; nos. 16 and 17, both 20 March 1920; and no. 19, 23 May 1921; see also *The Outlook,* 7 July 1920, 28 July 1920, 8 September 1920, 6 October 1920, and 12 January 1921). Reclamationists were busy, too, promoting the dams. Five key issues emerged in the rhetoric, with the reclamationists and conservationists at loggerheads. An examination of these themes follows.

Major theme 1: dangerous precedent. Conservationists deplored the fact that if these dams were permitted, they would set a dangerous precedent, opening all national parks for commercial exploitation. McFarland, president of the American Civic Association, was the first to see this threat. In an article in *The Independent* on 8 May 1920 he called Smith's bill "the entering wedge of commercialism" (McFarland 1920c). Yard picked up on this fear shortly thereafter, and repeatedly articulated it: "One thing we certainly know, and that is that *the granting of even one irrigation privilege in any national park will mark the beginning of a swift end; within five years thereafter all our national parks will be controlled by local irrigationists, and complete commercialization inevitably will follow"* ([Yard] 1920d: 6; emphasis in original). He strongly felt that this was a nationally significant threat, stating: "[The Walsh bill] constitutes the most insidious and dangerous blow ever aimed at American Conservation, because it seems to ask for so little while really demanding the entire National Parks System, for if Congress grants Senator Walsh his way with Yellowstone it cannot refuse to grant others their way with other national parks" ([Yard] 1921b: 1). Mather agreed with Yard and McFarland, stating that "one misstep is fatal" ([Mather] 1920: 34)

The Hetch Hetchy precedent was indeed a welcome mat for the irrigationists. In its literature promoting the dam on Yellowstone Lake, the Yellowstone Irrigation Association noted that "[t]here is already a dam in Yosemite park, by congressional permission." Although the association went on to argue that Hetch Hetchy was not a precedent, they clearly knew about it—and were promoting the same idea in Yellowstone (Yellowstone Irrigation Association 1921). Downplaying the similarity did not remove the threat.

Conservationists were quick to grasp the Hetch Hetchy parallel, and knew the Yellowstone attacks were key to overturning its precedent. *The Outlook's* editor was the first to articulate the parallel in an article entitled "Another Hetch Hetchy," published 7 July 1920. Evidently, the editor felt that the Hetch Hetchy story was so well known that he did not include explanation of it or of its parallel to Yellowstone in that article *(The Outlook* 1920a). McFarland made the parallel more explicit in *The Outlook* three weeks later, but seemed to downplay Hetch Hetchy's significance, perhaps out of fear it would be repeated. For example, he felt that the Yellowstone dam situation was more significant than Hetch Hetchy because the dams on Yellowstone Lake would ruin a key feature of Yellowstone, where the dam at Hetch Hetchy did not impair Yosemite's key feature, the valley. Further, he felt that the fact that few people would benefit from damming Yellowstone, as opposed to the great numbers of San Franciscans who benefited from damming Hetch Hetchy, made the Yellowstone dams all the more egregious (McFarland 1920d). Further evidence that conservationists saw, and feared, the parallel is the fact that they referred to Hetch Hetchy only two more times through 1938—in Mather's annual report for 1920 and in an article by Hough in *The Saturday Evening Post* the same year ([Mather] 1920; Hough 1920).

Fear of a dangerous precedent was a very common theme articulated in the literature at that time. Table 1 summarizes other authors and journals that mentioned it in some way.

Major theme 2: populism. Irrigators felt they needed the dams to build democratic society in the West—the same thing Easterners had already done. When they encountered opposition to their dam proposals, they felt as though the Easterners were intruding into someone else's business, as if wealthy elites were dictating how they should be allowed to run their lives. "I am getting a little tired," said Major Fred Reed, managing director of the Idaho Reclamation Association, "of having everything that the West tries to do, opposed by those super-men of the East, who stand with their heads in the clouds, agitating against the constructive development of the West..." ([Reed] 1920: 7). This was a common perception at the time, particularly repeated in the *Livingston Enterprise:*

> Montana shall never build up manufacturing industries in Yellowstone National park if George Byrd [sic] Grinnell, professional conservationist and writer of New York, can prevent. That Montana capital is getting ready to exploit Yellowstone park and turn it into one vast factory in [is] Grinnell's latest nightmare.…Mr. Grinnell should stick to his legitimate field *(Livingston Enterprise*, 11 May 1920; see also *Livingston Enterprise*, 4 June 1920, and *Boise Statesman,* 26 April 1920).

Yet, the national parks are national property, so the conservationists justifiably felt the dams intruded upon public property. The populism argument—that few would profit at the expense of the many—was articulated especially by *The*

Outlook. The few to profit were the irrigationists, who clearly stood to gain by damming Yellowstone waters. The many to lose were the citizens of the United States, who owned Yellowstone and would lose its resources under water. Writing in *The Outlook,* McFarland characterized irrigationists as a thoughtless minority:

> That their claims and desires are as wholly selfish as that of any others who would take the public property for private benefit is also obvious....[I]t will cost more money if these men must pay, as other irrigation farmers now pay, for developing their own sources of water. They desire, to put it plainly, to profit at the public expense...(McFarland 1920d: 578).

The Outlook found the fact that some dam proposals called for government financing of the dams to be particularly galling: "It is bad to have natural resources, which belong to the people, taken by private interests; it is worse to have these resources used for exploiting the people who really own them; it is unbearable to require the people to pay for building the plants to be used in the exploitation" *(The Outlook* 1920b: 68). The magazine's editor continued questioning these "anti-Progressive" dams into the next year (Waugh 1921).

