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Yellowstone Volcano Observatory

2017 Annual Report

Circular 1456

U.S. Department of the Interior
U.S. Geological Survey

Location map showing thermal areas (in red) and noteworthy geographic features in the Yellowstone National Park region. The red line marks Yellowstone Caldera.

Cover. Photograph of Grand Prismatic Spring looking south-southwest, Yellowstone National Park. Reuters photograph by Jim Urquhart.

Facing page. Photograph of Guardian Geyser in Norris Geyser Basin, Yellowstone National Park. U.S. Geological Survey photograph by Deborah Bergfeld.

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DAVID BERNHARDT, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2019

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Photograph of Global Positioning Station P709 on Promontory Point of Yellowstone Lake in Yellowstone National Park. This sensor can detect millimeter-scale movements of the ground surface. UNAVCO photograph.

Photograph by Corey Tran on Unsplash.

Yellowstone Volcano Observatory

2017 Annual Report

By the Yellowstone Volcano Observatory[1]

Introduction

The Yellowstone Volcano Observatory (YVO) monitors volcanic and hydrothermal activity associated with the Yellowstone magmatic system, conducts research into magmatic processes occurring beneath Yellowstone Caldera, and issues timely warnings and guidance related to potential future geologic hazards (see sidebar on volcanic hazards on p. 2). The observatory is a collaborative consortium made up of the U.S. Geological Survey (USGS), National Park Service, University of Utah, University of Wyoming, UNAVCO, Wyoming State Geological Survey, Montana Bureau of Mines and Geology, and Idaho Geological Survey (see sidebar on YVO on p. 3). The USGS arm of YVO also has the operational responsibility for monitoring volcanic activity in the intermountain west of the United States, including Arizona, New Mexico, Utah, and Colorado.

This report summarizes the activities and findings of YVO during the year 2017, focusing on the Yellowstone magmatic system. The most noteworthy event of the year was the Maple Creek earthquake swarm of June–September, about 15 kilometers (9 miles) north-northwest of West Yellowstone, Montana. Over 2,400 earthquakes were located, including a felt magnitude 4.4 earthquake on June 15. Deformation was mostly consistent throughout the year, with uplift of the Norris Geyser Basin area and subsidence of the caldera, both at rates of a few centimeters (or inches) per year. The only significant interruption in this pattern was an ~2-week period of subsidence at Norris Geyser Basin in early December, after which deformation returned to uplift.

Field work in 2017, conducted under research permits granted by the National Park Service, included routine maintenance visits to seismic and geodetic stations as well as

- Deployment of a semipermanent Global Positioning System (GPS) network during the summer months,
- Installation of Multi-GAS and eddy covariance systems for tracking gas emissions at the Solfatara Plateau thermal area,
- Deployment of a nodal seismic array in Upper Geyser Basin, and
- Collection of gas and water samples from Boundary Creek on the western side of Yellowstone National Park.

Throughout 2017, the aviation color code for Yellowstone Caldera remained at "green" and the volcano alert level remained at "normal." Total seismicity—3,427 located earthquakes—was elevated relative to previous years, but not significantly above levels that would be considered background.

YVO Staff Changes

The year 2017 saw major changes in YVO staff. On September 1, Michael Poland assumed the role of YVO Scientist-in-Charge, succeeding Jacob Lowenstern after his 15 years of service. Wendy Stovall likewise succeeded Peter Cervelli as Deputy Scientist-in-Charge. Both Wendy and Mike are based at the USGS Cascades Volcano Observatory in Vancouver, Washington. In addition, Jamie Farrell succeeded Robert Smith—one of the founding members of the YVO consortium—as the Chief Seismologist. Finally, Erin Campbell was named the State Geologist of Wyoming and Director of the Wyoming State Geological Survey upon Tom Drean's retirement from the position.

Seismology

Earthquakes have been monitored in the Yellowstone area since the 1970s (see sidebar on seismicity on p. 4–5). The Yellowstone Seismic Network is maintained and operated by the University of Utah Seismograph Stations, which records data from 46 stations in the Yellowstone region. On average, about 1,500–2,500 earthquakes are located in and around Yellowstone National Park every year (most of which are too small to be felt by humans), making the Yellowstone region one of the most seismically active areas in the United States.

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[1]This report was prepared jointly by members of the Yellowstone Volcano Observatory consortium, including Michael Poland, Debroah Bergfeld, Daniel Dzurisin, Shaul Hurwitz, Jennifer Lewicki, Blaine McClesky, Lisa Morgan, Pat Shanks, Mark Stelten, Wendy Stovall, R. Greg Vaughan, and Charles Wicks of the U.S. Geological Survey; Jefferson Hungerford and Behnaz Hosseini of the National Park Service; Jamie Farrell and Robert Smith of the University of Utah; and David Mencion of UNAVCO. Jacob Lowenstern and Seth Moran of the U.S. Geological Survey reviewed this report.

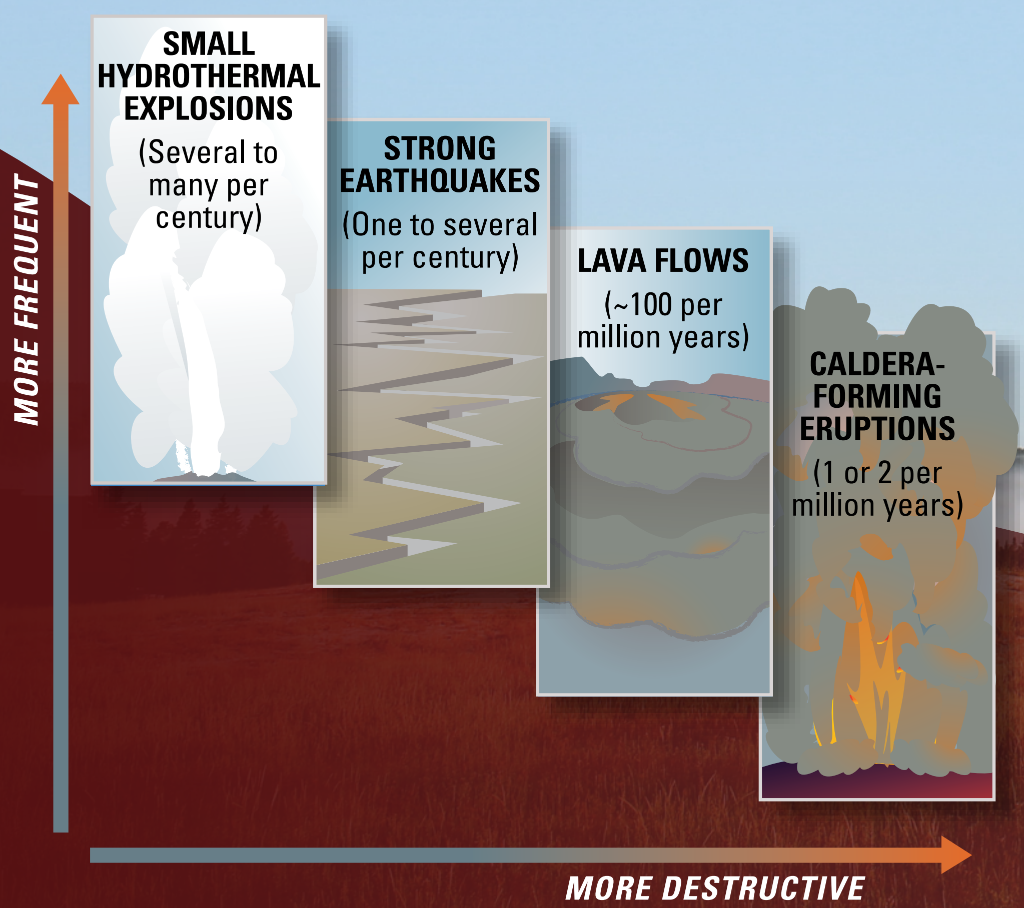
Sidebar Hazards in the Yellowstone Region

The Yellowstone Plateau in the northern Rocky Mountains of Wyoming, Montana, and Idaho is centered on a youthful, active volcanic system with subterranean magma (molten rock), boiling and pressurized waters, and a variety of active faults that pose significant earthquake hazard. This combination creates a diversity of hazards, but the most catastrophic hazardous events—large volcanic explosions—are also the least likely to occur.

Over the past 2.1 million years, Yellowstone Caldera has had three immense explosive volcanic eruptions that blanketed large parts of the North American continent with ash and debris and created sizable calderas. Yellowstone Caldera, which comprises nearly one third of the land area in Yellowstone National Park, formed 631,000 years ago during the most recent of these large explosive phases. Its formation was followed by dozens of less explosive but massive lava flows, the latest of which erupted 70,000 years ago.

Tectonic extension of the western United States has created a series of regional faults that are responsible for large earthquakes in the Yellowstone region along faults such as the Teton and Hebgen Faults. Most recently, a devastating magnitude 7.3 earthquake in 1959 killed 28 people, and a strong magnitude 6.1 earthquake near Norris Geyser Basin in 1975 was widely felt.

Yellowstone National Park's famous geothermal waters create fabulous hot springs and geysers but occasionally explode catastrophically to create hydrothermal explosion craters found throughout the park. At least 25 explosions that left craters greater than 100 meters (328 feet) wide have occurred since the last ice age ended in the Yellowstone area 16,000–14,000 years ago. Much smaller explosions, which leave craters only a few meters (yards) across, happen every few years in the Yellowstone area.



The most destructive hazards in the Yellowstone area, including volcanic explosions and lava flow eruptions, are also the least likely to occur. On human timescales, the most likely hazards are small hydrothermal explosions and strong earthquakes. Modified from U.S. Geological Survey Fact Sheet 2005–3024 (Lowenstern and others, 2005).

Sidebar What is the Yellowstone Volcano Observatory?

The Yellowstone Volcano Observatory (YVO) was formed on May 14, 2001, to strengthen the long-term monitoring of volcanic and seismic unrest in the Yellowstone National Park region. YVO is a “virtual” observatory that does not have an on-site building to house employees. Instead, it is a consortium of eight organizations spread throughout the western United States that join together to monitor and study Yellowstone’s volcanic and hydrothermal systems, as well as disseminate data, interpretations, and accumulated knowledge to the public. The partnership provides for improved collaborative study and monitoring of active geologic processes and hazards of the Yellowstone Plateau volcanic field, which is the site of the largest and most diverse collection of natural thermal features on Earth, the world’s first national park, and the United States’ first World Heritage Site.

Each of the eight consortium agencies offers unique skill sets and expertise to YVO. The U.S. Geological Survey has the Federal responsibility to provide warnings of volcanic activity and holds the ultimate authority over YVO operations. Key geophysical monitoring sites were established and are maintained by the University of Utah and UNAVCO, and scientists from these two organizations analyze and provide data to the public. Yellowstone National Park, operated by the National Park Service, is the land manager and is responsible for emergency response to natural disasters within the national park boundaries. The Wyoming State Geological Survey, Montana Bureau of Mines and Geology, and Idaho Geological Survey provide critical hazards information and outreach products to their respective citizens. The University of Wyoming supports research into Yellowstone’s volcanic and hydrothermal activity, as well as the geologic history of the region. YVO agencies also aid and collaborate with scientists outside the consortium.

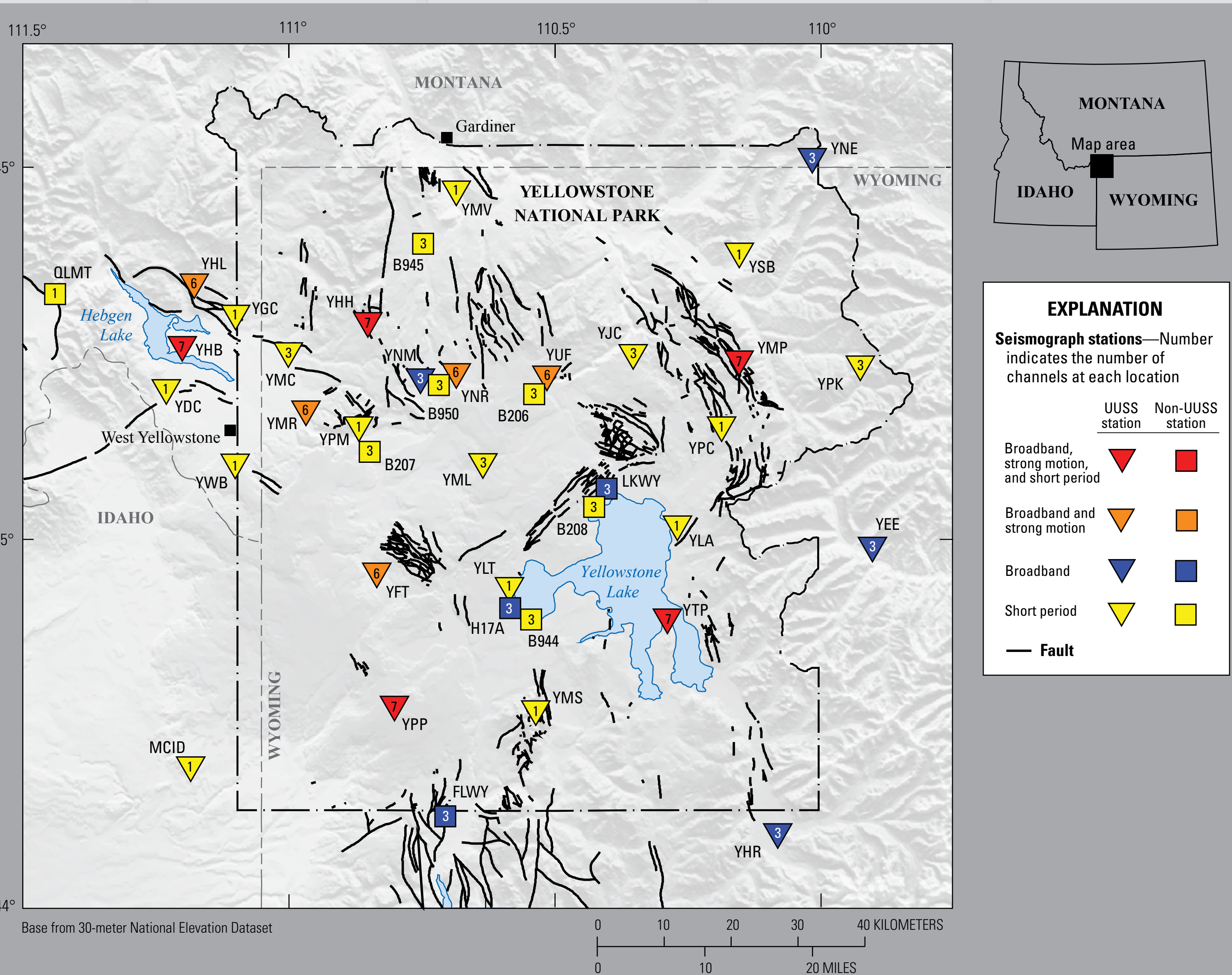
Member agencies of the Yellowstone Volcano Observatory.
Background photograph by Emily Campbell on Unsplash.

