

Chapter 2

*Mapping the
Last Frontier in
Yellowstone National
Park: Yellowstone
Lake*

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Despite a history of doing earth science and geologic mapping in the Park since the 1870's, no one had created a geologic map of Yellowstone Lake. The Hayden Expedition explored and mapped the shoreline in 1871 and produced the first map of the floor of the lake. Others followed but it was not until 1999 when USGS geologists Lisa Morgan and Pat Shanks with a multi-disciplinary research group began the first comprehensive mapping studies. Their aim was to produce the most detailed maps modern technology allowed. To do so they employed an array of high tech sensors attached to a National Park Service boat and an underwater rover similar to the one that explored the Titanic. They processed five years of data to produce maps of incredible resolution and revealed a host of underwater features and geologic wonders.

Yellowstone Lake is the product of glacial processes that scoured the Yellowstone River valley and, dramatic volcanic and hydrothermal activity that originates deep in the earth's crust. Imagine an eruption 640,000 years ago where Yellowstone is today. Over 1,000 cubic kilometers of pyroclastic flows – a mixture of hot, dry ash, rock fragments, and hot gases blasted across an area nearly 7500 square kilometers. The resulting caldera (volcanic depression) formed the core of YNP and the northern portion of Yellowstone Lake. The maps produced by Morgan and Shanks' team show that the lake itself holds all manner of dramatic thermal features, including -hydrothermal vents, large circular craters due to steam explosions, hydrothermal domes, and subterranean faults and fissures. The vents are sources of various chemicals – notably mercury, a substance with well-known toxic properties at high levels that has turned out to be useful to ongoing ecological studies on the Yellowstone grizzly bear.

The maps show a complex landscape of past geothermal events, landslides, faults, changing shorelines and evidence of potentially hazardous seismic activity; it will be decades before geologists fully understand these features. The true value of the maps may be the capacity to meld the science of the hidden geology of Yellowstone Lake with our understanding of the terrestrial landforms that fascinate scientists and visitors alike.

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Yellowstone Lake (Thermal Biology Institute, MSU)



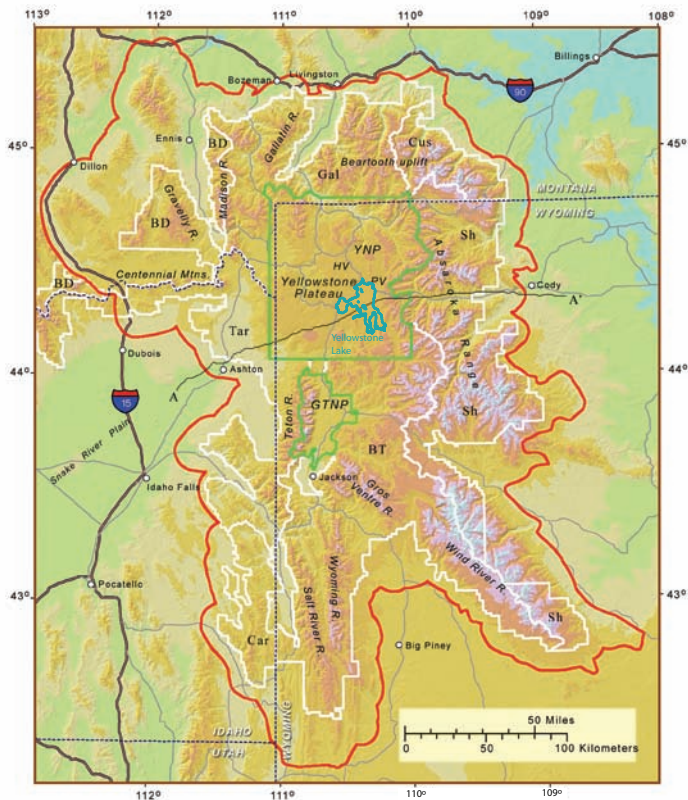
Chapter 2

Mapping the Last Frontier in Yellowstone National Park: Yellowstone Lake

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▲ FIGURE 2.1 Index map of the greater Yellowstone geocosystem (GYE) (outlined in red) with Yellowstone Lake in the center of the geocosystem. (Ken Pierce, USGS)

Yellowstone Lake is the centerpiece of the Greater Yellowstone Ecosystem. The lake is the largest high-altitude (>2134 m in elevation) lake in North America, covering 341 km² and carrying 16.54 km³ of water.

The headwaters of the Yellowstone River, Yellowstone Lake figured prominently in determining the course of the 1871 Hayden survey expedition of the Yellowstone region. A primary scientific interest of Hayden was watersheds; thus, a principal goal of the Yellowstone survey was to reach the headwaters of the Yellowstone River and map Yellowstone Lake. The latter goal was accomplished by survey party members Henry Elliott

and others who collected in 24 days over 300 soundings using triangulation for navigation and produced the first bathymetric map of Yellowstone Lake. A bathymetric map displays the ocean or lake floor terrain as contour lines called depth contours or isobaths.

Since the Hayden survey, several other maps of Yellowstone Lake have been created, each using more advanced technology than the previous bathymetric map. Each map represents a step forward in more accurately defining the lake boundary and lake floor morphology and has improved understanding of what is present in the lake and how it may have formed. Up until 1990, however, accurate navigational systems were not readily available and map resolution was relatively low. Thus, details of the lake floor could not be accurately defined. In the late-1990's, a collaborative effort between various organizations to study the chemistry of fluids from hydrothermal vents on the floor of Yellowstone Lake resulted in the recognition that the maps available at the time were inadequate in identifying the locations of individual hydrothermal vents or fields. In 1999, the U.S. Geological Survey (USGS) in collaboration with the National Park Service at Yellowstone National Park began a 5-year, high-resolution mapping survey of Yellowstone Lake. This survey would be the first to utilize and integrate new technologies involving differential GPS for navigation, multi-beam swath sonar, and high-resolution sub-bottom seismic-reflection profiling. The data sets were complimented by sampling and photographic documentation using a submersible remotely operated vehicle (ROV). The final map produced a data set with navigational accuracy of <1 m, multi-beam swath sonar data accurate to <1 m both horizontally and vertically, and seismic reflection profiles of the upper 25 m of the lake floor to a vertical resolution of 10 cm and horizontal resolution of 3 m (at 10 m water depth) to 13 m (at 50 m water depth). What this means in practical terms is that features as small as one meter could be observed with the newer technology.