The populist argument took other tacks as well. Mather, for example, in his report to Lane, noted that other reservoir sites were available (such as Henry's Lake on the upper North Fork of the Snake River), but would involve the pur-

Table 1. Other authors and journals that argued against the precedent of damming in national parks.

Author/Journal	**Relevant Quote**
Joseph Bird Grinnell (1920).	"There is now before Congress a bill that alarms all conservationists because it threatens the integrity of the Yellowstone, our most important national park, and if it should pass would establish a precedent for commercial demands on other national parks all over the country."
Field and Stream (1920, n.p.).	"Let us, the people, create our own precedent right here, with this 'beneficent' bill. Let us demand that Congress declares itself by soundly defeating this sneaking beginning of a great conspiracy to destroy the glory of our national parks, ..."
Robert Sterling Yard (1920, 208).	"The irrigation attack is centered on Yellowstone Park, but its success will furnish precedent for a score or more of projects already organized to seize the waters of other national parks."
Emerson Hough (1920, 95).	"It was only the prompt objection of Secretary Payne that kept irrigation dams out of Yellowstone Park. The other parks would have been merely a matter of detail. It would have been Hetch-Hetchy everywhere."
William E. Colby and William Frederic Bade (1920, n.p.).	"Lose no time in writing to the three men ... who represent you in the Senate and the House, ... that Congress establish the policy of holding our parks inviolate against all commercial exploitation."
Bird Lore (1921a, 65).	"Already other commercial interests are looking forward to repeating the benefit from the precedent they expect to be set by Congress in passing [the Smith Bill]."
Colorado Mountain Club (1920, n.p.).	"Such legislation is vicious in itself and would create a precedent dangerous, insidious, and utterly at variance with the interests of the whole people..."

chase of private lands. He felt that the irrigationists were pursuing the Yellowstone sites because they were less expensive, and wondered: "Are we justified in allowing the use of national park lands just because they belong to the government and could be developed with less expense?" (Mather 1920b). Other authors who used such populist arguments against the dams included Hough in "Pawning the Heirlooms," a very influential *Saturday Evening Post* article, and T. Gilbert Pearson of the Audubon Society (Hough 1920; [Pearson] 1921; see also *American Forestry* 1920).

Major theme 3: landscape character. Irrigators believed that their dams would not threaten, but would rather enhance, park resources. The Bechler dam "will result in replacing what is now mostly an unattractive swamp with a mountain lake" (Swendson 1920: 6). The swamp had "no value or scenic beauty, but [was] infested with flies and mosquitoes during the summer months." Besides eliminating the swamp and its pests, the reservoir and its attendant roads would provide greater access to this area of the park, thereby reducing the fire danger (Bickel 1920: 8). In a similar manner, the Yellowstone Lake dam would enhance the park by replacing Fishing Bridge, a "rickety old pile structure," with "[a] permanent, artistic bridge." Further, the topography surrounding Yellowstone Lake was steep, meaning few banks of mud would be created and few trees drowned through inundation (Yellowstone Irrigation Association 1921).

As one would expect, conservationists felt differently. They thought nature was beautiful in its intact condition. For them, extolling the virtues of the threatened areas was another successful argument, though they found themselves scrambling to determine just what the virtues of the Bechler region were, as it was not well known (almost fifty years after the park was created!). To answer the question, William C. Gregg, a New Jersey member of the NPA, explored the area in 1920 and again in 1921. He was very impressed at the waterfalls in the Bechler region, stating "those areas of the park contain divine beauties of which the men who fixed the limits of the park had no knowledge whatever.…[We] found more falls and cascades than in all the known parts of the park put together" (Gregg 1921: 469). Likewise, he claimed that the "Bechler Valley is the widest, most level and most beautiful in the Yellowstone National Park" (Gregg 1920: 83). His findings were widely reported in the press at the time ([Mather] 1921).

Besides its beauties, the Falls River basin was important for wildlife, particularly for moose. As with most wildlife, moose populations were reduced throughout the West at this time, with the Bechler region remaining a stronghold for them. Conservationists noted the obvious implications of the Bechler dams for moose: "If Congress passes [the Smith] bill, Congress will sign the death warrant of one of America's noblest wild animals…the famous Yellowstone moose" *(Field and Stream* 1920; see also Hough 1920; Mather 1920a).

Yellowstone Lake's virtues were easier to promote, as the lake was well known. Dams there would flood important resources overlooked by the irrigators, such as the white pelican rookery on the Molly Islands and geothermal features such as the Fishing Cone at West Thumb. Mather and Albright estimated that a 25-foot dam on Yellowstone Lake (the average of the various proposals) would flood about 9,000 acres, much of that in the low-lying Pelican and upper Yellowstone river valleys. In flooding them, "several thousand acres of the finest feeding grounds for elk, deer, and other game would be made worthless" ([Mather] 1920: 26; see also *The Outlook* 1920c; Mather 1920a; Hough 1920; [Yard] 1921b). George Shiras III (for whom the Shiras subspecies of moose found in the northern Rockies is named) publicized the resources of the remoter portions of Yellowstone Lake in *Forest and Stream* in February 1921. He noted: "By raising the Lake to the proposed level, all the sand beaches, coves, and all the islands…would be obliterated, while the water would cover the lower delta of the Yellowstone for a number of miles," thereby destroying important waterfowl and moose habitat (Shiras 1921).