Sidebar Seismicity in Yellowstone Plateau

Seismicity in the Yellowstone Plateau is monitored by the University of Utah Seismograph Stations. The earthquake monitoring network, known as the Yellowstone Seismic Network, consists of about 46 seismometers installed in the seismically active Yellowstone National Park and surrounding area. It is designed for the purpose of monitoring earthquake activity associated with tectonic faulting as well as volcanic and hydrothermal activity. Data are also used to study the subsurface processes of Yellowstone Caldera.

Seismic monitoring in the Yellowstone area began in earnest during the early 1970s, when a seismic network was installed by the U.S. Geological Survey. This network operated until the early 1980s when it was discontinued for budgetary reasons. The network was re-established and expanded by the University of Utah in 1984 and has been in operation ever since. Over the years, the Yellowstone Seismic Network has been updated with modern digital seismic recording equipment, making it one of the most modern volcano-monitoring networks in the world.

Presently, data are transmitted from seismic stations in the Yellowstone area to the University of Utah in real-time using a sophisticated radio and satellite telemetry system. Given that Yellowstone Plateau is a high-elevation region that experiences heavy snowfall and frigid temperatures much of the year, and that many of the data transmission sites are located on tall peaks, it is a challenge to keep the data flowing during the harsh winter months. It is not uncommon for seismometers to go offline for short periods because the solar panels

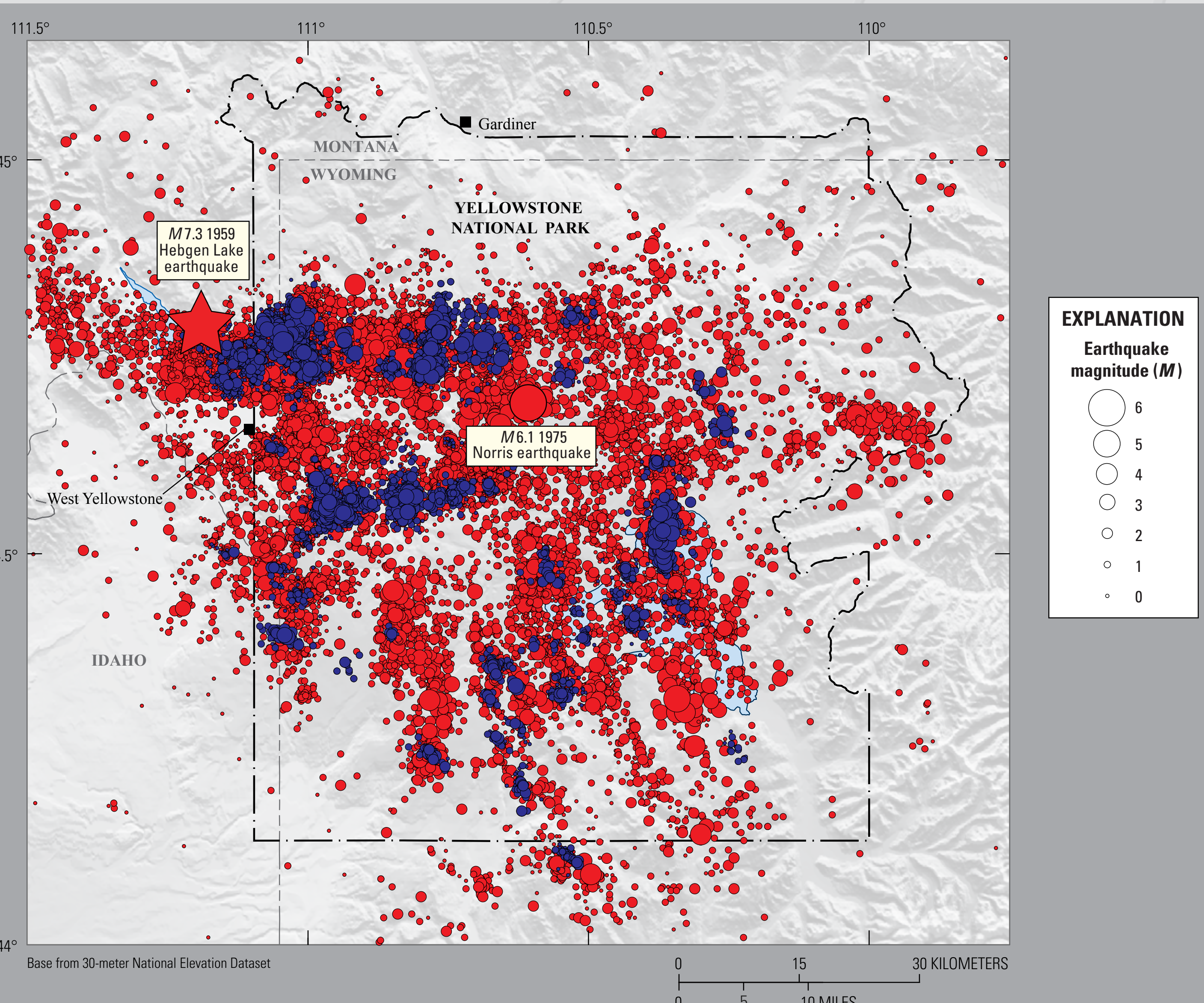


Map of the seismometer station locations operated by the University of Utah Seismograph Stations (UUSS) and other agencies. Map view shows the Yellowstone earthquake catalog region.

or antennas get covered in snow and ice. Sometimes seismometers that go offline during the winter cannot be accessed until the following spring.

Since 1973, there have been over 48,000 earthquakes located in the Yellowstone region. More than 99 percent of those earthquakes are magnitude 2 or below and are not felt by anyone. During that time, there has been one magnitude 6 event—the 1975 magnitude 6.1 Norris earthquake located near Norris Geyser Basin (the largest earthquake ever recorded in Yellowstone National Park). There have also been two earthquakes in the magnitude 5 range, 29 earthquakes in the magnitude 4 range, and 379 earthquakes in the magnitude 3 range. The largest earthquake ever recorded in the Yellowstone area was the 1959 magnitude 7.3 Hebgen Lake earthquake, which was located just west of the national park boundary and north-northwest of West Yellowstone, Montana. That earthquake was responsible for 28 deaths and had a major impact on the hydrothermal systems of nearby Yellowstone National Park, including Old Faithful Geyser.

Earthquake swarms (earthquakes that cluster in time and space) account for about 50 percent of the total seismicity in the Yellowstone region. They are most common in the east-west band of seismicity between Hebgen Lake and the Norris Geyser Basin. Most swarms are small and short, containing 10–20 earthquakes and lasting for 1–2 days, although large swarms of thousands of earthquakes lasting for months do occur on occasion (for example, in 1985–86 and in 2017).



Map of Yellowstone earthquakes as located by the University of Utah Seismograph Stations from 1973–2017. Red circles represent individual earthquakes and blue circles indicate individual earthquakes that were part of swarms. The size of the circles is scaled to the magnitude (*M*) of the earthquake, where larger circles represent stronger earthquakes.

Overall Seismicity During 2017

During 2017, the University of Utah Seismograph Stations located 3,427 earthquakes in the Yellowstone region (fig. 1). Of these earthquakes, 19 were felt, meaning that people reported some shaking. The largest event of the year was a magnitude 4.4 earthquake that occurred on June 15, 2017, at 5:48 p.m. local time and was reported felt by over 120 people in Yellowstone National Park and the surrounding communities, including West Yellowstone, Montana.

Nearly 80 percent of all the earthquakes that were located in 2017 occurred as part of 13 swarms, which are defined as the occurrence of many earthquakes in the same small area over a short period of time. The largest of these was the Maple Creek swarm, located on the west side of Yellowstone National Park and a few miles north-northeast of West Yellowstone, Montana. The swarm, which included 2,440 located earthquakes, began on June 12, was punctuated by the magnitude 4.4 earthquake on June 15, and continued until late September. By these measures, the Maple Creek swarm was the second largest and

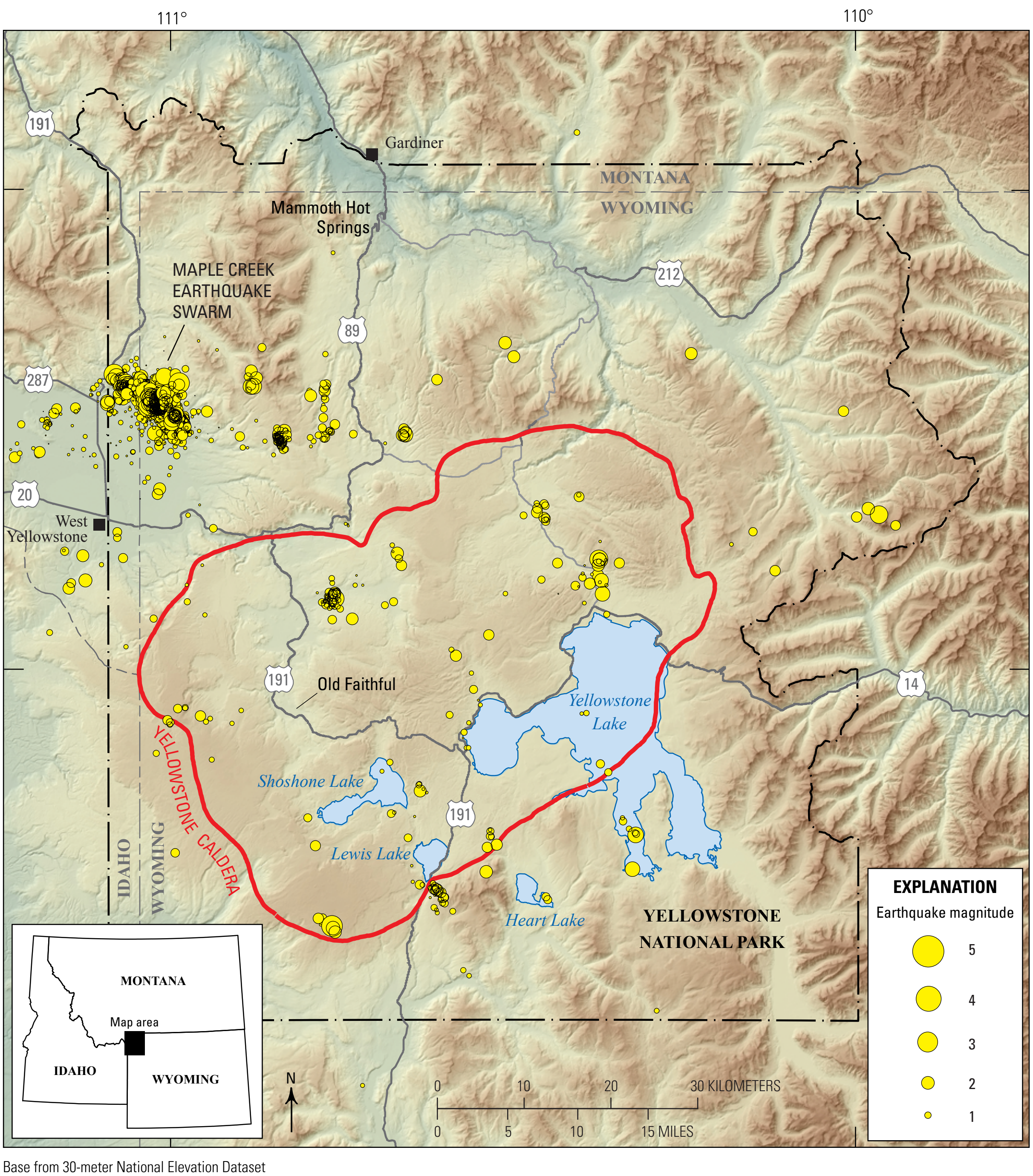


Figure 1. Map of earthquakes (yellow circles) that occurred during 2017 in the Yellowstone National Park region.

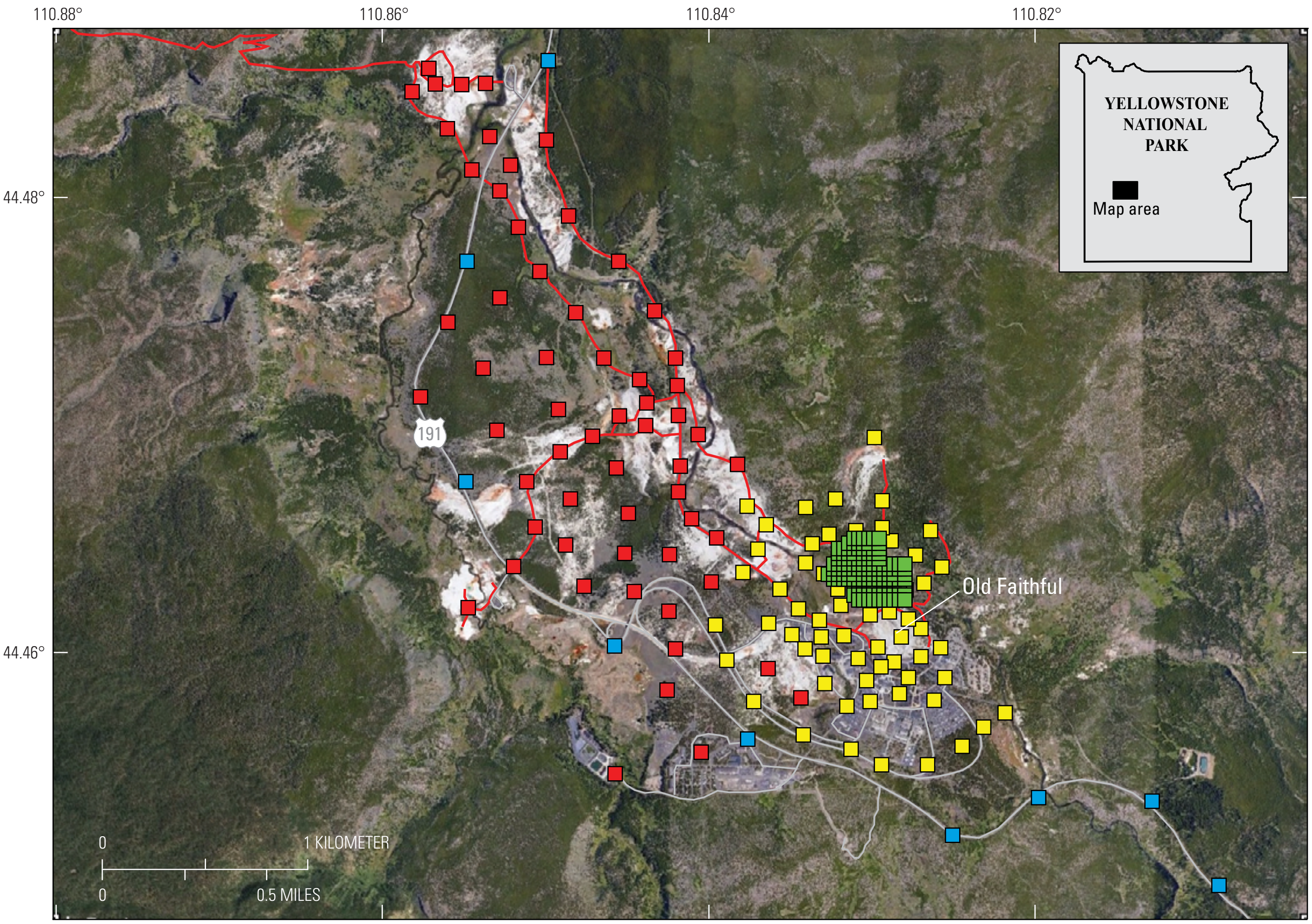
second longest Yellowstone-area swarm ever recorded (only the November 1985–February 1986 swarm was larger in terms of total seismicity and duration). Earthquakes continued in this area throughout the rest of the year, although never reaching the intensity of the June–September period.