The merits of such a high-resolution map of the lake were well justified. Significant advances had been made in the 1990's in developing high-resolution maps of the depths of the ocean floor; however, no high-resolution

Deep Water Exploration

The array of available technology for underwater mapping and geophysical surveys has changed dramatically over the last couple decades. Various sonars and acoustic sensors, magnetometers, and free-swimming, tethered rovers allow scientists to see highly detailed, three-dimensional images of the floor of large bodies of water like Yellowstone Lake. The resolution can be as accurate as 10s of centimeters. Below are short descriptions of some of the methods used to produce the highly detailed maps of the Lake.

► **SEISMIC-REFLECTION PROFILING.** A variety of sources, including explosives, pneumatic air guns, and high-frequency “chirp” systems, are used in seismic-reflection surveys. A “chirp” sonar system that transmits computer-generated pulses of acoustic energy was used in Yellowstone Lake. The sound travels down through the water and penetrates into the layers of sediments and rocks on the lake floor directly beneath the boat. Some of this sound reflects (echoes) off the layers, and travels back up to the surface where it is recorded by a hydrophone. The return time and intensity of the returning energy helps researchers know the structure of the lake floor and underlying layers. A series of pulses over time establishes a profile of the lake bottom as the boat drives along a prescribed course. The sonar pulse is harmless to fish and the surrounding environment. High resolution seismic reflections surveys are particularly effective for assessing the sedimentary layering and other features in the upper 10-30 m of sub-bottom materials. Sub-bottom seismic-reflection profiling utilized an EdgeTech SB-216S, which sweeps a frequency range from 2 to 10 kHz and has a beam footprint that spreads over an angle of 15-20°.

► **HIGH-RESOLUTION MULTI-BEAM SWATH SONAR.** A hull-mounted transducer sends out 126 energy beams in a 150° fan-like array, somewhat like a peacock’s tail. The energy is bounced back to collectors that interpret the return signal to detail the bottom bathymetry (underwater topography). The fan-like array is oriented perpendicular to the direction the boat travels, so it maps a swath that is about 8-times water depth in width. The boat is driven on a back-and-forth course mostly in a 200-m north-south spacing so the swaths overlap, like mowing a lawn, giving continuous coverage of the bottom as the survey progresses. Swath mapping differs from seismic reflection profiling in focusing on obtaining a continuous map of the shape of the bottom. Higher frequency sound is generally used, which gives a sharp reflection off the bottom, but does not penetrate significantly into the sub-bottom sediments.

► **AEROMAGNETIC SURVEY.** Airborne geophysical surveys are carried out using a magnetometer aboard or towed behind an aircraft. The principle is similar to a hand-held metal detector, but allows much larger areas of the Earth’s surface to be covered quickly by aerial reconnaissance. The aircraft typically flies in a grid pattern with height and line spacing determining the resolution of the data. The magnetometer records tiny variations in the intensity of the earth’s magnetic field due to subsurface structures and the amount of magnetic minerals in the Earth’s crust. Aerial surveys are fast and magnetic properties can be used to detect different rock types and different degrees of hydrothermal alteration.

► **ROVERS/ORV.** A wide array of rovers (Remotely Operated Vehicle) are available to researchers. Some are manned, others are robots tethered to the mother ship, and a new class of autonomous underwater vehicles (AUVs) is untethered and can be programmed to carry out surveys. All of these vehicles have their own propulsion systems and are able to maneuver and investigate features of interest. In Yellowstone, we used a machine that relays live video to the surface and can take water, sediment, rock, and biota samples. One advantage of robots is that interesting features can be closely investigated without the risk associated with human dives to several hundred feet. They can be easily and safely controlled from the surface ship.



▲ PHOTOS 2.1 & 2.2 The National Park Service research vessel, the *RV Cutthroat*, was used to collect the bathymetric and seismic data as well as provide the platform for the submersible remotely operated vehicle (ROV). The boat is used by researchers mapping underwater features as well as taking biological samples of lake flora and fauna. (Big Sky Institute, MSU)

bathymetric map existed for Yellowstone Lake. In fact, because of the low resolution of previous lake maps, details of the shape and dimensions of the landforms and geology of the lake floor were poorly known. Yellowstone Lake was left as a large blue hole surrounded by detailed topographic and geologic maps on land. With no geologic map of Yellowstone Lake available, basic information such as how the lake formed, how the lake fits in with its surrounding geology, and what potential hazards or resources were present in the lake were poorly known. Furthermore, a high-resolution bathymetric map enabled discovery of several major new features and important details for a multitude of smaller features. Coupling the collection of high-resolution multi-beam swath sonar imaging of the lake

floor with high-resolution seismic reflection profiling gave the survey the first comprehensive coverage of ~30-m-thick sub-bottom slices into the lake floor. These two new surveys complimented data collected from a high-resolution aeromagnetic survey of Yellowstone National Park (YNP) by the USGS in 1996. Integration of these distinct but complimentary data sets resulted in the USGS producing high-resolution bathymetric and shallow seismic maps of Yellowstone Lake as well as the first geologic map that provides a basic framework in which to identify potential hazards in the lake and to effectively manage the various resources present.