Conservationists such as Gregg frequently used emotive and quasi-religious language to describe the area, thereby conferring such values on the place and stimulating public response. Gregg's description of the "divine beauties" of the Bechler region is one example, as is Hough's descriptions of Yellowstone as a place made by God, an "heirloom," and a place "sacred, never to be parted with" (Hough 1920: 12). Yard used such imagery as well, stating that "the essential quality distinguishing National Parks…is their condition of untouched Nature, their status as museums of the original American wilderness…" ([Yard] 1920b: 2). Conservationists consistently used such language to describe Yellowstone, giving it a sacredness that made the proposals to exploit it all the more offensive.

Major theme 4: reservoir characteristics. Reservoirs are ugly when drawn down, exposing bare mud along the shores. Irrigators were aware of this problem, and tried to minimize the "virtual" impact of that mud. For example, Idaho's Commissioner of Reclamation, Warren G. Swendsen, stated that "it is true, upon certain years of extreme drouth, [reservoir water] will be drawn out for irrigation uses, or partly so, at least during the period of perhaps two or three months" (Swendsen 1920). Swendsen's use of qualifiers befits his governmental position. Others felt that some sacrifice in beauty was necessary to build the good society: "Beauty is only skin deep; but usefulness combined with beauty is a wonderful combination and a blessing to those who have this, and a joy to all" (Bickel 1920). Note the theme of utilitarianism here, a theme far more common in reclamationist literature than that of natural sacredness. Irrigators believed in what they were doing, failing to see how dams could threaten the national park idea.

The conservationists found the muddy banks of a reservoir an easy weak spot to attack. Facilitating their dam opposition was the presence of Jackson Lake just south of the park, a handy example of what an irrigation impoundment would do to Yellowstone's natural scenery. The U.S. Reclamation Service (now Bureau of Reclamation) had raised the level of the natural Jackson Lake with a dam in 1907 (expanding it further in 1911 and 1916), but failed to log the inundated trees at that time. Consequently, there were "dead trees everywhere about its boundaries [that] pollute the water and kill the fish" ([Mather] 1920: 23). Further, as irrigators gradually drained the lake to its natural level every summer, they exposed a bathtub ring of mud around it. Conservationists found this deplorable; for example, *The Outlook* noted that “the gradual drawing down of [Yellowstone Lake’s] water ... will almost certainly leave those shores slimy, marshy, and depressing, just as the same process has utterly ruined the once notable beauty of Jackson Lake…” *(The Outlook* 1920c: 255; see also McFarland 1920d; [Mather] 1920).

Major theme 5: factual problems. In their zeal to see the dams built, proponents may have exaggerated their benefits. For example, they felt that both the Yellowstone Lake and Bechler sites were the only or best sites available, when in fact there were other potential sites downstream (Swendsen 1920; Yellowstone Irrigation Association 1921).

Conservationists were quick to note the factual problems evident in the promoters’ proposals. In his “Pawning the Heirlooms” article, Hough noted several problems. First, a dam on Yellowstone Lake would do little to control the floods plaguing the lower Yellowstone River valley, because many large tributaries joined the Yellowstone downstream of the lake and upstream of the suffering communities. Next, he pointed out an obvious dam site at Yankee Jim Canyon, about fifteen miles north of the park. This site would more effectively control floods, and would not inundate park land (recall that conservationists such as Mather made the same point regarding the Falls River Basin dam). Finally, he speculated that a dam on Yellowstone Lake “would disarrange and probably sometimes wipe out both falls of the Yellowstone River; would ruin the Grand Canyon some or all the time, leaving it the pathway of a mill-pond creek” (Hough 1920: 98).

In testimony at a congressional hearing on the Walsh proposal (see below), George Goodwin, chief engineer of NPS, concisely articulated the same points. Additionally, he noted that the additional six feet of water storage that Walsh’s dam would produce was only adequate to irrigate 20% of the acreage claimed by Walsh ([Yard] 1921b; see also Mather 1920c). In the end, none of the dam sites downstream were ever used.

Initial controversy resolved. Going into 1921, then, reclamationists had the upper hand, merely because theirs was the cause célèbre throughout the West. Although conservationist strength was growing, Yellowstone’s integrity was uncertain at best, and doubtful at worst. National parks faced the gloomy potential of destruction.

Yet, the tide turned. As 1921 unfolded, Congress made decisions on the various dam proposals—all in favor of Yellowstone preservation. The conservationists’ advocacy against the dams had its desired effect: public opinion turned against the various dam proposals. In February 1921, both the Smith and the Walsh bills met their fate. The Smith Bill was the first to die when it was not brought to a vote in the House before the session closed. Although Smith reintroduced it the following year, it did not go anywhere.

The Walsh bill was the next to see action. Hearings on it were scheduled for the start of the next congressional session, but when five members of the Yellowstone Irrigation Association arrived in Washington, Walsh held a surprise hearing on Washington’s Birthday, and did not invite any dam opponents. It goes without saying that testimony at that hearing was favorable to the dams, using the same flood control and irrigation arguments. Walsh did hold a hearing for the opponents, but tried to catch them off guard by holding it earlier than planned (on 28 February 1921; Haines 1996). This actually turned out to be somewhat providential, since Albright was then present in Washington. Four nights before the second hearing, he met with several other prominent conservationists such as Frederick Law Olmsted, Yard, and George Goodwin, to work on their responses. They broke up about midnight and went home (Albright 1921).