Additional earthquake swarms occurred outside the Yellowstone area during summer 2017 near Lincoln, Montana, and Soda Springs, Idaho. These swarms were each initiated by widely felt magnitude 5+ earthquakes, but they were not related to the Yellowstone magmatic system; instead, the earthquakes were caused by faulting associated with tectonic extension of the western United States.

Upper Geyser Basin Experiment

As part of a research project that began in 2015, 290 temporary seismometers (fig. 2) were installed in and around the Upper Geyser Basin in Yellowstone National Park (fig. 3) in November 2017. The study aimed to identify locations of

Figure 2. Seismologists from the University of Utah and University of Texas at El Paso prepare equipment for deployment as part of the 2017 Upper Geyser Basin seismic experiment. Photograph by Sin-Mei Wu, University of Utah.



Satellite image from Google Earth © 2016

Figure 3. Map of the Upper Geyser Basin temporary seismic network deployed in 2017. Green squares represent the dense Geyser Hill array; yellow squares are the “backbone” array that was deployed during experiments in 2015, 2016, and 2017; red squares are the “basin wide” array, which covers the entire Upper Geyser Basin; and blue squares are part of a north-south line of sensors along the road spaced about every 1 kilometer and extending northward about another 28 kilometers, almost to Madison Junction.

hydrothermal fluid flow (whether or not it is observable on the surface) and to record seismicity from hydrothermal features to better understand how these systems function, are connected, and influence each other. This was the third consecutive year of similar instrumentation deployments by the University of Utah, in conjunction with Yellowstone National Park and the University of Texas at El Paso. The focus of the 2017 work was Geyser Hill (an area of highly concentrated hydrothermal vents on the north bank of the Firehole River), where a dense array of 136 seismometers with an average station spacing of ~75 feet covered the entire area (green squares in figure 3). The instruments recorded data for about 2 weeks before being removed.

Preliminary results from 2017 indicate that Doublet Pool behaved differently compared to measurements collected in November 2015 and November 2016. Although Doublet Pool does not erupt water, it is famous for audible “thumping” and surface disturbances. In 2015 and 2016, these episodes occurred about every 40 minutes and lasted for 7–8 minutes each. In 2017, however, these episodes took place more frequently (about every 29–30 minutes) and lasted longer (8–9 minutes each). Analysis of the data collected from the area should reveal whether or not the changes in Doublet Pool’s characteristics are related to changes in the underlying hydrothermal plumbing system.

In addition to the dense array deployed on Geyser Hill, a more extensive array was established across the entire Upper Geyser Basin (red squares in figure 3), with the goal of better understanding the overall characteristics of the hydrothermal system within the basin. Combined with focused deployments around Old Faithful in 2015 and 2016, these data will provide a wealth of new information that will help scientists to better understand how these world-famous hydrothermal systems work and how they react to outside forces (such as large earthquakes and changes in weather).

Geodesy

Surface deformation and gravity change, collectively referred to as geodesy, constitute important indictors of subsurface processes (see sidebar on monitoring deformation on p. 12–13). In the Yellowstone region, deformation is measured by GPS stations, borehole tiltmeters and strainmeters, and with a technique called interferometric synthetic aperture radar (InSAR). The GPS, tiltmeter, and strainmeter networks are operated by UNAVCO; InSAR data are acquired from an international constellation of Earth-orbiting satellites.

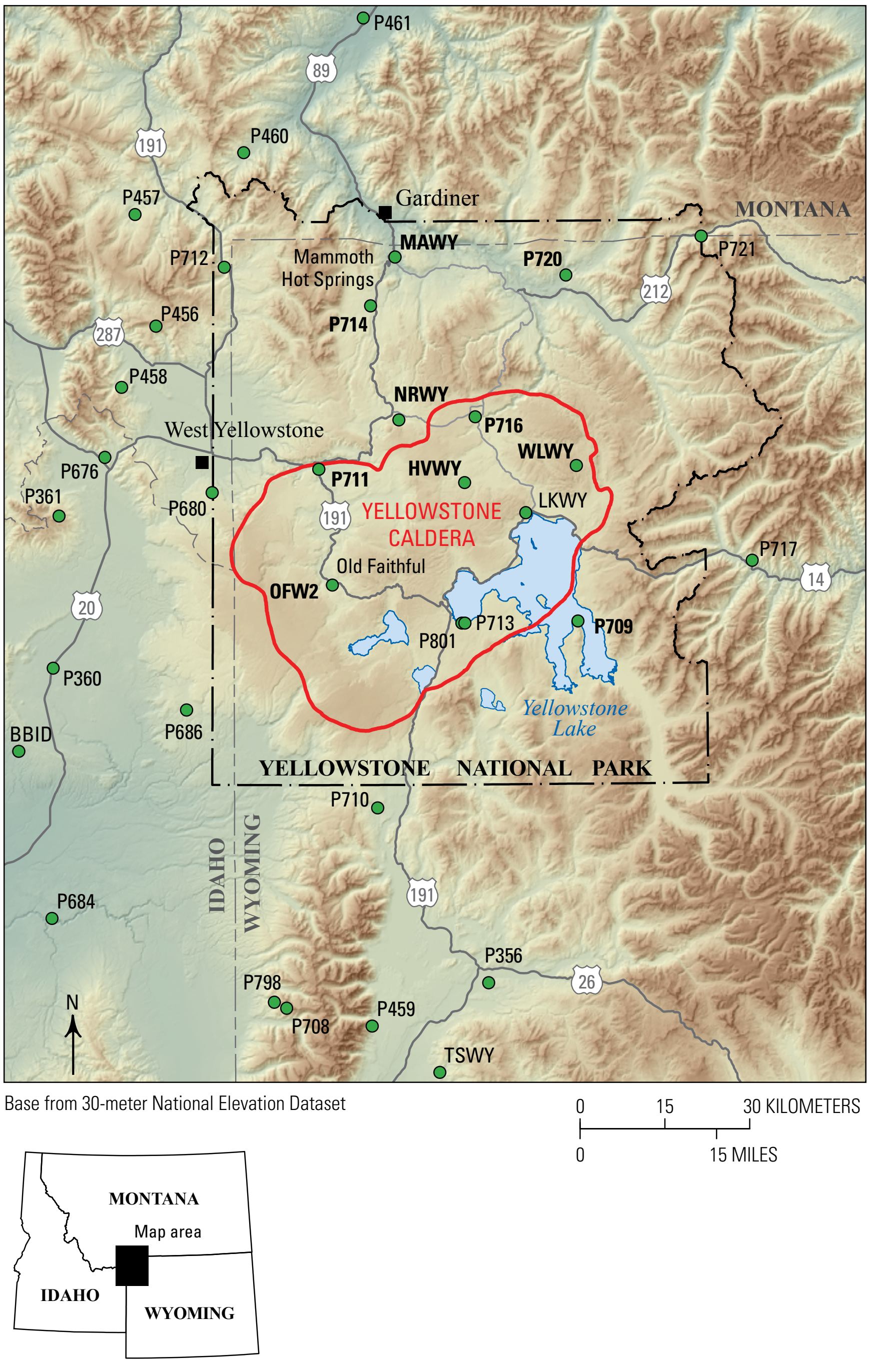
Overall Deformation in 2017

Deformation patterns indicated by GPS stations, 15 of which are located within Yellowstone National Park, were largely steady over the course of 2017 and continued trends that began in late 2015 and early 2016. Stations in the caldera subsided at rates of a few centimeters per year, whereas station NRWY, near Norris Geyser Basin, uplifted at a similar rate (fig. 4). This pattern was briefly interrupted in early December, when station NRWY subsided by approximately 2 centimeters over the course of 2–3 weeks. Stations within Yellowstone Caldera showed no change in the pattern of subsidence during this 2–3 week time period. By the end of December, the subsidence had ceased, and uplift resumed. The brief subsidence of the Norris Geyser Basin area did not correlate with any other geophysical or geological changes (such as seismicity or hydrothermal activity), and the cause of the short-term deformation is not clear, although the rapid nature of the deformation suggests a process involving the migration of hydrothermal fluids underground—probably water and gases.

In addition to GPS stations, there are 5 borehole tiltmeters and 4 borehole strainmeters that are operational within Yellowstone National Park. These stations are most useful for detecting short-term variations in deformation (for example, owing to earthquakes or sudden changes in ground movement), because these instruments (especially tiltmeters) can drift over weeks to months and show trends that are not related to deformation. In 2017, the tiltmeter and strainmeter networks did not detect any significant changes. Even the Norris Geyser Basin subsidence of December 2017 occurred too slowly to be detected by a nearby tiltmeter.

Semipermanent GPS Results

Starting in 2008, the Yellowstone continuous GPS network was densified by adding several temporary stations that are deployed each summer, generally from early May through late October, then removed prior to the start of the harsh Rocky Mountain winter. This type of deployment, sometimes referred to as semicontinuous or semipermanent GPS, has several advantages. Semipermanent GPS networks are less intrusive on the landscape than continuous GPS installations, which makes it easier to satisfy land-use restrictions in ecologically sensitive areas like Yellowstone National Park. All of the Yellowstone semipermanent GPS sites are close to roads and trails for ease of deployment but are kept out of sight (including while the equipment is deployed). At other times, all that remains is a small steel pin attached to rock that serves as a benchmark. Semipermanent GPS stations are much easier to install and less expensive to operate than continuous GPS stations, which require radio telemetry to continuously transmit data and sufficient power to operate year round. Of course, a disadvantage of semipermanent GPS compared to continuous GPS is that semipermanent GPS data are intermittent whereas continuous GPS data are collected year round. Together, the two approaches complement one another by providing precise ground deformation data from more than 25 sites in and around Yellowstone National Park. The large number of stations is necessary to adequately characterize deformation patterns at Yellowstone Caldera and Norris Geyser Basin, which can be complex and change rapidly. Currently, the Yellowstone semipermanent GPS network consists of 11 stations in Yellowstone National Park and 1 station in the U.S. Forest Service Hebgen Lake Ranger District (fig. 5).