At the same time, the National Park Service was facing a significant challenge in managing certain natural resources in Yellowstone Lake. In 1994, aggressive fish-eating lake trout were discovered in the lake. Each lake trout in Yellowstone Lake is estimated to consume about 60 native cutthroat trout annually, rapidly decimating the cutthroat population. Lake trout live their entire life cycle within Yellowstone Lake. In contrast, spawning cutthroat trout annually swim up one of the 141 tributaries that drain into Yellowstone Lake where they become an important food source for the grizzly bear, bald eagle, osprey, and river otter. Without the availability of cutthroat trout as an integral part of their diet, these species are compromised creating a ripple effect through the entire ecosystem and adversely affecting an area much larger than Yellowstone Lake. The National Park Service was interested in a high-resolution map of the lake to help identify areas where lake trout might spawn, then focusing gill-netting operations on those areas to reduce the population.

The five year collaborative survey of Yellowstone Lake by the USGS and the NPS cost about \$600,000 for outside contract services alone, supported through a combination of mostly public funds with some private contributions. Multiple divisions and programs in the USGS (including the Mineral Resources Program, Volcano Hazards Program, Climate History Program, Northern Rocky Mountain Science Center, Biologic Resources Division, Geologic Division Venture Capital Program, and the Central Region Office of the Director) contributed to this effort as did the NPS (Yellowstone

National Park), the Yellowstone Foundation, and the Yellowstone Association.

Previous Geological and Geophysical Studies

A variety of detailed field studies in YNP have been conducted by the USGS since the Hayden survey in 1871. In the late 1960's, in an effort to improve our understanding of young volcanic terrains and how these young volcanic terrains may be applicable to lunar and planetary geology, NASA supported a major mapping effort by the USGS to map the entire park. Detailed field mapping of the young (<2.1 million year) volcanic rocks of YNP was completed, and set the stage for understanding the geologic framework of Yellowstone Lake.

A 1977 a heat flow map of the lake showed that the Mary Bay area in the northern basin of Yellowstone Lake had the highest heat flow values in the lake and depth to magma may be five to eight kilometers, some of the shallowest magma in the park.

In 1996, the USGS collected high-resolution aeromagnetic data for the entire area of YNP. This survey was flown along closely spaced (every 400 m), north-south trending flight lines at low flight elevations (draped at <350 m above existing terrain) allowing resolution of low amplitude, short-wavelength magnetic anomalies that could be used to resolve features at scales useful for mapping individual geologic units, faults, and areas of alteration. This mapping replaced the previous lower resolution aeromagnetic maps that were flown in 1973.

Methodologies

A multi-disciplinary approach was used in mapping Yellowstone Lake. Existing data included detailed geologic maps of YNP and the surrounding on-land areas around the lake as well as high-resolution aeromagnetic data of YNP. To this set, we added two sonar surveys (swath multi-beam sonar and seismic reflection profiling). Navigation for the surveys used a real-time, differentially corrected global positioning system (GPS), which resulted in a location accuracy for the survey

vessel of <1 m. Features identified in the seismic and bathymetric surveys were verified using a submersible remotely operated vehicle (ROV) to photographically document the lake floor and sample for solids and fluids. The solid and fluid samples were then analyzed for trace element chemistry and isotopes. Several samples were radiometrically dated and probed with a scanning electron microscope.

Bathymetric surveys of Yellowstone Lake occurred in four campaigns between 1999 through 2002 and utilized a Sea-Beam 180 kHz instrument with a depth resolution of <1% water depth. Water depth in Yellowstone Lake varied from ~4 m to 133 m in the areas surveyed. The multi-beam instrument used has 126 beams arrayed over an angle of 150° angle to map a swath width of 7.4 times water depth. Data were collected primarily along north-south lines spaced approximately every 200 m; in areas with shallow water, the spacing between collection lines was closer. Multiple east-west tie lines were collected for increased accuracy. Over 240,000,000 soundings were collected to produce the first high-resolution, continuous and overlapping coverage of the bathymetry of Yellowstone Lake.

Coupled with the bathymetric survey, sub-bottom seismic reflection profiling utilized an EdgeTech SB-216S, which sweeps a frequency range of 2-15kHz, and has a swath angle of 15-20°. Both the swath unit transducer and the sub-bottom unit were rigidly mounted to the transom of an 8-m long aluminum boat used for survey purposes. Approximately 2400 linear km of high-resolution seismic reflection data, which penetrated the upper 25 m of the lake bottom, were collected between 1999 and 2003.

The Eastern Oceanics submersible ROV is a small vehicle (~1.5 m x 1 m x 1 m) attached to the vessel (RV Cutthroat) with a 200-m tether, which was operated in tandem with these surveys. The ROV provides live videographic coverage and remote control of cameras and sampling equipment. The ROV has full-depth rating of 300 m and is capable of measuring temperature, conductivity, and depth, and can retrieve hydrothermal vent fluid samples and solid samples up to 40 cm long.