At the hearing, Albright spoke as expected, repeating many of the themes already discussed, such as deploring the submergence of valuable park resources. Olmsted spoke in opposition to the removal of management authority from NPS (Olmsted 1921). McFarland, Yard, and the new Secretary of the Interior, John Payne (who was more of a park defender than his predecessor Lane was) argued that the dam would open all national parks to exploitive commercialism: "when once you establish the principle that you can encroach on a national park for irrigation or water power, you commence a process which will end only in the entire commercialization of them all" ([Yard] 1921c: 3; see also [Yard] 1921b). Goodwin pointed up the factual problems inherent in the proposal. The conservationist testimony, especially Goodwin's, "made such a shambles of the arguments of the promoters that the Walsh bill was not reported" out of committee (Ise 1979: 313). At least for now, the conservationists had won.

Walsh, however, was not so easily defeated, for he reintroduced his bill in 1922, and got the support of (another) new Secretary of the Interior, Albert Fall. Fall was initially ambivalent about the dam, but eventually stated the "Yellowstone dam will be built" ([Yard] 1922: 1). Walsh needed to get an identical bill introduced into the House, but the August 1922 election in Montana defeated his plans when Scott Leavitt, a conservationist opposed to the dams, was elected. Timing, again, was key—and fortunate (for the conservationists, anyway): Fall's involvement in the Teapot Dome scandal broke about the same time as the election. Anyone associated with him, such as Leavitt's opponent, did poorly (Ise 1979; Haines 1996). Further, Senator John Kendrick of Wyoming came out in opposition to the dam at about the same time. Leavitt's election and Kendrick's opposition combined to kill Walsh's bill for the time being, and the conservationists won again *(Billings* [Montana] *Gazette,* 15 September 1922).

The Water Power Bill's threat was addressed last. Upon learning of the new authority, Mather protested to Secretary of the Interior Payne. He in turn protested to President Woodrow Wilson, who unfortunately felt compelled to sign the act or risk losing support of several western states in the upcoming election. He did, however, exact a pledge from the bill's sponsors to amend the bill in the next congressional session to exclude the national parks (Miles 1995).

Yard, knowing that pressure for that amendment would be key to its actual passage, galvanized support among his allies nationwide. Probably due to that pressure, Senators Walsh of Montana and Wesley Jones of Washington, two of the bill's sponsors, kept their promise on 3 March 1921 (U.S. Congress, Senate 1921: S4554). They were reluctant to do so, but probably acted in response to public pressure, as Yard indicated in an article announcing Wilson's signature to the amendment: “The campaign’s greatest achievement…was…the impression made upon Congress of the people’s determination to hold their national parks and monuments in complete conservation” ([Yard] 1921c: 1; see also Shankland 1970). With the passage of this amendment, the third of the major reclamation threats to Yellowstone passed away—all three defeats occurring within two months!

Conservationists attributed their victories to their publicity campaign. Albright claimed that “the ‘Pawning the Heirlooms’article and Mr. Gregg’s article have absolutely stopped the irrigation legislation.…Several Wyoming papers have republished the ‘Heirlooms’ story.” He also felt the publicity turned *local* sentiment against the dams: “[E]qually important, [the articles] have served to align Wyoming against all schemes of every kind that threaten commercialism of Yellowstone Park; they have split sentiment in Montana in such a way that all of thinking people have come over to our side; and they have established large doubts in the minds of lots of people in Idaho” (Albright 1920).

Acting NPS Director Cammerer credited publicity of a different sort. He felt that by publishing their proposals, the irrigators led to their own undoing, because the public was horrified to see just what they proposed to do to the park (Cammerer 1923). Finally, letters written by thousands of Americans to their representatives must certainly have swayed those politicians *(Christian Science Monitor* 1921). Conservationists drew upon a national audience, while the irrigators’ audience was only regional; the larger national audience made the conservationists successful—and would continue to do so in the years ahead.

Inviolate policy is established. As time would tell, defeating these three threats turned the tide in favor of protection. For example, when Congressman Smith reintroduced his Falls River proposal in 1923, Albright stated: “I am not very much afraid of this Fall River Basin project any more” (Albright 1923). Likewise, Mather felt that in amending the Water Power Act, “Congress placed itself on record, upholding the inviolability of the national parks” ([Mather] 1921: 22; see also [Mather] 1924: 5). Dam proposals would surface time and again through 1937, but after the 1921 victories, these proposals went nowhere. Conservationists drew no more parallels with Hetch Hetchy in the next fifteen years, suggesting the emergence of a new, important policy of park security. Hetch Hetchy’s precedent was overturned, replaced by a new policy of inviolability. National parks were secure.

The opening address of the 1923 summer tourist season in Yellowstone provides further evidence that the tide had indeed turned. There, John Wesley Hill spoke for President Harding and (still another) new Secretary of the Interior, Hubert Work, and announced, “it is at last the established policy of the Government that our national parks must and shall forever be maintained in absolute, unimpaired form, not only for the present, but for all time to come” ([Yard] 1923a: 2; Haines 1996). Hill’s speech was widely reported as policy-setting. For example, NPA celebrated the fact that President Harding thus became the “first President to announce publicly a general Administration policy of absolute, uncompromising conservation for the National Parks System and every one of its component units" (Irrigation Scrapbook, 1921–1928).