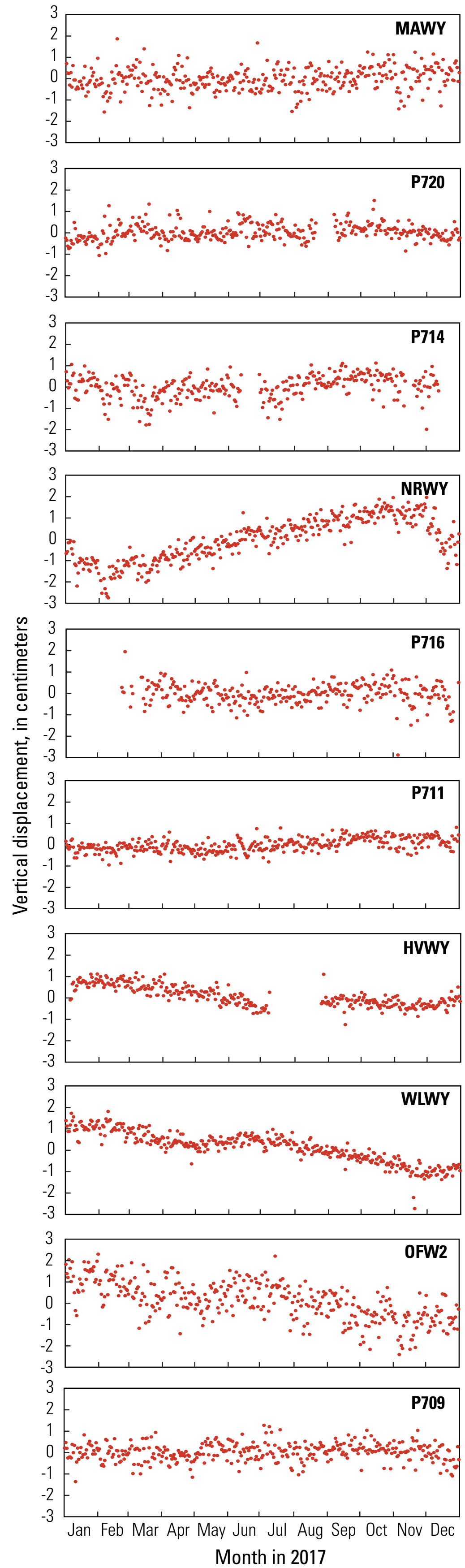
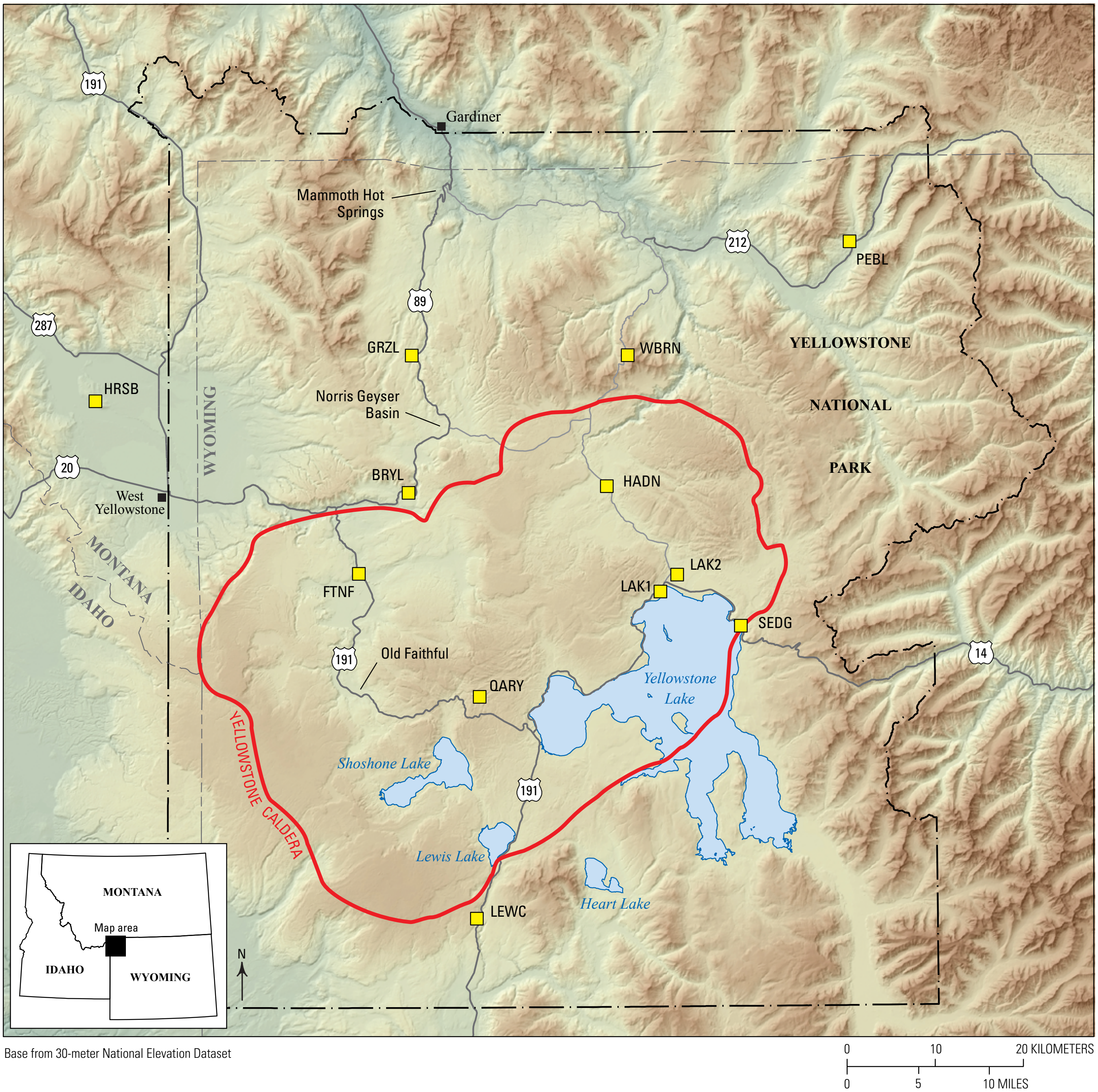


Figure 4. Map of Global Positioning System (GPS) stations and time-series data showing the deformation observed in Yellowstone National Park in 2017. Vertical displacement (up or down movement of the ground) throughout the year is plotted for 10 selected GPS stations (green dots with bold labels) located around the park. The vertical axis of all plots is in centimeters, where downward trends indicate subsidence and upward trends indicate uplift. General trends during 2017 are subsidence within the Yellowstone Caldera (exemplified by stations WLWY and OFW2), uplift near the Norris Geyser Basin (at station NRWY), and no significant vertical motion elsewhere.



Base from 30-meter National Elevation Dataset

Figure 5. Locations of semipermanent Global Positioning System stations in the Yellowstone National Park area.

In 2017, nine of the twelve semipermanent GPS stations were deployed during April 23–27. Road conditions at the time prevented the deployment of three other stations (LEWC, QARY, WBRN) until June 21–23. All twelve stations were retrieved during October 11–15. Ten of the twelve stations recorded data successfully for the entire time they were deployed. Equipment problems prevented data from recording at station FTNF after mid-August, and at station SEDG from early June through late July. The data from station SEDG also were affected by deep snow that obstructed the sky view during the last week of April and first few days of May. As a whole, the network recorded about 95 percent of possible station-days.

An example of the utility of semipermanent GPS data for studying active processes is shown in figure 6. Two semipermanent GPS stations, LAK1 and LAK2, were added in August 2016 for the specific purpose of monitoring the loading effect caused by changing water levels in Yellowstone Lake. We hoped to learn if, and by how much, the shoreline is depressed during spring when lake level is high and then rebounds during summer when the level is lower. Heavy runoff from a thick 2016–17 winter snowpack produced large changes in lake level during the stations' first full field season in 2017, and the loading effect was well recorded at both sites. Station LAK1 moved down about 25 millimeters (~1 inch) from late April through late June, whereas station LAK2, farther from the shoreline, moved down about 20 millimeters. Unfortunately, data from station SEDG, another near-shore semipermanent GPS station, are unreliable because deep snow at the station obstructed the sky view during late April–early May. Thereafter, station SEDG tracked stations LAK1 and LAK2 reasonably well. There may be a small loading effect at continuous GPS station LKWY, as well, although the signal is near the level of uncertainty in the measurement. Planned semipermanent GPS deployments in 2018 and beyond will provide additional information in support of an ongoing modeling effort.

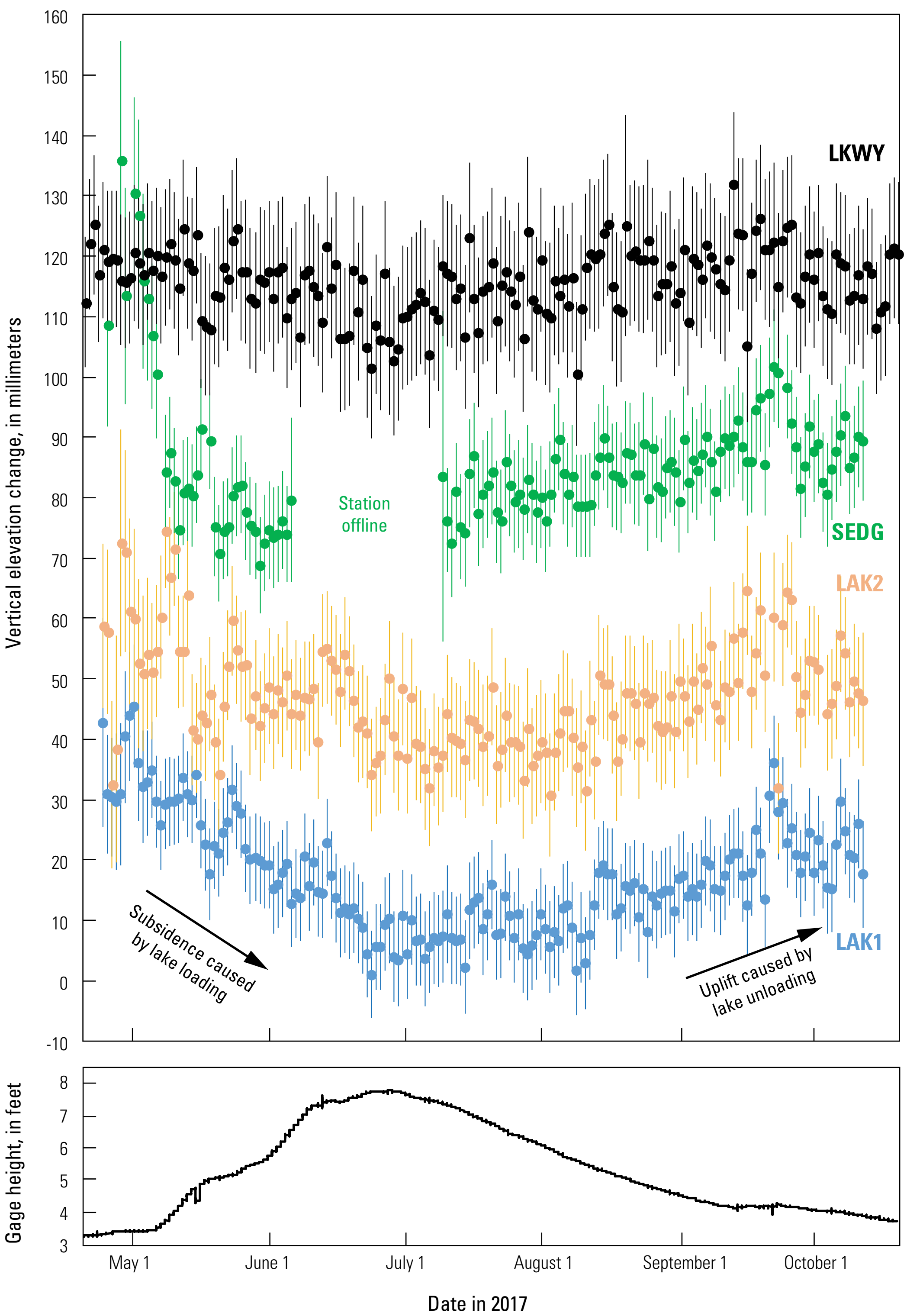


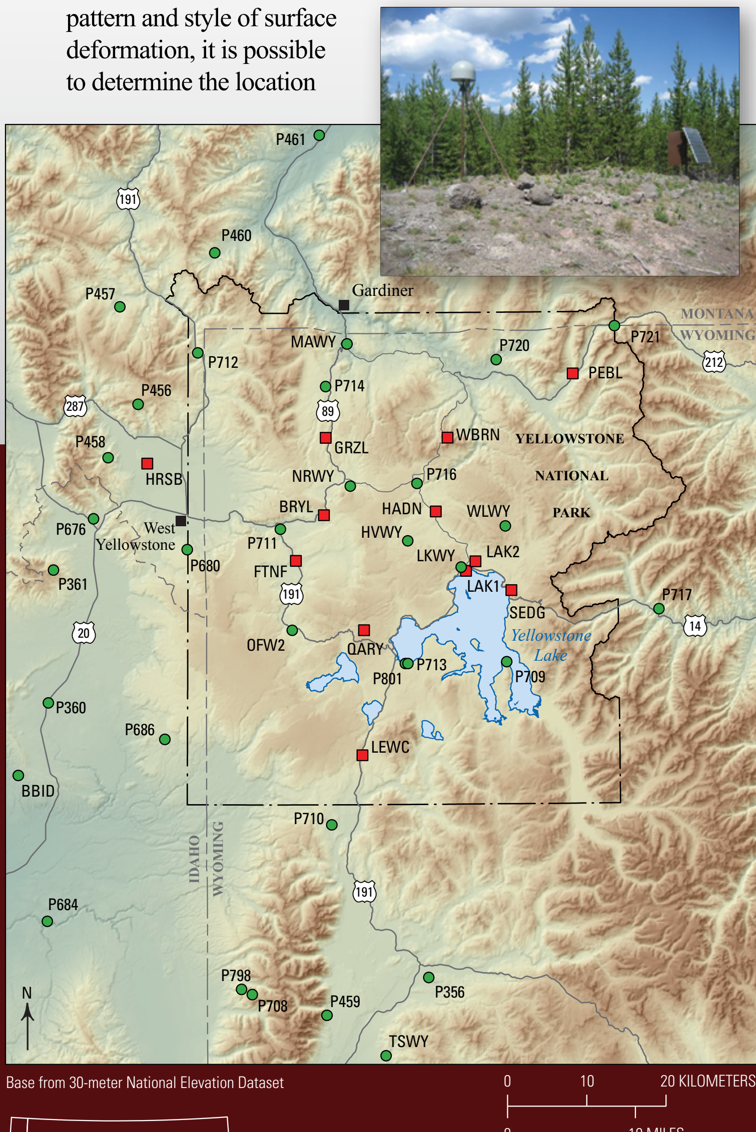
Figure 6. Time series of vertical displacements during April–October 2017 at four Global Positioning Stations near Yellowstone Lake. Downward trends indicate subsidence and upward trends show uplift. Uplift "spikes" in late September are related to inclement weather and do not show true deformation. Error bars are one standard deviation. See figures 4 and 5 for station locations. Bottom plot shows water level measured by stream gage USGS 06186500, located at the outlet of Yellowstone Lake. High gage levels correlate to high lake levels. Note that subsidence of the lake shore occurs simultaneously with increased lake level.

Sidebar Monitoring Deformation in Yellowstone Caldera

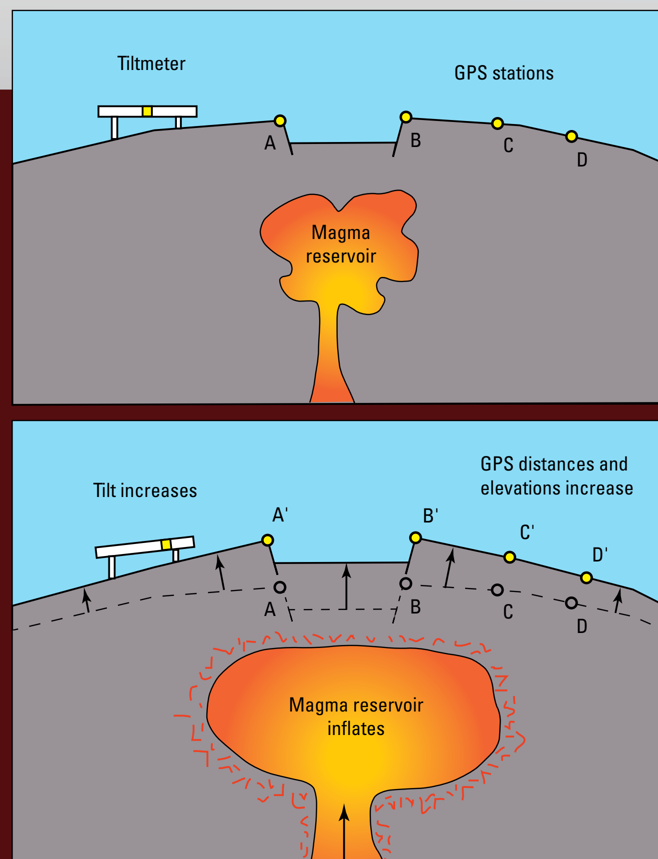
Subtle changes to the shape of a volcano's surface, called deformation, can manifest as swelling, sinking, or cracking. This deformation can be caused by the accumulation, withdrawal, or migration of magma, gas, or other fluids (typically water) beneath the ground, or by movements in the earth's crust owing to motion along faults. Often this deformation is very small in magnitude—a few centimeters (inches) or less—and so can only be detected and monitored with very sensitive instruments.