Results and Discoveries

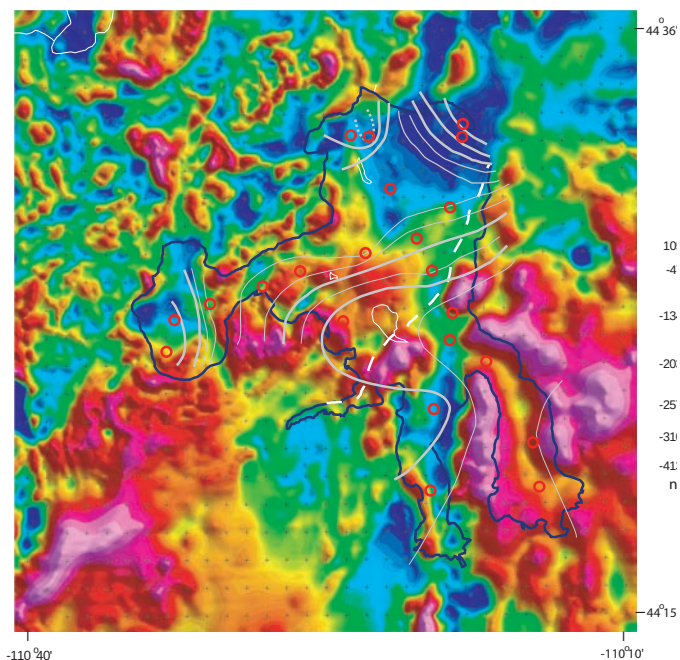
CHRONOLOGY OF DISCOVERIES FROM THE 1999-2003 CAMPAIGNS OF YELLOWSTONE LAKE

Mapping of Yellowstone Lake by the USGS in collaboration with NPS began in 1999 and concluded in 2003. Initial efforts started in the northern basin in 1999 and continued in 2000 in West Thumb basin. The central basin followed in 2001; all three surveys between 1999 through 2001 collected multi-beam swath sonar and sub-bottom seismic-reflection data contemporaneously. In 2002, multi-beam swath sonar data was collected for the Southeast, South, and Flat Mountains Arms in the southern reaches of the lake; additionally a small feature in the northern basin was remapped. In 2003, seismic-reflection data was collected from selected lines in all arms of the lake as well as certain other areas of interest the lake. In 2003, a significant effort was made into sample and photographically document the lake floor with the submersible ROV.

With subsequent years, our findings grew increasingly interesting and complex, building on knowledge of previous years. Our ROV surveys ranged from inventorying and identifying geographical features to discovering new and exciting ecological ties between the hydrothermal vents, the lake fishery, and their predators.

The primary discoveries from the mapping of Yellowstone Lake in 1999 were a broad range of features related to hydrothermal activity. These included individual hydrothermal vents, sets of vents, linear fractures (many lined with hydrothermal vents), large hydrothermal explosion craters, hydrothermal domes, and siliceous spires related to hydrothermal vents. The lake was found to be a complex network of hydrothermal features in a large previously unknown thermal basin. Other discoveries from the northern basin survey included identification of landslide deposits at several locations and the young, active Lake Hotel graben, a geological two-sided fault whose precise location was determined in the new survey.

In 2000, mapping focused in the West Thumb basin.



▲ FIGURE 2.2 The rainbow-colored shaded relief bathymetric map of Yellowstone indicating depth throughout the lake is based on multibeam sonar imaging. Yellowstone Lake is outlined in black, the caldera margin is represented by dashed thin white line. The most recent bathymetric and seismic maps reveal new faults, hot springs and craters beneath Yellowstone Lake. (Lisa Morgan, USGS)

Page 26 FIGURE 2.3 High resolution reduced to pole aeromagnetic map of Yellowstone Lake at a 100 m grid, magnetic inclination = 69.8, magnetic declination = 14.3. (Lisa Morgan, USGS)

The basin erupted less than 200,000 years ago within the Yellowstone caldera. The high concentration of hydrothermal activity makes it an area of scientific interest. Several previously unknown large hydrothermal vent fields and one large hydrothermal explosion crater were mapped. Another major discovery in 2000 was that rhyolitic lava flows were emplaced into the lake-filled West Thumb caldera created by the eruption of the tuff of Bluff Point ~180,000-190,000 years ago. Using the newly acquired bathymetry from West Thumb basin and draping it on top of the high-resolution magnetic intensity map of the same area, we noted a strong correlation between the two data sets. On land, sharp changes in magnetic amplitude were strongly associated with geologically mapped edges of rhyolitic lava flows; topography also reflects these changes.

Coupling the newly acquired bathymetric data with the aeromagnetic data showed similar relationships in the lake, and prompted our proposal that rhyolitic lava flows were also in Yellowstone Lake. These flows contributed significantly to shaping the northern two-thirds of the lake floor.