Harding himself visited Yellowstone later that summer, where he stated that "commercialism will never be tolerated here so long as I have the power to prevent it." In August 1923 President Coolidge announced that he would maintain his predecessor's policies, Harding having died shortly after visiting Yellowstone ([Yard] 1923b: 1; Albright 1985). The amendment to the Water Power Bill, the defeat of the Walsh and Smith bills, and Hill's speech collectively established the inviolate policy; from here on out, all battles were a defense of it, rather than the more daunting battle of establishing policy in the first place.

Reaffirming the Policy: "Keep the Looters Out!"

Now that conservationists had established important policy, they had to defend it. Droughts were inevitable, and irrigation was essential for agriculture in the area. Consequently, reclamationists were persistent, which gave the conservationists ample opportunity to uphold the new policy. Senator Walsh soon provided the first challenge to the policy when he introduced two more bills to dam the outlet of Yellowstone Lake in December 1923. With respect to the first of these bills, Yard noted that Walsh had "changed the ugly word 'dam' to the pretty word 'weir,' which means dam" ([Yard] 1924a: 6). The other bill would have appropriated $10,000 for a reclamation survey of Yellowstone Lake. Walsh could not raise that money in Montana itself, so his bill directed Congress to finance the survey (Ise 1979). Secretary Work, though, reported adversely on the bills the following spring, stating:

> [A]bsolute preservation should be the unwavering policy of Yellowstone administration, for inestimably valuable and precious as this great park now is to the Nation, it will prove of increasingly greater value with each passing year as the common heritage of coming generations.…Any plan for the commercial exploitation of the park must therefore, in my opinion, by the very nature of its aims and purposes, immediately be foredoomed to failure, and I therefore can not recommend favorable consideration of the pending measure (Work 1924).

Work's letter effectively killed the two bills. Senator Walsh was not to be heard from again, although the idea of damming Yellowstone Lake persisted.

Compared with earlier dam proposals, Walsh's last two bills garnered little opposition, perhaps because Work was so staunchly protective of the parks, or perhaps due to the strength of the policy established in 1921. Still, the NPA remained opposed to the Walsh bills, as did *The Outlook*, which published one article restating their former position: "Hands Off the National Parks!" (*The Outlook* 1923: 357). Women's clubs continued to be active in opposing the dams. For example, the General Federation of Women's Clubs declared for "defending national parks, maintaining their standards and perfecting protective laws…until Congress definitely recognizes the National Parks System as a beneficent national institution whose conservation and highest standards must by no means be imperiled, but maintained for the Nation's benefit for all time" ([Yard] 1924b: 5).

Conservationists enjoyed a reprieve for a couple of years, but in 1926

Representative Addison Smith of Idaho concocted another plan to build dams in Cascade Corner. Smith could see the futility, after the conservationist victory in proving national parks inviolate, of attempting to build his dam *within* the park. He reasoned, then, that if he could not build Idaho's dam in the park, why not cut that land out of the park? Eliminating Bechler Meadows from Yellowstone was precisely the proposal he made in 1926 (he had circulated the idea as early as 1921; see Smith 1921; Little 1921; *Boise Idaho Statesman,* 10 August 1921). Further, to make the excision palatable to his opponents, he offered a carrot in exchange for the 12,000 acres of Bechler: the addition to the park of the 64,000-acre Fremont Game Reserve, which was just west of the park and north of Bechler. Smith linked this proposal to a bill regarding other boundary changes for Yellowstone that was circulating at the same time, and threw his support behind the addition of another 200,000 acres to Yellowstone, the Yellowstone River headwaters area, on the park's southeast side. President Coolidge, perhaps too tempted by the prospect of adding the spectacular headwaters area to Yellowstone, endorsed the measure (Lovin 2000). Smith's proposal was very popular in southeast Idaho, where 1,500 people stacked a hearing in favor of the Bechler dam in 1926 *(Boise Idaho Capital News,* 19 August 1926).

Conservationists did not appreciate the compromise, however. Both NPA and *The Outlook* launched vigorous attacks against the proposal in 1926 and 1927. They recycled many arguments from their successful campaigns earlier in the decade. NPA used its strongest language to date to describe the inviolability of national parks, stating: "A National Park…should be as sacred as a temple" (van Dyke 1926: 8). Both organizations published descriptions of the Bechler area: an article by Horace Albright in the *National Parks Bulletin* (Albright 1926; see also Albright 1928) and one by Eleanor Marshall Thurman, extension secretary of the American Civic Association, in *The Outlook.* Thurman eloquently concluded her article by stating that "In my six days [in the park] I saw no other section which offered such facilities for the man or woman or family seeking to spend a few days of quiet and peace away from the honk and fumes of automobiles, the noise and smoke of trains, and the hue and cry of the typical tourist" (Thurman 1926: 435). The groups again compared the proposed reservoirs to Jackson Lake's "low-water horror of muck," "deprecated desolation," ([Yard] 1927: 17) and "gaunt skeletons of timber and its ugly mud shores" (Thurman 1926: 434; see also *The Outlook* 1926b). They also questioned whether it was "good national policy to establish a precedent for cutting large areas out of national parks to serve local purposes" ([Yard] 1927: 17; see also Albright 1928), and answered: "Before ever Idaho was a State this land was reserved for the people of the Nation. No State has a right to it. No special interest has any business there. Americans, keep the looters out" *(The Outlook* 1926a: 229).