By measuring the pattern and style of surface deformation, it is possible to determine the location of subsurface fluid storage areas. For example, as magma or water accumulates in a reservoir below ground, the surface above will swell. The pattern of this surface inflation can be used to identify the depth of fluid accumulation, and the scale of the deformation can provide information on how much fluid is accumulating. By monitoring changes in deformation over time, it is possible to assess how magma, water, and gas are moving in the subsurface. The technique is an important tool for forecasting potential future eruptions. In the days, months, and years before a volcanic eruption, many volcanoes inflate as magma accumulates underground. Rapid changes in deformation may be a sign that magma is ascending towards the surface. Yellowstone Caldera presents a complicated situation because deformation may be caused by magma, water, or gas.

A variety of instruments help to monitor ground deformation in the Yellowstone region. UNAVCO, a non-profit consortium funded by the National Science Foundation, operates and maintains a network of Global Positioning System (GPS) instrumentation, as well as borehole strainmeters and tiltmeters. Borehole strainmeters and tiltmeters are designed to detect very small changes in deformation style especially over short time intervals (even down to minutes), but they tend to drift over days to weeks so cannot track long-term ground motion. This is where GPS, the backbone of the Yellowstone Caldera deformation monitoring network, comes into play. There are 15 continuously recording GPS stations within Yellowstone National Park and many more in the



Map showing locations of continuous (green dots) and semipermanent (red squares) Global Positioning System (GPS) sites in the Yellowstone area. Photograph inset shows continuous GPS station P711 in Yellowstone National Park.

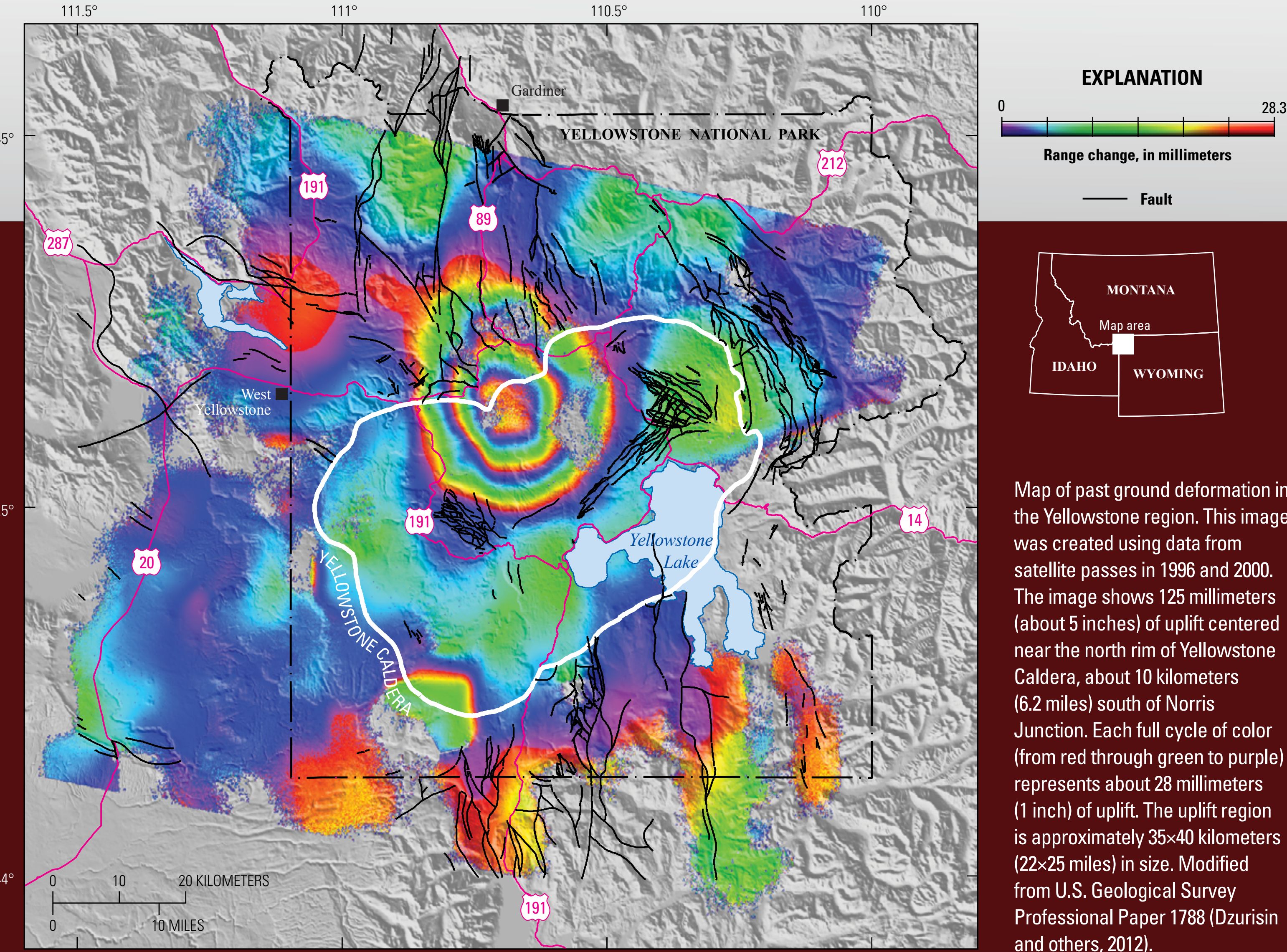


Schematic cartoon showing how the ground changes shape as magma accumulates beneath the surface. GPS, Global Positioning System.

surrounding region. Data from these sites, as well as temporary deployments of GPS stations ("semipermanent GPS"), are employed to precisely record the horizontal and vertical positions of fixed points at the surface. Variation in the positions over time, relative to the rest of the North American continent, gives an indication of how the ground in the Yellowstone region deforms owing to local processes, such as subsurface fluid accumulation and withdrawal, and faulting caused by earthquakes. Data from continuous GPS stations in the Yellowstone region are transmitted via radio and satellite links to UNAVCO's archives, where they are made publicly available at https://www.unavco.org/data/gps-gnss/data-access-methods/dai2/app/dai2.html#.

YVO scientists use satellite measurements, called interferometric synthetic aperture radar (InSAR), to take a broad snapshot of deformation. Two radar images of the same area that were collected at different times from similar vantage points in space are compared against each other. Any movement of the ground surface toward or away from the satellite is measured and portrayed as a "picture"—not of the surface itself but of how much the surface moved during the time between images. Unlike visible or infrared light, radar waves penetrate most weather clouds and are equally effective in darkness, so, using InSAR, it is possible to track ground deformation even in bad weather and at night.

InSAR greatly extends scientists' ability to monitor volcanoes because, unlike other techniques that rely on measurements at a few points, InSAR produces a map of ground deformation that covers a very large area with centimeter-scale accuracy. This technique is especially useful at remote, difficult-to-access volcanoes and at locations where hazardous conditions prevent or limit ground-based volcano monitoring. However, unlike continuous GPS, which provides data all the time, InSAR data are only available once every few days or weeks—when one of several radar satellites is overhead.



Base from 30-meter National Elevation Dataset

Map of past ground deformation in the Yellowstone region. This image was created using data from satellite passes in 1996 and 2000. The image shows 125 millimeters (about 5 inches) of uplift centered near the north rim of Yellowstone Caldera, about 10 kilometers (6.2 miles) south of Norris Junction. Each full cycle of color (from red through green to purple) represents about 28 millimeters (1 inch) of uplift. The uplift region is approximately 35×40 kilometers (22×25 miles) in size. Modified from U.S. Geological Survey Professional Paper 1788 (Dzurisin and others, 2012).

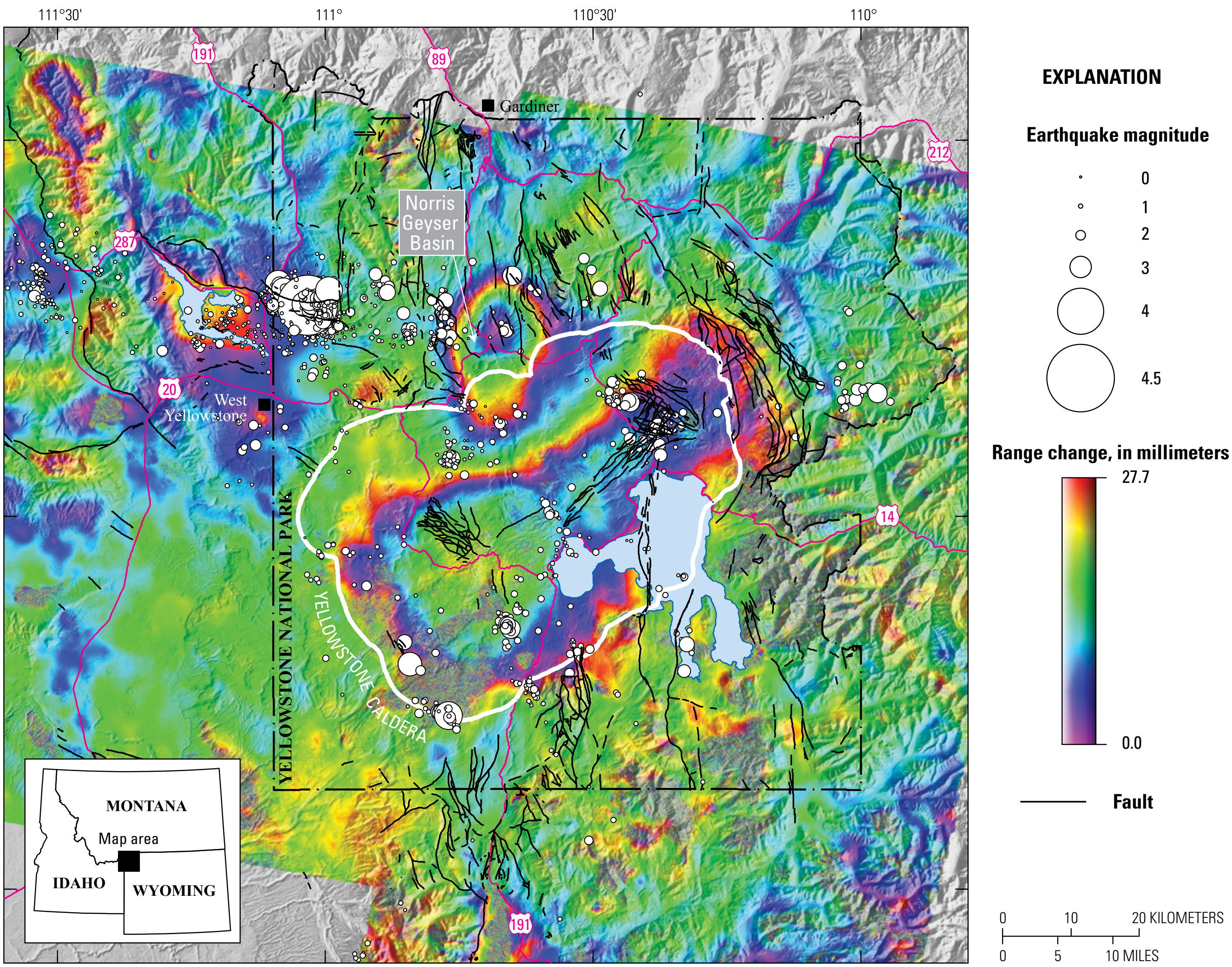
Interferometric Synthetic Aperture Radar (InSAR) Results

Satellite InSAR uses data from orbiting satellites to map deformation of the ground surface. The technique compares the distance between the satellite and ground at different times to determine how much the ground surface moved during the time spanned. Resulting images are called interferograms.

In the Yellowstone region, InSAR data are not usable during winter months because snow cover causes problems with image comparability. The best views of surface deformation from InSAR typically span years, with acquisitions in summer or fall months. Interferograms spanning October 2016 to October 2017 reveal deformation patterns that are consistent with those discerned from GPS—subsidence of the caldera and uplift of the area around Norris Geyser Basin (fig. 7). No significant deformation is apparent in the area of the 2017 Maple Creek earthquake swarm.

Lake-Level Gage

A semipermanent water pressure/depth gage was installed on June 28 near the Grant Village dock to record Yellowstone Lake levels. The new instrument is a Paroscientific 8WD Series 8000 Intelligent Depth Sensor (fig. 8), and the data have been corrected



Base from 30-meter National Elevation Dataset

Figure 7. Interferogram created from data collected on October 1, 2016, and October 8, 2017, by the Sentinel-1 satellite system. Colored fringes indicate a change in distance between the satellite and ground surface (or range change), which is caused by surface deformation. In this interferogram, the fringes indicate subsidence (an increase in the range between the ground and the satellite) of Yellowstone Caldera and uplift (a decrease in the range between the ground and the satellite) in the area of Norris Geyser Basin. White circles show earthquakes that occurred during the time spanned by the interferogram, where the circle size scales with magnitude.

for barometric pressure collected from a station about 6 meters from the depth sensor. The lake level is determined as centimeters of water relative to an arbitrary benchmark on the Grant Village boat dock (1 centimeter = 0.39 inches).

The average lake level is a balance between water flux into the system from precipitation (rain and snowmelt) and discharge at the lake's outlet, the Yellowstone River. Lake level decreased over the second half of 2017 during the dry season (fig. 9, bottom).