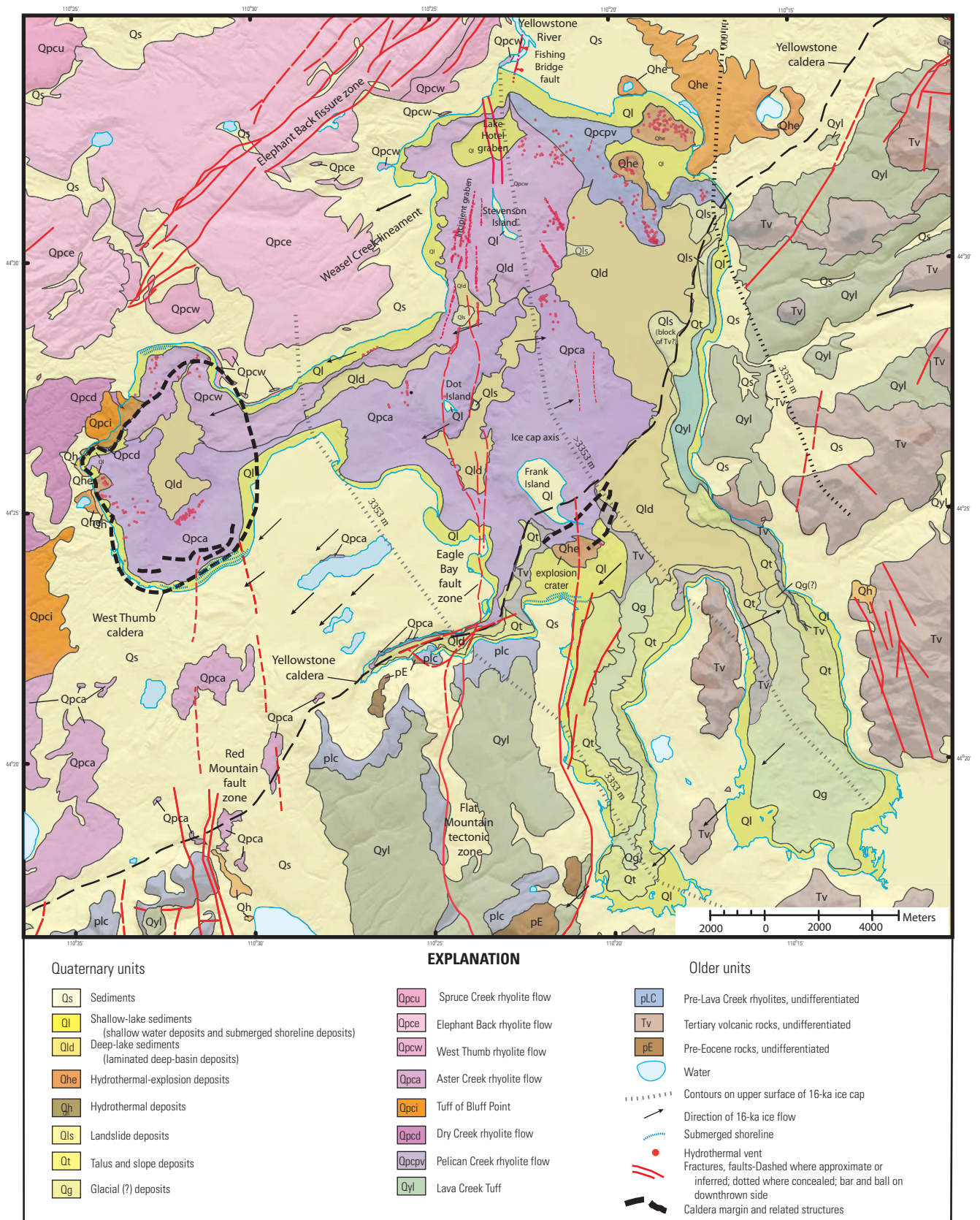
Newly acquired seismic reflection profiles across the West Thumb basin showed a pronounced high amplitude reflector identified at about 9 m depth along a north-south transect in the northern part of West Thumb basin. This is interpreted as the top of a rhyolitic lava flow covered by laminated glaciolacustrine sediments (glacially-derived sediments deposited in the lake). Older geologic maps of the northern and western sides of the lake show exposures of similar post-Yellowstone-caldera lava flows adjacent to the lake. Based on this spectrum of data, we identified and mapped rhyolitic lava flows as present in the northern, West Thumb, and central basins of Yellowstone Lake. In fact, these lava flows are the major contributors to the overall morphologies present in the northern two-thirds of the lake. Prior to this, most researchers thought the landforms in these basins of the lake were related to the advance, deposition, and retreat of glaciers. In fact, glacial debris is mapped on the various islands within Yellowstone Lake; however, based on the 2000 survey data, these thinner glaciolacustrine (glacier deposited) units cover the larger, more impressive forms created by the rhyolitic lava flows in the northern two-thirds of the lake.

What all this means is that the creation of Yellowstone Lake is a combination rarely seen in high mountain environments. Normally, lakes in environments like Yellowstone are the result of being gouged out by glaciers as they moved across the landscape and Yellowstone is no exception. However, the northern two-thirds of the lake has been shaped by a combination of dramatic geologic processes including Yellowstone caldera formation, emplacement of rhyolitic lava flows, glacial advances and retreats, hydrothermal explosions, and relatively rapid changes in lake level due to deformation (inflation and subsidence) of the Yellowstone caldera.

The opportunity to map the expansive central basin of Yellowstone Lake began in 2001 and more discoveries ensued. Our mapping continued to identify multiple hydrothermal vents, several large hydrothermal explosion craters, small landslide deposits, and large areas covered by rhyolitic lava flows. For the first time, the precise location of the topographic margin of the 640,000-year-old Yellowstone caldera was defined. In addition, the linkage of the young and active north-south Eagle Bay fault system with the newly mapped fissure system located due west of Stevenson Island to the north, continuing north to the Lake Hotel graben on the northern outlet of the lake was made. On the eastern side of the basin a large (1 km diameter) detached block of Tertiary volcanic rock was discovered on the lake floor. In each of these new discoveries, the interpretation of the data was supported by the bathymetry coupled with the magnetic intensity map and/or data from the seismic reflection profiles, which thereby strengthened the interpretation. The submersible ROV provided the “ground truth” in the form of high quality photographic images and solid and fluid samples.

Efforts in 2002, the final year for collecting multi-beam swath sonar data had a two-fold focus. One objective was to complete the mapping of Yellowstone Lake and finish the southern-most parts of the lake, including the Flat Mountain, South, and Southeast Arms. The second objective was to re-map an area in the northern basin of the lake, which has been interpreted as a large (~700 m in diameter) and active hydrothermal dome. We wanted to determine if any movement could be detected by comparing newly collected data with the 1999 survey of the same area. No differential movement was detected (within the 60 cm margin of error) in the four years between 1999 and 2002.

Mapping the Arms in 2002 revealed a glaciated and faulted landscape bounded on its north by the topographic margin of the Yellowstone caldera. The bathymetry of the lake floor, especially in the Southeast Arm, shows many glacial meltwater features and stagnant ice block features. Similar features, such as Alder Lake, are mapped on land at the Promontory. Both the Southeast and South Arms are bounded by active



normal faults and, in tandem with glaciation, contribute to the overall form of the southern valleys.

The topographic margin of the Yellowstone caldera was determined to enter the western end of Flat Mountain Arm and continue along the channel of the arm. The caldera margin then enters and continues east-northeastward across the central lake basin. From the eastern shore of Frank Island, the caldera margin cuts northwest and emerges between the older Tertiary volcanic Lake Butte and the younger Turbid Lake hydrothermal explosion crater.

The campaign in 2003 was devoted to 1) sampling hydrothermal vent fluids and solids from the floor of Yellowstone Lake using a submersible ROV and 2) collecting sub-bottom seismic-reflection data for areas of special interest in the South and Southeast Arms and Central and Northern Basins. Just south off the Rock Point area, multiple young and active faults with small displacements that penetrate the lake floor were discovered in seismic profiles.

