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

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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.

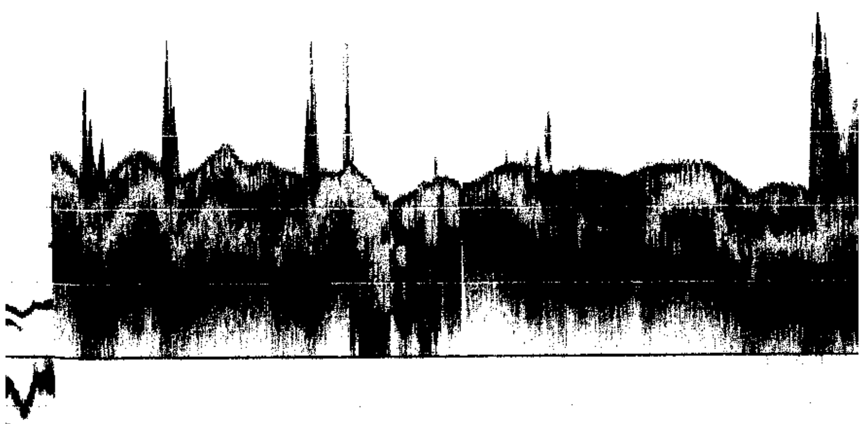

Figure 1. Bridge Bay spires are clearly visible on 1996 depth sounder charts from the R/V Cutthroat.

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

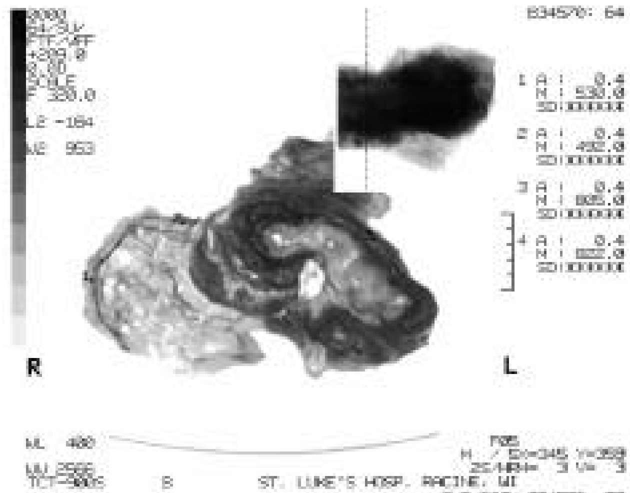

Figure 6. An X-ray cross-section of the spire at about one-third of the length from the base (vertical line on inset) reveals spongy, low-density (lighter shades) sinter in the bulb to the left side. The adjoining main spire section shows rings of higher-density material (darker shades) surrounding sinter 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)

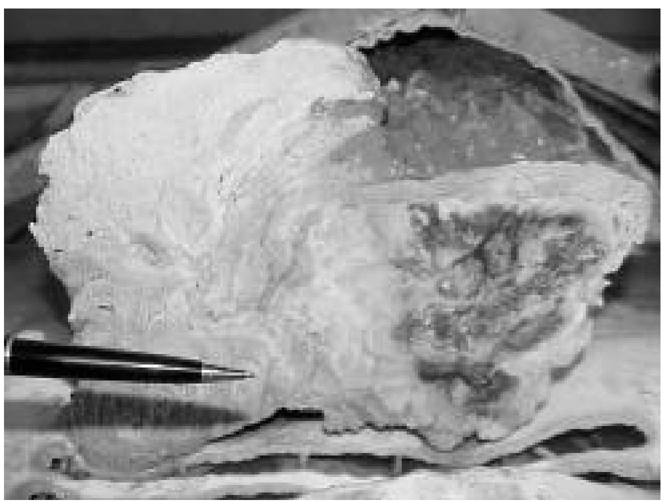

Figure 9. Cross-section of the spire viewed from the bottom reveals the porous sinter on the left and the harder main spire with dark precipitates to the right. Pen segment is 3 inches long. (Russell Cuhel)

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-

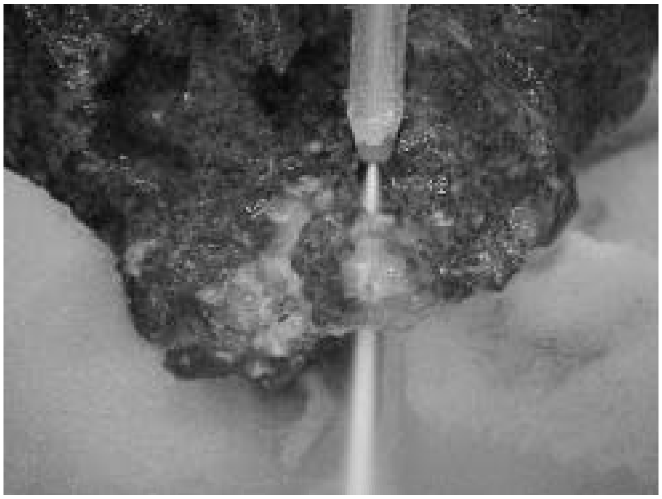

Figure 12. No sample disintegration occurred even as the cut approached the thin, delicate tip of the main spire segment. (Russell Cuhel)

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, empha - sizing 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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