Occasionally, a seiche (pronounced "say-sh"), or standing wave, that is only a few centimeters tall causes short-term variation in the surface level of Yellowstone Lake. Seiche waves, which are too subtle and slow to be noticed by the human eye, can be triggered by atmospheric phenomena such as high winds or barometric pressure changes and usually take a few days to die off. The seiches change the distribution of water in the lake, which affects the water load on the surface of the Earth over time. Deformation patterns recorded by borehole strainmeters located throughout Yellowstone National Park reveal the presence of these seiches and can provide insights into the structure of the subsurface—for example, the depth and viscosity of the magma reservoir beneath Yellowstone Caldera. Tracking seiches is therefore important for better understanding the characteristics of the Yellowstone magmatic system. Seiches are evident at various times throughout the lake-level record (fig. 9, bottom), have a period (that is, the time between wave peaks) of approximately 76 minutes, and have amplitudes as large as ~10 centimeters (4 inches) (fig. 9, top).

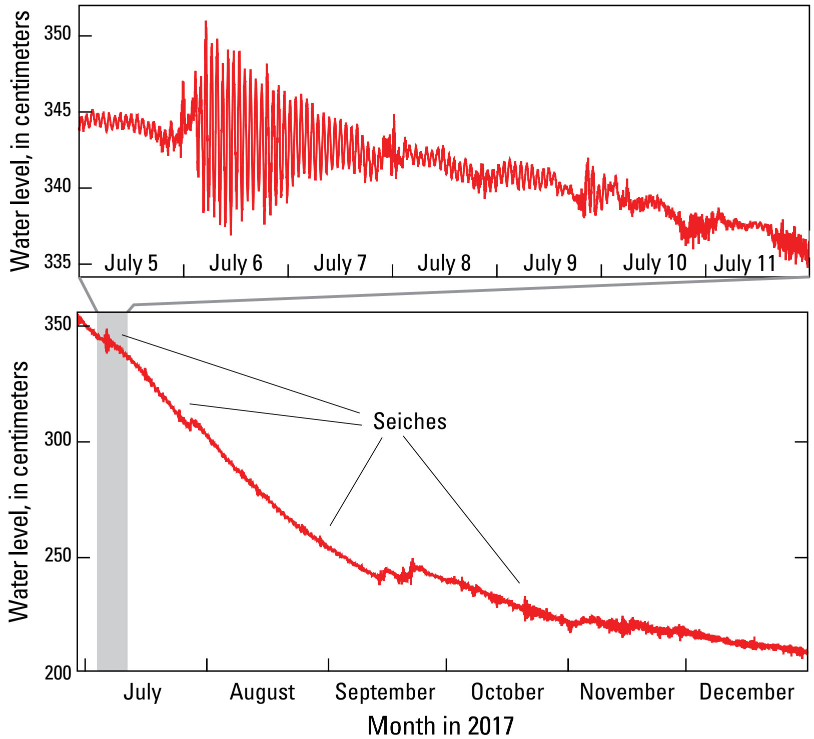


Figure 9. Plots of Yellowstone Lake level from July–December 2017, expressed as centimeters of water relative to a benchmark attached to the Grant Village boat dock. The overall trend from the installation time in July to the end of the year was a decrease in lake level by more than 1 meter as Yellowstone National Park experienced a dry autumn. The top plot zooms to July 5–11 and shows a particularly well-expressed seiche wave with an amplitude as high as ~10 centimeters (~4 inches) that lasted several days. The seiche would not be easily detectable to humans, but the changing water load on the lake over time can be picked up by sensitive strainmeter instruments that monitor surface deformation around the national park. Study of these deformation records has provided insight into the depth and viscosity of the magma reservoir beneath Yellowstone Caldera.

Figure 8. Water depth sensor (circled in red) at the Grant Village boat dock. Photographs by David Mencin, UNAVCO.

Geochemistry

Yellowstone National Park is home to more than 10,000 individual thermal features, including geysers, pools, mud pots, and fumaroles. Gases from these features are emitted as vapor in air or dissolved in water. By measuring the amount and compositions of these gases, we learn important information about processes like magma degassing from the subsurface reservoir, metamorphism of crustal rocks, interactions between hydrothermal water and crustal rocks, conditions within hydrothermal reservoirs, and biological communities (see sidebar on geochemical monitoring on p. 17). Repeated sampling of gases and waters throughout Yellowstone National Park is therefore critical for both monitoring volcanic activity and assessing subsurface conditions.

Continuous Gas Emissions and Sampling

During May–September, a study of variations in gas and heat emissions through time was carried out at the Solfatara Plateau thermal area. The primary objectives of this work were to (1) quantify baseline changes to gas emissions associated with variations in environmental parameters, such as temperature, precipitation, and barometric pressure on daily to seasonal time scales, and (2) discern and quantify any anomalous changes in gas emissions that might occur during periods of caldera unrest. The instrument deployment also provided a chance to test continuous gas measurements, which are not commonly performed in the Yellowstone region.

The measurements were carried out using three techniques that provide different, but complementary, assessments of various gas species and heat emissions. Eddy covariance is a meteorological technique that measures the turbulent flux of CO_2, H_2O, and heat emitted from ground areas (on the order of square kilometers in scale) upwind of the sensors. Soil CO_2 flux and temperature at 30 centimeters depth were also measured at equally spaced intervals on a grid across the study area using an accumulation chamber placed directly on the soil and a thermocouple, respectively. Finally, a Multi-GAS (multi-component gas analyzer system) instrument measured concentrations of H_2O, CO_2, H_2S, and SO_2 in the atmosphere near the ground surface.

Figure 10 shows a map of simulated soil CO_2 flux, based on accumulation chamber measurements (black dots) made during May 10–11. Integrating soil CO_2 flux over the study area yields a total CO_2 emission rate of 5.5 metric tons per day—a minute amount compared to the total CO_2 emitted by Yellowstone Caldera (which is on the order of 45,000 metric tons per day). Half-hourly measurements of eddy covariance CO_2 flux are plotted versus wind direction on figure 11*A* and were relatively low when wind was from the south. Whereas eddy covariance CO_2 fluxes were highly variable on a half-hourly basis, the 28-day running mean CO_2 flux was stable at around 180 grams per square meter per day (fig. 11*B*). Overall, measured eddy covariance CO_2 flux, as well as heat fluxes, provide a baseline against which future changes can be assessed in the context of caldera unrest. Measuring how hydrothermal CO_2 and heat emissions change in association with, for example, earthquakes can provide clues about the nature of the water and (or) magma moving in the subsurface, including the volume of fluid and its chemical composition.

Gas compositions measured by the Multi-GAS station displayed high variability throughout the study period (fig. 12). Background CO_2 is 450–500 parts per million at the station with excursions as high as 800 parts per million, whereas hydrogen sulfide (H_2S) ranged from about 0.5 to 2 parts per million. This variation is not unexpected, as the measurement of gases emitted by the vents is dependent on the wind direction that transports the gases to the Multi-GAS sensors from vents 3–20 meters away. Higher CO_2/H_2S (fig. 12, bottom plot) corresponds with times of low wind and high humidity, suggesting that under stable atmospheric conditions, such as calm nighttime conditions

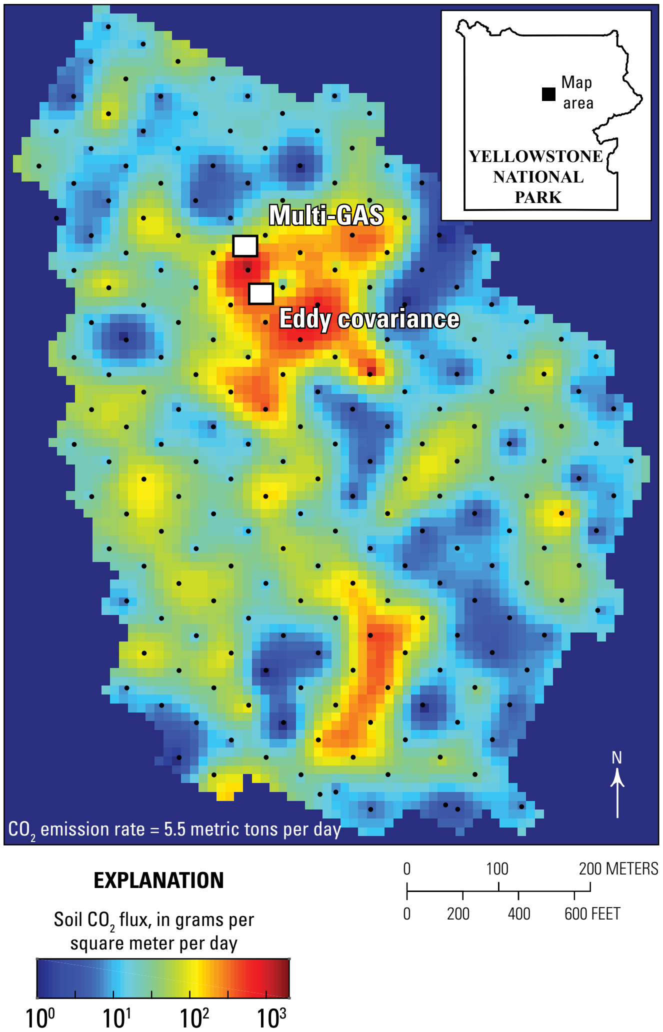


Figure 10. Map of log soil CO_2 flux at the Solfatara Plateau thermal area, simulated based on accumulation chamber measurements (black dots). These measurements indicate the rate at which CO_2 is released from the ground. Locations of eddy covariance and Multi-GAS stations are shown by white squares.

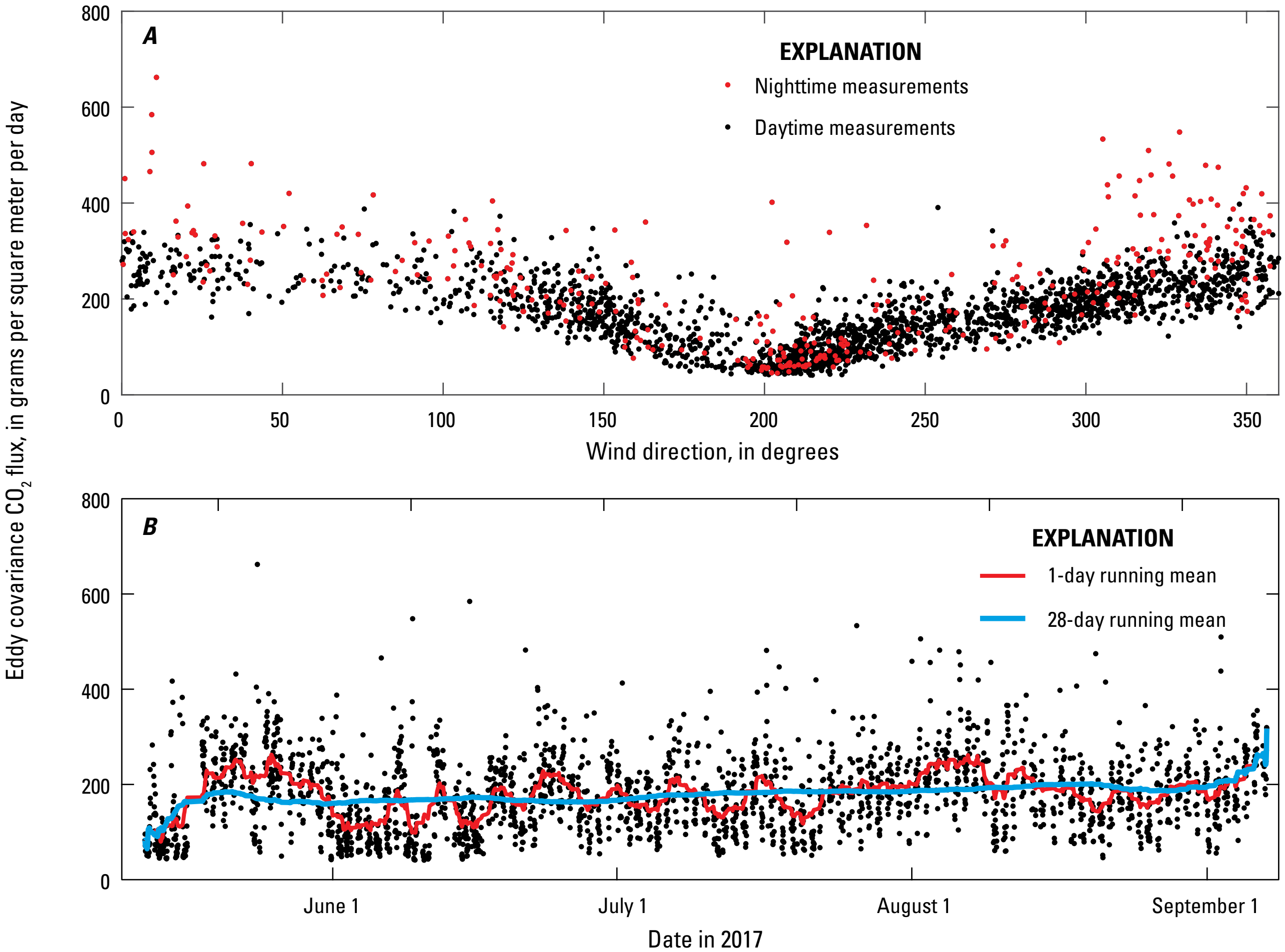


Figure 11. Plots of eddy covariance CO_2 flux (*A*) versus wind direction and (*B*) throughout the summer. The 28-day running average shows relatively steady values over the course of the deployment, which indicates constant production of CO_2 over time with no variations caused by volcanic or hydrothermal activity.

Sidebar Geochemical Monitoring in Yellowstone Caldera

Deep beneath the surface, gasses are dissolved in magma, but as magma rises toward the surface the pressure decreases and gases separate from the liquid to form bubbles. Because gas is less dense than magma, the bubbles can rise more quickly and be detected at the surface of the Earth.

Similarly, water can also transport material up to the surface where it can be studied by scientists. Groundwater circulates deep within the Earth's crust in volcanic regions, where it can be heated by magma to over 200 °C (around 400 °F). This causes it to rise along fractures, bringing dissolved material up toward the surface. By studying the chemical makeup of this thermal water, scientists can gain a better picture of the conditions deep within a volcano.

In Yellowstone Caldera, volcanic gas emissions are usually sampled by hand directly from fumaroles (gas vents), although some temporary automated measurements of certain types of gases have been employed. Likewise, measurements of water chemistry are typically done by collecting samples and analyzing the chemical makeup of the water in the laboratory.