Significant Findings from Mapping of Yellowstone Lake

FIRST GEOLOGIC MAP OF YELLOWSTONE LAKE

Until the recent effort to map Yellowstone Lake, it remained a final frontier in the midst of detailed geologic mapping on land in Yellowstone National Park. As a result of the recent detailed mapping, we understand that the processes forming Yellowstone Lake can be separated into two major areas of the lake: 1) the northern two-thirds of the lake, including West Thumb basin, was formed primarily by volcanic and later hydrothermal processes; and 2) the southern third was shaped primarily by glacial and alluvial processes. Tectonic forces have and continue to influence all areas of the lake.

Yellowstone Lake is the centerpiece of the Yellowstone geocosystem and has been shaped by the main geologic forces that have created the Yellowstone landscape.

Formation of the lake probably predates formation of the 640,000-year-old Yellowstone caldera and may extend as far back as 2.05 million years ago when the Huckleberry Ridge caldera erupted. The eastern edge of that caldera is estimated to extend north-south through the central part of the lake. Physical evidence for formation of a lake can be inferred as far back as 640,000 years ago when the Yellowstone caldera erupted and formed a topographic basin bounded by a topographic rim on its southeastern part, now preserved in Yellowstone Lake. Shortly thereafter, large, previously unmapped rhyolitic lava flows were emplaced in the northern basin area.

Approximately 190,000 to 180,000 years ago, another caldera-forming eruption, this time much smaller and within the larger Yellowstone caldera, created the West Thumb basin formed from the eruption of the tuff of Bluff Point, which is now exposed along the east side of West Thumb basin. Around 154,000 to 150,000 years ago, several large rhyolitic lava flows were emplaced, first into the southern half of West Thumb caldera as the Aster Creek rhyolite flow and shortly after, into the northern half of West Thumb caldera as the West Thumb rhyolite flow. Both of these were massive lava flows from outside the West Thumb crater toward the east into the northern and central basins.

Glacial activity also played a dominant role in formation of Yellowstone Lake. Major and minor glacial advances and retreats occurred from ~180,000 to 140,000 years ago and from ~70,000 to 16,000 years ago. A north-south-trending axis of ice over 3000 feet thick is estimated to have covered the central basin before receding about 16,000 years ago.

Starting around 13,000 years ago, large (>100 m in diameter) hydrothermal explosion craters began to form in and around Yellowstone Lake; at least four to six large explosion craters have been mapped in the lake. At least six other large, post-glacial hydrothermal explosion craters have been mapped on land around or near Yellowstone Lake, making this area noteworthy for having the highest concentration of large hydrothermal explosion craters or domes in the park. Overlapping this time frame, various lake shore lines have been mapped

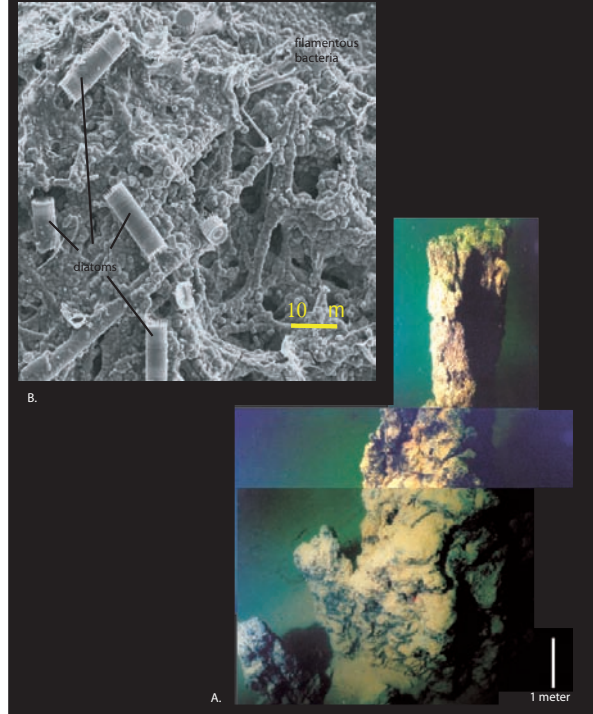
along the perimeter of Yellowstone Lake, which reflect the inflation and deflation of the Yellowstone caldera. Faulting associated with the mostly north-south trending fault segments such as the Lake Hotel graben, the Eagle Bay fault zone and the faults /seismic activity due south of West Thumb basin, has been contemporaneous with the current deformation of the caldera.

These geologic processes are reflected in the geologic map of Yellowstone Lake. Numerous large-volume, post-caldera rhyolitic lava flows, hundreds of hydrothermal vents, large hydrothermal explosion craters, fissures, faults, landslide deposits, hydrothermal domes, and submerged shoreline deposits also have been mapped. The identification of these deposits or features as landslide and hydrothermal explosion deposits, faults, and chemical dissolution craters indicate potentially hazardous events that have occurred recently in the lake and possibly could occur again.

CHEMISTRY OF SUBLACUSTRINE HYDROTHERMAL VENTS

Using multi-beam swath sonar and seismic-reflection profiling, over 650 hydrothermal vents were mapped as vent craters in Yellowstone Lake. Fluids from many of these vents, as well as from 44 of the 141 tributaries entering Yellowstone Lake, have been sampled and analyzed for chemical and isotopic composition. Results show that about 10% of the total chloride flux (used as an indicator of geothermal activity) in Yellowstone National Park occurs in Yellowstone Lake. Only Lower and Upper Geyser Basins are more significant thermal basins than the Yellowstone Lake basin.