Of the two magazines, *The Outlook* staged the more novel campaign against what it called "The Yellowstone Grab." In three different issues, the editor poked fun at, or criticized, Idaho's residents. In the first article, the editor compared Idaho's per capita wealth and automobile ownership to that of other U.S. residents, finding figures "that [do] not make Idaho look impoverished." The editor then wondered why “Idaho wants to take land that belongs to the American people…and put it to making more money for the people of two of her counties” *(The Outlook* 1926a: 229–230). In the second article, the editors suggested that irrigation proponents might be blinded to the area’s beauty by their agricultural needs: water for their sugar beets. The editors then rhetorically asked, “What is beauty to a beet?” *(The Outlook* 1926c: 301). In the final article, they offered basic lessons in American geography to teach Idahoans that Yellowstone belongs to the nation, not Idaho, and wondered: “[C]annot somebody provide a fund for sending Idaho editors to school to relearn their geography?” *(The Outlook* 1926d: 394). In these three articles and throughout its yearlong campaign, *The Outlook* consistently cried “Hands Off!” to “the looters,” and “invite[d] the co-operation of public and press in its campaign for the maintenance of the integrity of Yellowstone National Park” *(The Outlook* 1926a: 230). Specifically, they called upon the public to write their congresspersons *(The Outlook* 1926e: 554).

The matter festered for a number of years, finally ending up before the Yellowstone National Park Boundary Commission, which Congress established in February 1929 to render judgment on all the boundary revisions. The commission spent two weeks examining the contested areas, and held hearings on the matter in Cody and Jackson in 1929 (Lovin 2000). As Albright forecast, opposition to the Bechler excision ran strong in Wyoming; those present at the hearings were nearly united “against giving Bechler Meadows over to any commercial or irrigation project” (Albright 1926: 6). Some sportsmen’s groups such as the Wyoming division of the Izaak Walton League and the Montana Sportsmen’s Association opposed the project as well (Lovin 2000).

The commission delighted the conservationists in 1930 by ruling against the irrigationists, listing two primary factual reasons. First, “[t]he Bechler River meadows are of scenic charm and afford an engaging foreground to natural features of unusual interest,…[including] the beautiful falls of Dunanda, Silver Scarf, and Ouzel.…This region with its setting and surroundings forms a worthwhile part of the Yellowstone Park.” Second, “there is an available site on the Teton River, outside of the Yellowstone National Park, which in [the committee’s] judgment proves to be more economical and serviceable to the local irrigation interest than the proposed Bechler River site.” Perhaps the strongest statement was the commission’s conclusion: “Therefore, in the absence of a demonstrated public necessity, the commission finds that it is unnecessary and undesirable to break into the integrity of the Yellowstone National Park by the elimination of the Bechler River meadows from its boundaries” (Yellowstone National Park Boundary Commission 1931: 9). Once again, the inviolate policy was upheld: taking bites from national parks for commercial purposes was not appropriate. Irrigators would have to find another site for their dams.

Interestingly, the commission also endorsed the construction of a road from Idaho through Bechler Meadows and Canyon to Old Faithful to make the area more accessible to the public, and the addition of the Yellowstone River headwaters–Thorofare region to the park (Yellowstone National Park Boundary Commission 1931). The Bechler road was never built, and Wyoming sportsmen defeated the headwaters proposal because they did not want to lose valuable hunting territory. In the end, the failure to add the headwaters area to Yellowstone ironically resulted in greater protection for it, because NPS would have constructed a road over Two Ocean Pass and up the east side of Yellowstone Lake to make the area accessible to the public (Haines 1996). By retaining that area in the Teton National Forest, the area was kept in its wilderness condition.

For the next four years, dam proposals involving both the Bechler region and the park's large lakes continued to circulate. There may have been collusion between the three local states in a project to dam Yellowstone Lake, sending some reserved water downstream to Montana while diverting the rest through a tunnel bored under the Continental Divide to the Snake River and thence to Wyoming and Idaho. All of these plans, however, failed when the three-state triumvirate fell apart in the early 1930s (Haines 1996). These plans received little overt attention from conservationists, perhaps because Secretary of the Interior Harold Ickes strongly opposed all of them (Bartlett 1985).

Clearly, conservationists were generally successful throughout this period in upholding national park integrity. The final round of the "war" began in 1937 when Congress approved the Colorado-Big Thompson project, which involved the construction of a tunnel under Rocky Mountain National Park to bring west slope water to the dry Front Range cities (Bartlett 1985). Rocky's integrity seemed violated, even though the tunnel did not mar the surface of any portion of the park. Whether it violated Rocky's integrity or not, the tunnel project soon woke the sleeping reclamation giant outside Yellowstone and inaugurated the final dam battle. Idaho's irrigationists reasoned that if it was acceptable to tunnel under Rocky Mountain, what could be wrong with damming Yellowstone Lake and tunneling its water over to the Snake River? Idaho Senator James P. Pope and Representative Compton I. White introduced bills into Congress in 1937 to effect precisely such a project (Yard 1938).

Once again, NPA swung into action, despite enduring the greatest financial stress of its history (Miles 1995). The venerable Robert Sterling Yard editorialized against the project in 1938. Seasoned by his previous efforts to defend Yellowstone, Yard saw the many parallels with the dam battles of the early 1920s. For example, he noted that the Idaho irrigationists again called their proposed dam a "weir," echoing Senator Walsh's moniker. He suspected that Walsh "shivers in his grave, for he wanted those waters for Montana!" He echoed himself and John Payne in stating: "'When once you establish the principle that you can encroach on a National Park for irrigation or water power, you commence a process which will end only in the commercialization of them all.'" As expected, Yard called for vigorous defense against the irrigation bills (Yard 1938: 11).