Scientists collect water samples from the Firehole River in Yellowstone National Park. U.S. Geological Survey photograph by Jim Ball, 2014

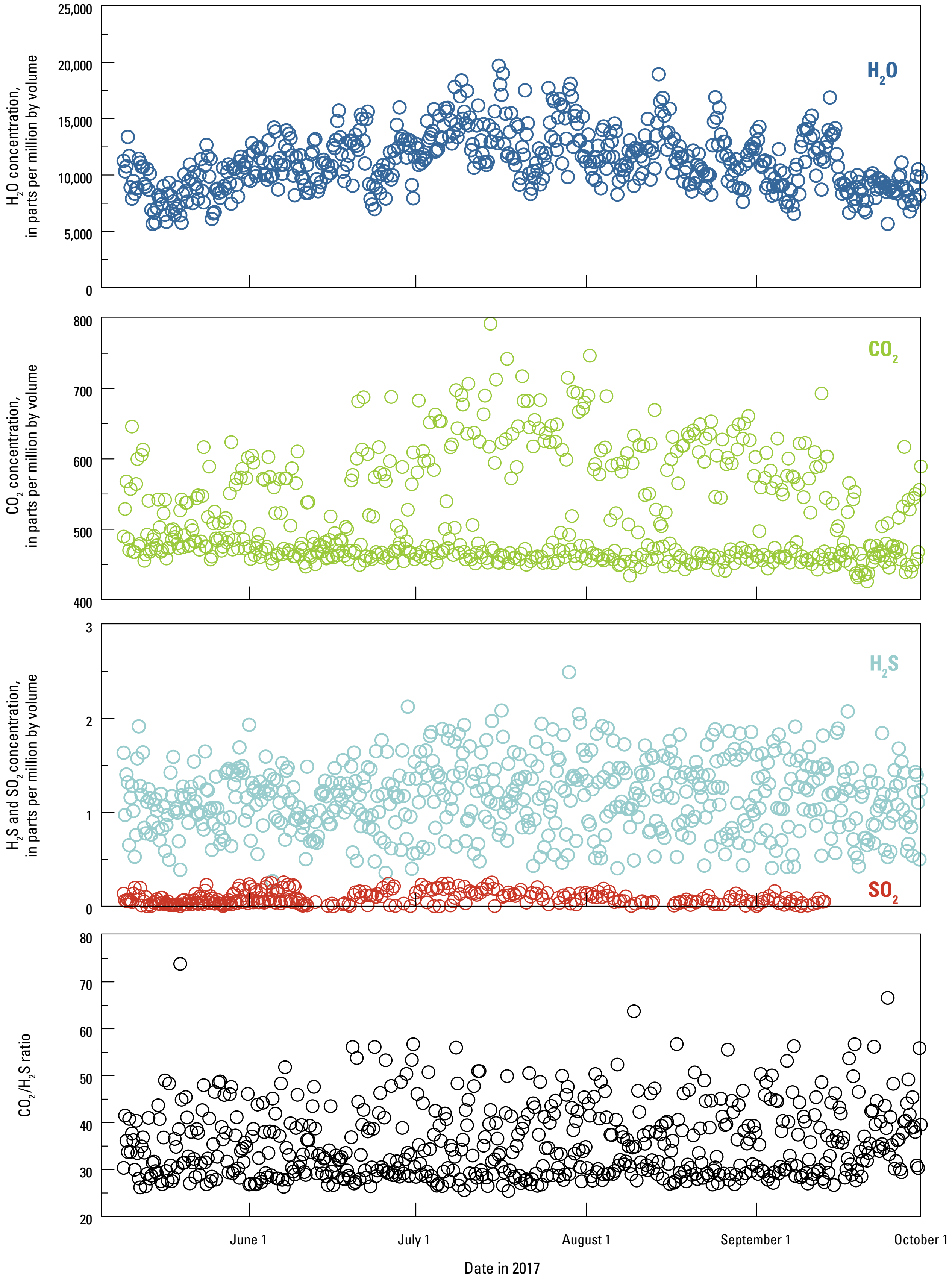


Figure 12. Time series of H_2O, CO_2, H_2S, and SO_2 concentrations (in parts per million by volume) and CO_2/H_2S ratios measured by the Multi-GAS station at Solfatara Plateau thermal area. No variations over time are discernable in these plots, thereby providing an indication of background levels of degassing. The spread in the measurements provides an indication of the uncertainty.

when solar effects are minimal, hydrothermal CO_2 ponds in the low-lying basin. The compositional diversity observed during this study can be fully explained by meteorological dynamics. If the output of the fumaroles had changed during this period, we might expect more variation in CO_2/H_2S ratios at higher H_2S concentrations. Like the eddy covariance CO_2 measurements, these Multi-GAS results provide data for time periods that are typical of background levels of degassing. Any future changes in gas composition or flux should be readily discernable thanks to the baseline established by these measurements.

Sampling at Boundary Creek

During September 16–17, gases and waters were sampled at thermal features that discharge into Boundary Creek. The field study focused on the northern Boundary Creek, central Boundary Creek, and Silver Scarf thermal areas in the southwest corner of Yellowstone National Park (star in figure 13). These sites are located upstream (north) of the junction of Boundary Creek with the Bechler River. There are no known previous studies of gases from thermal features at these sites, and thermal waters were

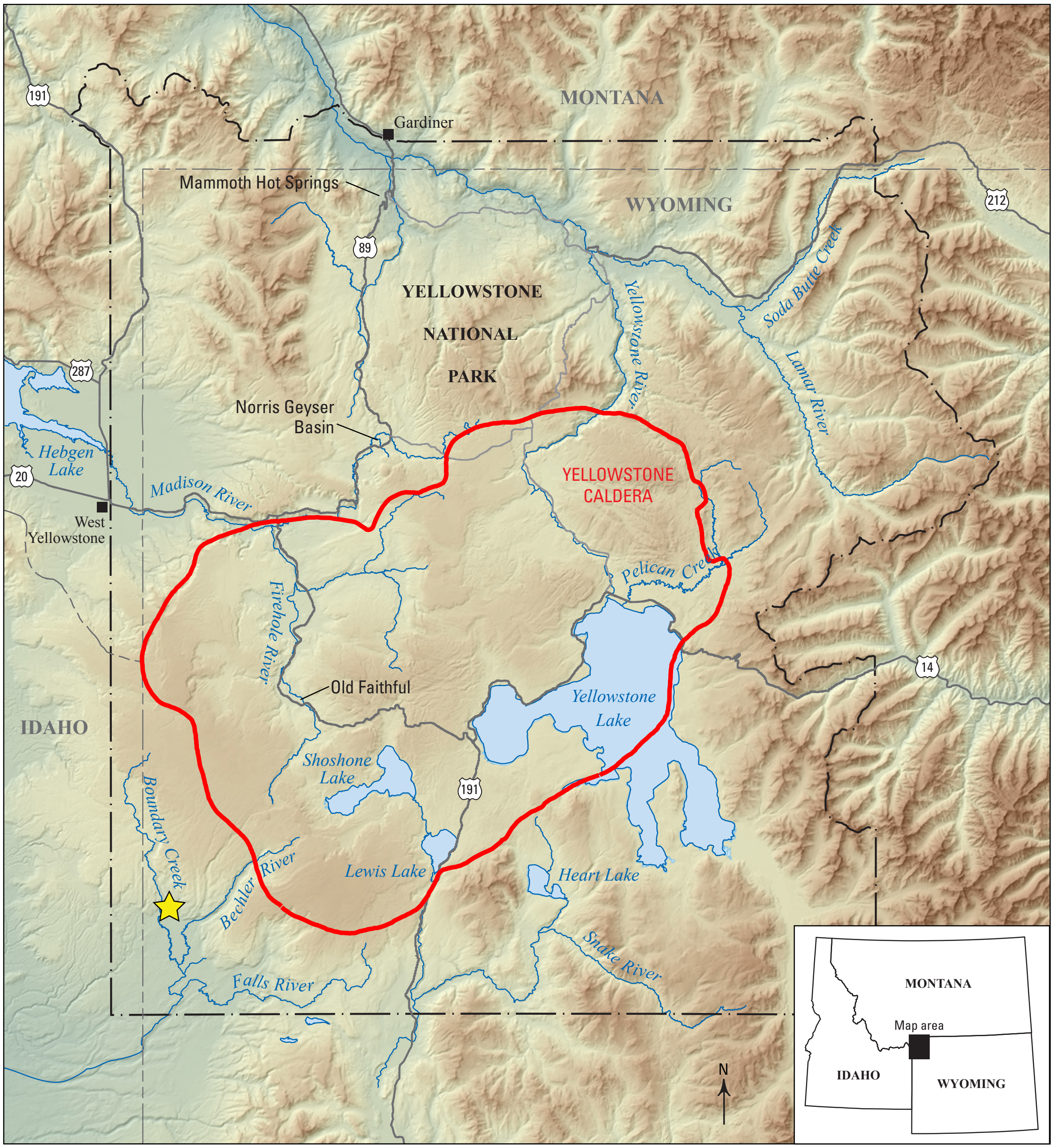


Figure 13. Map of major river systems in the Yellowstone region. Yellow star marks the Boundary Creek sampling site.

last sampled about 30 years ago. Additionally, measurements of chloride flux were made above (0.05 grams per second) and below the thermal areas (30 grams per second) along Boundary Creek.

The main gas discharge in this area occurs in the northern part of northern Boundary Creek thermal area from two patches of barren ground. Gas was collected (fig. 14) from three sites: a fumarole, steaming ground, and a dry frying pan (a term used to describe a thermal area where gas upflow causes pooled water to sizzle and jump). At the southern part of the northern Boundary Creek thermal area there were numerous plumes of steam, but at all sites the steam was associated with discharging thermal water and there was no discharge of free gas. Water was collected (fig. 14) into copper tubes at two hot springs for determination of the dissolved noble gas contents.

Values of $\delta^{13}C$ in CO_2, which measure the relative abundance of different carbon isotopes and can provide evidence of the source of the carbon (for example, biological versus magmatic), range between −4.0 and −3.7 parts per thousand and are typical of CO_2 from fumaroles and frying pans across Yellowstone National Park. Results from compositional analyses show the gas to be relatively rich in helium, hydrogen, and hydrogen sulfide, suggesting contributions from a crustal gas source.

Figure 14. Photographs of 2017 field work in Boundary Creek thermal area. *Top*, U.S. Geological Survey (USGS) scientist David Susong measures water discharge in Boundary Creek. *Bottom*, A fumarole in the northern Boundary Creek thermal area. Research conducted under National Park Service research permits YELL-SCI-5194 and YELL-SCI-5406.

Water was collected (fig. 14) at 4 hot springs with temperatures between 67.3 and 90.0 °C. The waters were neutral with pH values between 6.83 and 7.72. The main anion in the thermal waters is bicarbonate (HCO_3^-), at concentrations of 49.2–294 milligrams per liter, and the main cation is sodium (Na^+), at 22.6–176 milligrams per liter. Silica (SiO_2) concentrations were between 146 and 206 milligrams per liter. An unnamed hot spring in Silver Scarf Basin has the highest temperature (90 °C) and the highest SiO_2, Cl^-, and Na^+ concentrations (206, 95.6, and 176 milligrams per liter, respectively).

Geology

Geologic research at Yellowstone National Park is focused on interpreting the rock record as a means of better understanding the conditions that preceded and accompanied past eruptions. The primary tools for this work include mapping rock compositions and structures and determining the ages of specific rock units. This work established the foundation for understanding Yellowstone area eruptions (see sidebar on the geology of Yellowstone Plateau on p. 22–23) and continues to be refined as new analytical tools become available.

Eruption of Rhyolite Lava Flows

As part of a project begun in 2015, researchers performed high-precision $^{40}Ar/^{39}Ar$ dating and paleomagnetic analysis of rhyolite lava flows and domes (fig. 15) from the second volcanic cycle of the Yellowstone Plateau volcanic field, which culminated in the caldera-forming rhyolitic eruption of the Mesa Falls Tuff 1.2957±0.0011 million years ago (fig. 16). Research efforts were focused on rhyolite lava flows and domes that preceded and postdated the Mesa Falls Tuff, with the goals of improving our understanding of the eruptive history of the Yellowstone Plateau volcanic field and constraining the timespan over which these lava eruptions took place.

Figure 15. Photograph showing exposures of crystal-rich Island Park Rhyolite at Osborne Butte—one of the post-Mesa Falls Tuff rhyolite domes erupted as part of the second cycle of Yellowstone area volcanism.