Vent fluid samples obtained by ROV were analyzed for dissolved gases, chemical constituents, and stable isotope composition (Hydrogen, Oxygen, and Sulfur). Results show that the major dissolved gases are Carbon Dioxide (CO_2) and Hydrogen Sulfide (H_2S). Stable isotope studies show that vent fluids are meteoric water (rainfall and snowmelt), while H_2S is derived from deep magmatic degassing or leaching of sulfide minerals in the underlying volcanic rocks. Geochemical studies of dissolved constituents in hydrothermal vents show



▲ PHOTO 2.3 Images of siliceous spires mapped in Bridge Bay of Yellowstone Lake. A) Photomosaic of a small siliceous spire. Dimensions are ~5 m tall and ~3 m wide at base. B) Scanning electron photomicrograph of material from the interior of a spire showing that the spire is composed of silicified filamentous bacteria and diatoms. (David Lovatso)

that vent fluids are strongly enriched with a variety of potentially toxic elements, notably mercury, arsenic, molybdenum, and tungsten. In general, this composition is similar to other subaerial hot springs, thermal pools, and geysers in the park.

Vent fluids carry significant dissolved silica (SiO_2) and can deposit silica in conduits below the lake floor, as veins or zones of silicification in sediments, and in some cases as significant structures referred to as spires up to 8 m tall on the lake floor. Another major discovery of these studies, beautifully linking chemical and geological studies, shows that under certain conditions of mixing and cooling, vent fluids can dissolve silica in a wholesale fashion from sediments at the vent sites. This mechanism produces some of the vent craters observed by bathymetric and seismic reflection mapping.

Mercury is one of several potentially toxic metals emitted from hydrothermal vents on the floor of Yellowstone Lake and, as such, has a significant impact on its uptake into the food chain. As part of the hydrothermal studies and mapping in Yellowstone Lake project, a site called

the “cutthroat jacuzzi” near West Thumb Geyser Basin was visited and sampled. This site, a low-temperature hydrothermal vent (hot spring) in about 5 m of water depth, was named by a University of Wisconsin-Milwaukee research group after noticing persistent populations of 5-20 cutthroat trout frequenting the vent area. The trout were occasionally observed feeding on bacterial mats and amphipods (small shrimp-like crustaceans) in vent waters. We immediately recognized that this might constitute a biochemical pathway introducing potentially toxic elements into the ecosystem and set about sampling cutthroat and lake trout tissue. Chemical analyses of fish muscle proceeded along with analyses of lake water, hydrothermal vent fluid, and related silica-rich sinter deposits.

Results soon indicated that both fish muscle and sinter deposits from Yellowstone Lake carry significant mercury. This resulted in a letter to then Superintendent Mike Finley about the mercury content of the fish, which was mostly below the EPA (1.0 mg/g wet weight) and World Health Organization limits (0.5 mg/g) for edible fish, with occasionally samples above these limits. The park was immediately notified and agreed to provide funding for a more thorough job of analyzing fish of different sizes and ages, and from different parts of the lake. Results indicated an average of about 0.25 mg/g mercury, which is far enough below established limits that the risk to humans from occasional consumption is small. As an interesting side note, one early proposal in the struggle to save the native cutthroat trout in Yellowstone Lake from lake trout predation considered establishing a commercial fishery in the lake to target the lake trout. With the availability of this new data, the Park Service discarded this possible plan in part because of the discovery of mercury concentration in the trout.

We then turned our attention to mercury sources and pathways in the ecosystem. Recalling our observations of trout feeding at the “cutthroat jacuzzi,” we obtained and analyzed stomach contents of several lake and cutthroat trout. While large lake trout often have cutthroat in their stomachs, cutthroat trout often have abundant amphipods. In both cases, analyses showed



▲ PHOTO 2.4 When high levels of mercury were discovered in the native Yellowstone trout fishery, it was feared that grizzly bears, eagles, and other predators on the trout may be suffering. To date, there is no evidence that mercury from the deep lake vents is detrimental to the complex food web in the Park. (Big Sky Institute, MSU)

that the mercury concentrations in the stomach content were similar to, or somewhat lower than, that in the fish muscle, suggesting amphipods as the source of mercury. The mode of bioaccumulation from vent fluids to amphipods to fish has not been studied in detail, but presumably involves bacterial conversion of mercury to methyl mercury, which is incorporated into the bacterial cells and then transferred to small crustaceans during feeding.

On the other end of the food chain, we were interested in whether the mercury in cutthroat trout was accumulating in predators such as grizzly bear, osprey, eagle, and otter. Coincidentally, our colleague Bob Rye, working with Chuck Schwarz (U.S.G.S. Interagency Grizzly Bear Study Team), used stable isotopes of C, S, and N on

bear hair to see if food sources could be determined using relatively new isotope techniques. We obtained hair samples collected both around tributary streams to Yellowstone Lake where the cutthroat spawn and from remote areas. Results indicated dramatically higher mercury concentration in the hair of bear that feed on cutthroat trout. Subsequent studies have shown that the spawning trout are the only source of mercury in bear foods in Yellowstone, and that the levels of mercury the bears accumulate is not detrimental to their health. Similar studies for osprey, eagle, and otter have not been carried out yet.

Policies

High-resolution geophysical mapping of Yellowstone Lake was a joint effort supported by the US Geological Survey and Yellowstone National Park from 1999-2003 and addressed key issues for both agencies. By producing a high-resolution (<1 m accuracy) bathymetric map of the lake floor with complimentary seismic reflection profiles, a detailed geologic interpretation has been developed. The new data sets were used to make an interpretive geologic map of the lake, which identified potentially hazardous deposits, features, and resources, and contributed to the volcanic and hydrothermal hazard assessment for Yellowstone National Park. The new bathymetric map allows the National Park Service Fisheries Division to focus on various management techniques in areas interpreted as prime spawning habitat for lake trout. Additional research characterizing specific sites on the lake floor have continued. The new bathymetric and geologic maps are available through several distribution centers, the authors, or on line at: <http://pubs.usgs.gov/sim/2007/2973/>.

Policies affected by the recent mapping of Yellowstone Lake may include: 1) new management policies toward lake trout populations in the lake; 2) the understanding of potentially hazardous events in the lake, and 3) the location and subsequent protection of rare and unusual geologic deposits. Long-standing policies regarding the exploitation of thermal species and protection of thermal features in Yellowstone are firmly in place and may now be applied to the underwater resources.