Again, many different organizations passed measures in opposition to the dams, including the Sierra Club (Chapman 1938), *Nature Magazine* (1938), the American Association for the Advancement of Science (Cammerer 1938b), the Prairie Club (Lehman 1938), the Emergency Conservation Committee (Edge 1938), the Izaak Walton League (Cammerer 1938a), and The Wilderness Society (The Wilderness Society 1938). As with the previous battles, they used many of the same arguments. *Nature Magazine*, for example, recycled the precedent argument, stating: "Give them an acre and they'll soon have a whole watershed" *(Nature Magazine* 1938: 426).

President Franklin D. Roosevelt visited Yellowstone in 1937 and promised to oppose any reclamation dams involving Yellowstone Lake. Realizing already the economic value that an intact Yellowstone Park possessed, the Wyoming State Planning Board advised against the dams in 1937 (Greenburg 1937). Even the Secretary of the Swedish Government Committee on Planning for Recreation, Professor L.G. Rommell, opposed the dam: "If commercial interests should be allowed to encroach upon Yellowstone Lake, this would mean far more than despoliation of a place.…It would be a terrific blow to the entire National Park idea which could not fail to have its repercussions throughout the world" (National Park Service 1938: 4).

Given the level of opposition to this proposal and the record of conservationist successes in the previous two decades, it comes as little surprise that Idaho's proposals were defeated. Both bills died in their respective committees on Irrigation and Reclamation in 1938 ([Yard] 1938a; [Yard] 1938b; Bartlett 1985). With them died the last serious proposal to dam any of Yellowstone's waters.

Interestingly, a compromise of sorts had been struck for the Idaho irrigators three years before. The Bureau of Reclamation agreed to add two dams to the Minidoka project, one of them the Grassy Lake Dam at the head of Cascade Creek, a tributary to the Falls River (Haines 1996). The Grassy Lake Dam is only about one hundred yards from Yellowstone's south boundary. The reservoir is much smaller than the Bechler reservoir would have been, but does serve the needs of Idaho's irrigators in dry years. Still, the fact that Idaho's irrigators jumped on the irrigation bandwagon in 1938 with their proposal to impound Yellowstone Lake speaks to their devotion to reclamation—or to the resiliency of dinosaurs.

In Montana's case, the Yellowstone River never was dammed, although the Bureau of Reclamation proposed a large dam just upstream from Livingston at the Allenspur dam site in 1972. As with the dams in Yellowstone Park, citizen opposition and testimony stopped this dam, preserving the Yellowstone as the nation's longest remaining free-flowing river outside of Alaska (Wilkinson 1992).

Conclusion

After nearly two decades of fighting, the war seemed to be over. Through it, conservationists established, tested, and interpreted a new policy for the national parks: that they are inviolate, inappropriate as places for commercial exploitation. In winning every battle and the full war, conservationists overturned the defeat at Hetch Hetchy. In so doing, they proved both themselves (as conservation groups) and the nascent NPS capable of adequately protecting their charges. At least in the parks, *preservation* prevailed over *conservation.*

Why did the conservationists win at Yellowstone when they had lost just a few years earlier at Yosemite? There are several likely reasons. By the time of the

Yellowstone battle, NPS existed and was able to act aggressively to defend the park. This, the first major attack to national park integrity faced by NPS, gave it the opportunity to prove that it was not to be pushed around as the new kid on the block. In successfully defending Yellowstone, NPS proved itself an agency capable of protecting its parks. Hetch Hetchy, in contrast, was in part victim of administrative neglect: while the Army did an admirable job protecting Yosemite, they were not as zealous a protector of it as the NPS administrators were in Yellowstone.

Furthermore, Yellowstone benefited in another way from the unique position of its battle in time: not only was there now a National Park Service, but there was also a National Parks Association. This private group of individuals was expressly devoted to preservation of the national parks, and acted repeatedly to defend Yellowstone. It is true that Yosemite had its Sierra Club, but the Club at that time was primarily an outing association, not as much a conservation group. Indeed, the Hetch Hetchy issue deeply divided the Sierra Club; while it responded in defense of the park, its defense was not as vigorous as that of NPA with Yellowstone. NPA had no such division; it cut its teeth on the Yellowstone dam battle, galvanized conservationists nationwide in support of preservation, and stuck to its cause tenaciously.

Additionally, the balance of people who stood to profit versus those who stood to lose from the two dams had shifted. All the residents of San Francisco stood to benefit from the Hetch Hetchy Dam, whereas a relative few irrigators stood to benefit from the Yellowstone dams. Only a few people knew Hetch Hetchy well enough to sense the aesthetic loss of damming it; by contrast, almost all visitors to Yellowstone stood to lose in the damming of Yellowstone Lake. The Montana and Idaho irrigators were unable to overcome this sensitive weakness, whereas San Francisco derived strength from its large numbers.

Finally, and perhaps most important, there was no formal policy at the time of Hetch Hetchy against dams in national parks. As this article has detailed, the Yellowstone dam battle established that policy by 1923. But, the Yellowstone dam battle would probably not have been won without Hetch Hetchy. In a way, the country needed a Hetch Hetchy somewhere in the national parks to illustrate what did not belong in them, to demonstrate that national parks should be inviolate. It may be easier to actually see what is wrong in a park than to imagine it; Yosemite provided the illustration of what not to do in Yellowstone.