Future Research

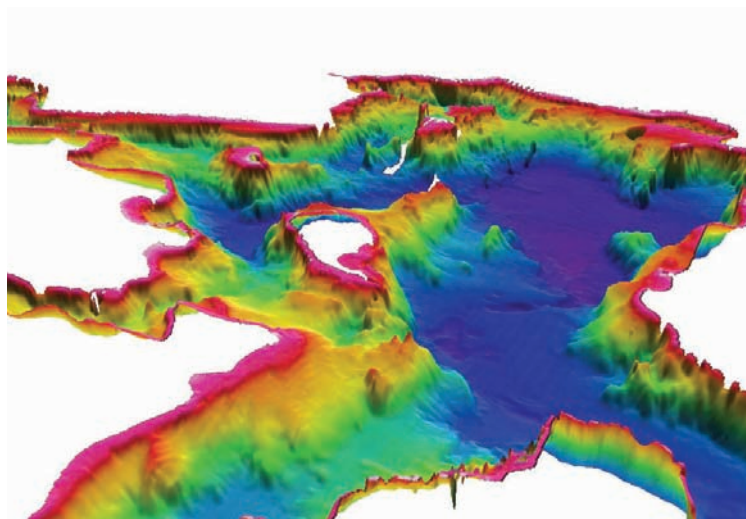
The new bathymetric and geologic maps of Yellowstone Lake serve as the foundation for more detailed studies regarding its recent geologic history and potential hazards, a lake-wide all-taxa inventory, a baseline datum of the lake floor; and a high-resolution map to a natural laboratory allowing one to examine the interrelationships between geology and biology. Collaborative efforts are underway among microbiologists, geologists, and geochemists to conduct an all taxa inventory throughout Yellowstone Lake with an emphasis on the microbial species present. The goal of this endeavor is to improve understanding of the interrelationship between geology, geochemistry, and microbiology.

Future research may propose a selective coring program in the lake that will focus on the broad range of features and deposits created by a variety of geologic processes and their details. For example, along the northeastern edge of the lake, landslide deposits are mapped yet the data currently available sheds no or little information to determine whether these deposits represent one landslide event or many. The answer to this question is significant because different scenarios will produce different volumes of water potentially displaced by future landslides of varying volumes. Coring such deposits would help resolve the question of how large a landslide might reasonably be expected, how many events have occurred, when did these events occur, what triggered the landslide events, and when might the next event be. Additionally a detailed modern analysis of cores from Yellowstone Lake would yield detailed insights into the climatic evolution recorded in lake sediments for at least the past 200,000 years. Other important geologic histories that require additional information could include details about hydrothermal domes and explosion craters.

Yellowstone Lake is still a relatively unknown corner of the park. Technology and scientific interest, however, have changed and the scientific foundation established by new mapping will be built upon by future generations interested in the geology and ecosystem of Yellowstone Lake. New developments in ever-higher resolution

mapping and imaging, increasingly by autonomous underwater vehicles, will allow more detailed mapping and imaging of smaller features, and monitoring of dynamic crustal movement in the Yellowstone Caldera. New microbiological studies will increasingly link understanding of chemical and biological processes and their effects on the ecosystem. Finally, studies of the effect of potentially toxic elements generated by hydrothermal activity in the lake and elsewhere should be carefully evaluated by studying transference up the food chain, including eagles, osprey, and otters. All of these activities will inform the public and lead to better management of the Park's resources and better understanding of possible hazards under the aegis of the Yellowstone Volcano Observatory.

ACKNOWLEDGMENTS: The authors acknowledge individuals at the National Park Service (Yellowstone National Park) and the U.S. Geological Survey whose support contributed greatly to the success of mapping Yellowstone Lake. These individuals include John Varley, Mike Finley, Kate Johnson, Ed du Bray, Geoff Plumlee, Pat Leahy, Steve Bohlen, Tom Casadevall, Linda Gundersen, Denny Fenn, Elliott Spiker, Dick Jachowski, Tom Oliff, Paul Doss, and Connie Nutt. Our collaboration with Dave Lovalvo of Eastern Oceanics, Inc. over the past decade has been great and has allowed for unparalleled mapping and exploration of the lake floor. Our partnership with John Varley, Ken Pierce, Bill Stephenson, Sam Johnson, Steve Harlan, Carol Finn, Jim Maki, Pat Bigelow, Jacob Lowenstern, Henry Heasler, Robert Christiansen, Bill Seyfried, Kang Ding, Bill Inskeep, Tim McDermott, and Rich Macur on various aspects of this research has enhanced our understanding of processes associated with Yellowstone Lake. We gratefully acknowledge our collaboration and work with individuals from L-3 Communications,



▲ FIGURE 2.4 Several years, multiple scientists, and sophisticated technology helped produce the first comprehensive map of the floor of Yellowstone Lake (view to the NW). (Lisa Morgan, USGS)

Boris Schulze, Jorg Duhn, Joerg Brockhoff, and Peter Gimpel. We thank Dan Reinhart, Lloyd Kortge, Paul Doss, Rick Fey, John Lonsbury, Ann Deutch, Jeff Alt, Julie Friedman, Brenda Beitler, Charles Ginsburg, Jim Bruckner, Pam Gemery-Hill, Rick Sanzalone, Maurice Chaffey, Dave Hill, Bree Burdick, Erica Thompson, Eric White, Bob Evanoff, Wes Miles, Rick Mossman, Gary Nelson, Christie Hendrix, Tim Morzel, and many others for assistance with field studies. We are grateful to Coleen Chaney, Debi Dale, Maggie Gulley, Joan Luce, Mary Miller, Vicky Stricker, Maggie Gulley, Sandie Williamson, and Robert Valdez for their skillful assistance with project logistics. We are grateful for the constructive reviews by Brad van Gosen, Bruce Heise, and Jerry Johnson. This research was supported by the U.S. Geological Survey, the National Park Service, and the Yellowstone Foundation.