Given the popularity of utilitarian conservation in the time between the two presidents Roosevelt, it is somewhat surprising that reclamation was stopped in Yellowstone. The fact that this strong public policy was stopped speaks to Yellowstone's strength as a preservation icon, to the zeal of those defending the park, and to the popularity of the national park idea. Although the irrigators had the best of motives in mind, their desires were irreconcilable with the preservation of Yellowstone. Moreover, their attacks on the park affirmed and cemented its preservation; few would think of tampering with Yellowstone in the future.

The policy was broadened to all national parks with the Echo Park controversy in Dinosaur National Monument in the 1950s, and with the Grand Canyon dam controversy in the 1960s. In both of these battles, the Bureau of Reclamation proposed placing large dams in the national parks, but was prevented from doing so by conservationists. David Brower, leader of the Sierra Club, was a leading figure in both of these latter efforts, effectively leading conservationists on nationwide campaigns against the dams. As with the later rounds of dam proposals in Yellowstone, these two battles reaffirmed that national parks are inviolate.

Conservationists established a very strong principle with Yellowstone. Indeed, it is one that they defended perhaps too vigorously in future years, when the question of including Jackson Lake in Grand Teton National Park came up in the 1930s. After using it for years as an example of ugly commercialism, conservationists were hard put to support its inclusion in the proposed park. Believing that any industrial use did not belong in national parks, and nervous about opening the door to the irrigators again, organizations such as NPA and the Wilderness Society opposed its inclusion, into the late 1940s (The Wilderness Society 1938; Righter 1982). Clearly, they had good reason to uphold the policy. However, it can be argued that all policies need exceptions—wisely chosen ones, of course. The magnificence of the Tetons perhaps justified such; certainly the ticky-tack commercialism already present there in the 1940s did. Eventually, conservationists made that exception with Jackson Lake, in such a way that more cries for national park reclamation did not appear. They were able to have their cake and eat it too.

It seems as though each generation of Americans must relearn the important lesson of national park inviolability. In 1991, the Clear Rock Resources Company of Sheridan, Wyoming, proposed still another dam at Fishing Bridge: an eleven-foot dam that would have raised the level of Yellowstone Lake by five feet. As the reclamationists did sixty years earlier, Clear Rock promoted the dam's benefits, suggesting that its low profile "will make [it] nearly invisible to traffic crossing Fishing Bridge" and that it "would have a stabilizing influence on lake levels with potential benefits for the lake shore environment…" (Barker 1991). In response, NPS, thanks to the strong policy established earlier, was able to quash this threat with only one letter two weeks later (Ponce 1991). Still, this surprising proposal does bear truth to what Yard wrote in 1938 at the conclusion of the final dam battle: "[T]he threat has been staved off, [but] for as long as the waters of Yellowstone Lake are kept inviolate they will be a continual challenge to irrigationists.…The fight for Yellowstone will be a continuous affair" ([Yard] 1938a). National parks are secure, but only as long as they are defended.

Epilogue

After two hours of hiking in the rain across Bechler Meadows in Yellowstone, my friend Dave and I arrive at the fern-covered mouth of Bechler Canyon. The flat meadows offer glimpses of the Tetons through the clouds to the south. Now, though, the trail gradually begins to climb up the canyon through an open forest of huge spruce and fir trees. Right at the mouth of the canyon we see Ouzel Falls, the first of many we would pass the next two days.

We hike on through intermittent showers, crossing narrow log bridges, eating huckleberries, and stopping for breaks at Colonnade, Iris, and the recently renamed Albright Falls. In another three miles we finally arrive at our campsite, known as Three River Junction, for the three forks of the Bechler River that come together there: the Phillips, Gregg, and Ferris forks. That evening we carry our cook stove a mile farther upstream to the hotpot on the Ferris Fork, eating supper between bouts of soaking. The hot springs warming this fork are so large that we choose our desired water temperature by walking up or downstream. After the long day, we relax well into the evening, returning to our tent after dark (and stumbling over roots when the batteries in our only flashlight fails on the way back). The next day we follow the Ferris Fork farther upstream to another four waterfalls, then retrace our steps and hike out to our car in sunshine. We pass many hikers and fishers en route, as well as several moose. The last hike of my first summer in Yellowstone, I would be lured back to this marvelous—and undammed—corner of Yellowstone many more times.

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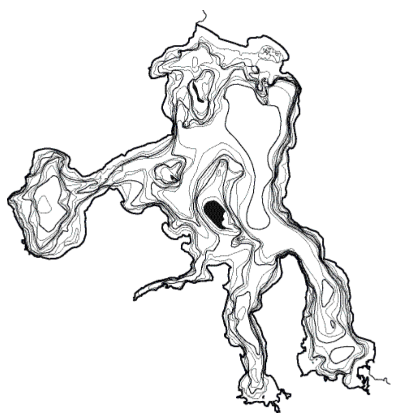

Greater Yellowstone Ecosystem Biennial Scientific Conferences

1991 Plants and Their Environments
1993 The Ecological Implications of Fire in Greater Yellowstone
1995 Greater Yellowstone Predators: Ecology and Conservation in a Changing Landscape
1997 People and Place: The Human Experience in Greater Yellowstone
1999 Exotic Organisms in Greater Yellowstone: Native Biodiversity Under Siege
2001 Yellowstone Lake: Hotbed of Chaos or Reservoir of Resilience?