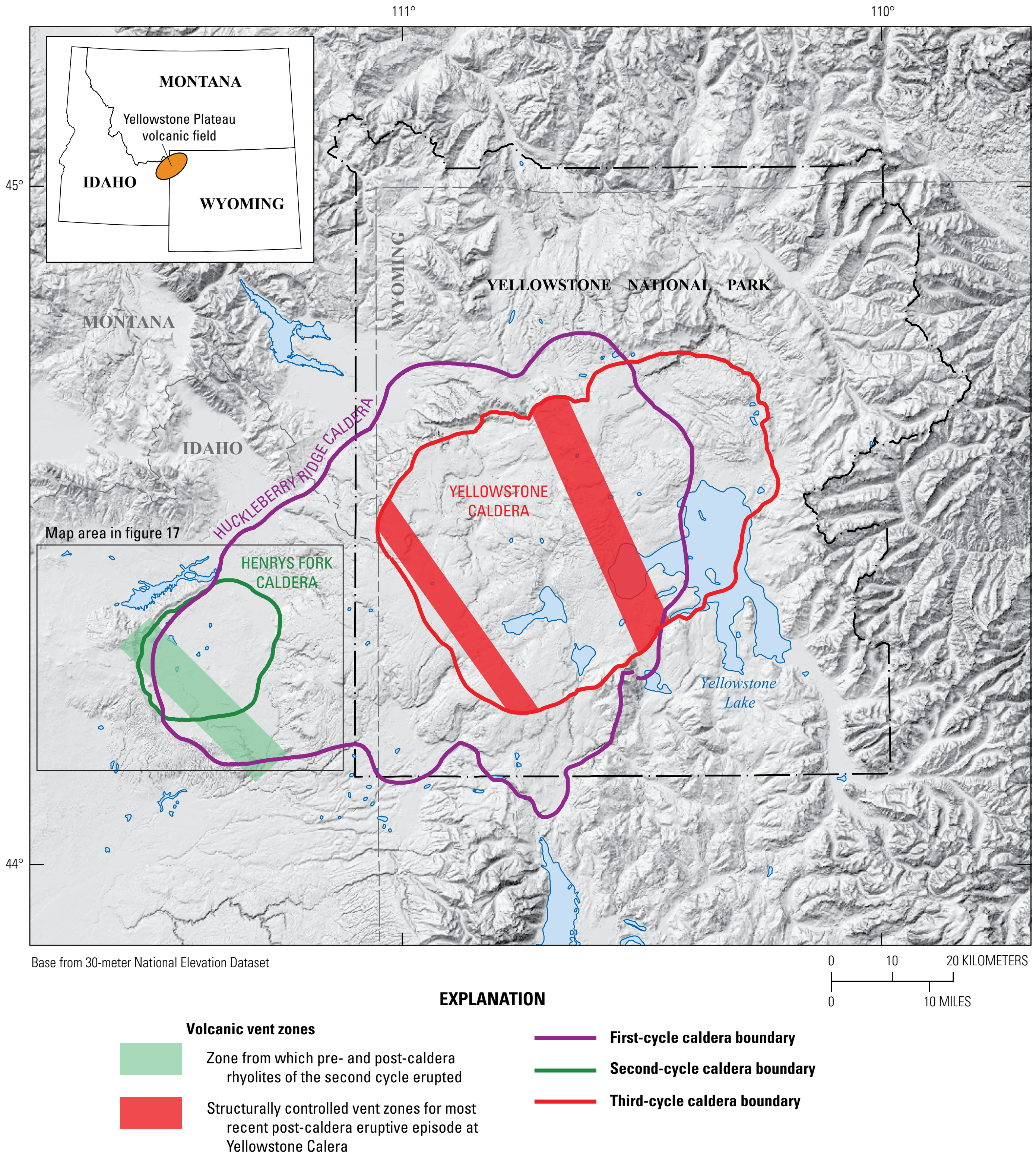
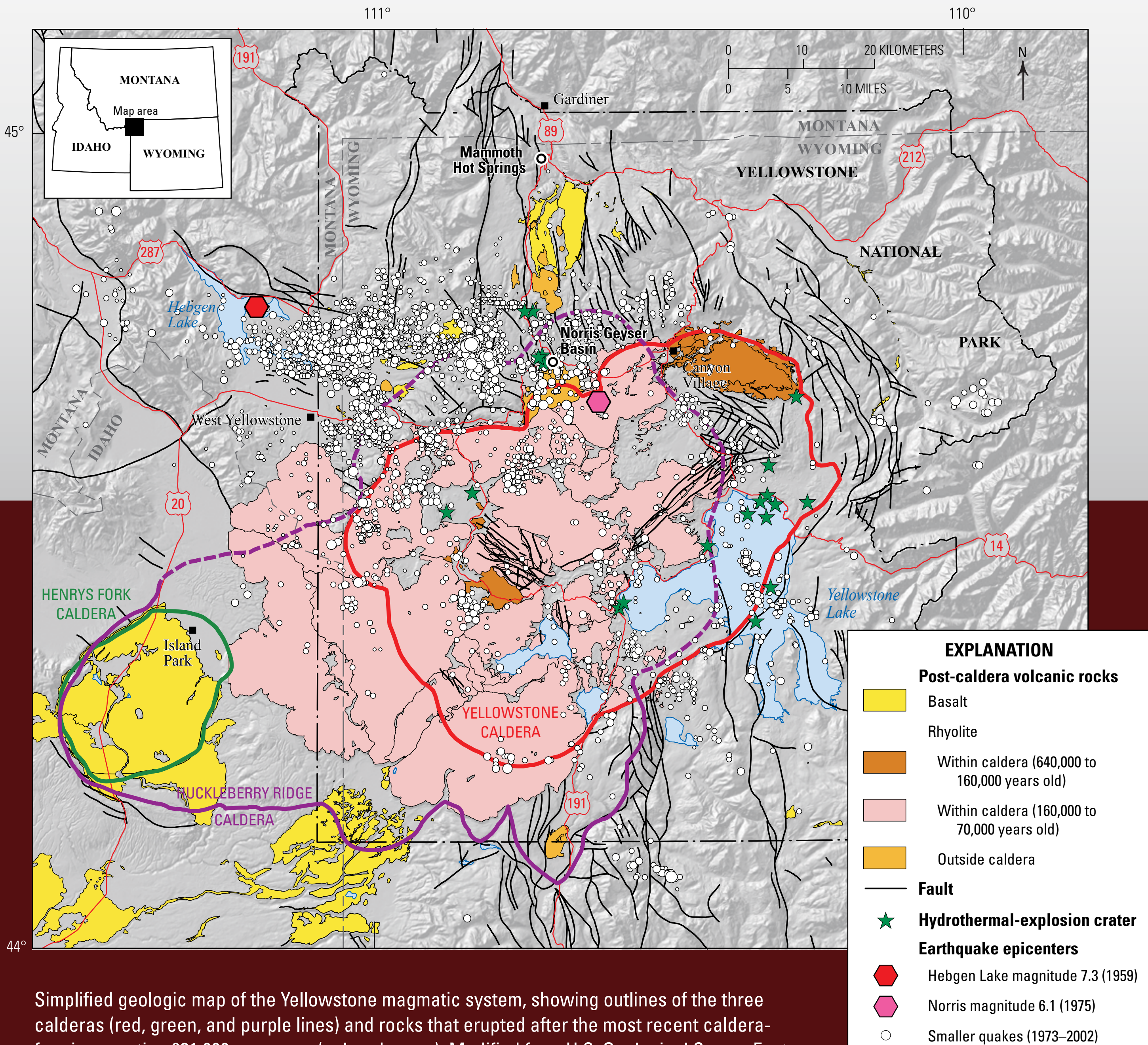


Figure 16. Shaded-relief map of the Yellowstone Plateau volcanic field and vicinity. Six post-Mesa Falls Tuff rhyolites erupted over a centuries-long time interval at about 1.3 million years ago (1.2905±0.0020 million years ago, precisely) from a 30-kilometer-long, structurally controlled vent zone related to Basin and Range extensional faults (green shaded area). Current work is underway to test whether the youngest rhyolites in the Yellowstone region, which erupted from two structurally controlled vent zones within Yellowstone Caldera (red shaded areas), also were clustered in time.

Sidebar The Geology of Yellowstone Plateau

The Yellowstone Plateau volcanic field developed through three volcanic cycles that span more than two million years and include two of the world's largest known eruptions. About 2.1 million years ago, eruption of the Huckleberry Ridge Tuff produced more than 2,450 cubic kilometers (588 cubic miles) of volcanic deposits—enough material to cover the entire state of Wyoming in a layer 10 meters (30 feet) thick—and created the large, approximately 75 kilometer (47 mile) wide, Huckleberry Ridge Caldera. A second cycle concluded with the eruption of the much smaller Mesa Falls Tuff around 1.3 million years ago and resulted in formation of the Henrys Fork Caldera. Activity subsequently shifted to the present Yellowstone Plateau and culminated 631,000 years ago with the eruption of the >1,000 cubic kilometer (240 cubic mile) Lava Creek Tuff and consequent formation of the 45×85 kilometer (28×53 mile) Yellowstone Caldera.

The three extraordinarily large explosive eruptions in the past 2.1 million years each created a giant caldera and spread enormous volumes of hot, fragmented volcanic rocks as pyroclastic flows over vast areas. The accumulated hot ash, pumice, and other rock fragments welded together from their heat and the weight of overlying material to form extensive sheets of hard lava-like rock. In

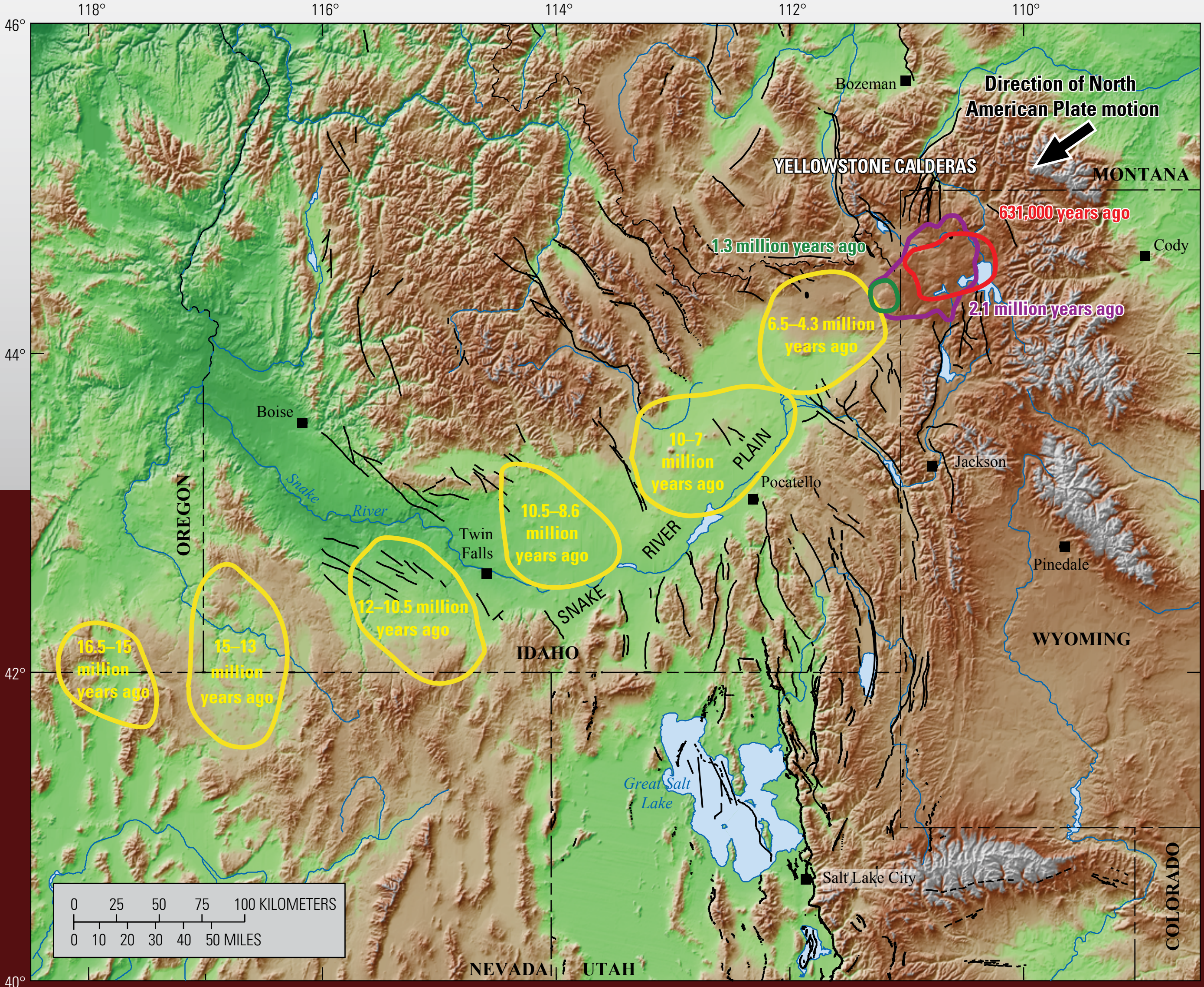


Simplified geologic map of the Yellowstone magmatic system, showing outlines of the three calderas (red, green, and purple lines) and rocks that erupted after the most recent caldera-forming eruption 631,000 years ago (colored areas). Modified from U.S. Geological Survey Fact Sheet 2005–3024 (Lowenstern and others, 2005).

some sections, these welded ash-flow tuffs are more than 400 meters (1,300 feet) thick. These ash-flow sheets account for more than half the material erupted from Yellowstone Caldera.

Before and after these caldera-forming events, eruptions in the Yellowstone area produced rhyolitic and basaltic rocks—large rhyolite lava flows (pink and orange colors on simplified geologic map on previous page), some smaller rhyolite pyroclastic flows in and near where the calderas collapsed, and basalt lava flows (yellow color on simplified geologic map) around the margins of the calderas. Large volumes of rhyolitic lava flows (approximately 600 cubic kilometers, or 144 cubic miles) were erupted in the most recent caldera between 180,000 and 70,000 years ago. No magmatic eruptions have occurred since then, but large hydrothermal explosions have taken place since the end of the last ice age in the Yellowstone region, 16,000–14,000 years ago.

Yellowstone Caldera's volcanism is only the most recent in a 17-million-year history of volcanic activity that has occurred progressively from near the common border of southeastern Oregon, northern Nevada, and southwestern Idaho to Yellowstone National Park as the North American Plate has drifted over a hot spot—a stationary area of melting within Earth's interior. At least six other large volcanic centers along this path generated caldera-forming eruptions; the calderas are no longer visible because they are buried beneath younger basaltic lava flows and sediments that blanket the Snake River Plain.



Volcanic centers are outlined where the Yellowstone Hot Spot produced one or more caldera eruptions—essentially "ancient Yellowstones"—during the time periods indicated. As the North American Plate drifted southwest over the hot spot, the volcanism progressed northeast, beginning at the common border of southeastern Oregon, northern Nevada, and southwestern Idaho 16.5 million years ago and reaching Yellowstone National Park about 2 million years ago. Mountains (whites, browns, and tans) surround the low elevations (greens) of the seismically quiet Snake River Plain. The low elevations of the Snake River Plain mark past calderas that have since been filled in by lava flows. Black lines show faults within the region. Modified from Smith and Siegel (2000) with permission.

Integrating $^{40}Ar/^{39}Ar$ ages and paleomagnetic data demonstrates that five post-Mesa Falls Tuff rhyolite domes (the Island Park Rhyolite geologic unit) erupted over a centuries-long time interval at 1.2905±0.0020 million years ago from a 30-kilometer-long, structurally controlled vent zone related to Basin and Range faults that can be found outside the caldera boundary (fig. 17). An additional rhyolite dome (the Moonshine Mountain dome) was originally thought to have preceded the Mesa Falls Tuff, but new $^{40}Ar/^{39}Ar$ age data demonstrate that this flow erupted 1.2931±0.0018 million years ago and is contemporaneous with the Island Park Rhyolite domes.

These data highlight the short time frame over which magma can be generated and erupted over large distances (≥30 kilometers) in the Yellowstone volcanic field. This conclusion is significant because the Island Park Rhyolite magmatic episode bears many similarities to the most recent period of rhyolitic volcanism in Yellowstone Caldera—the Central Plateau Member rhyolites, which erupted from two ~40-kilometer-long, structurally controlled vent zones within the present-day Yellowstone Caldera (fig. 16). Existing geochronology for the Central Plateau Member rhyolites lacks the precision to test whether these eruptions were clustered in time, similar to the Island Park Rhyolite domes.

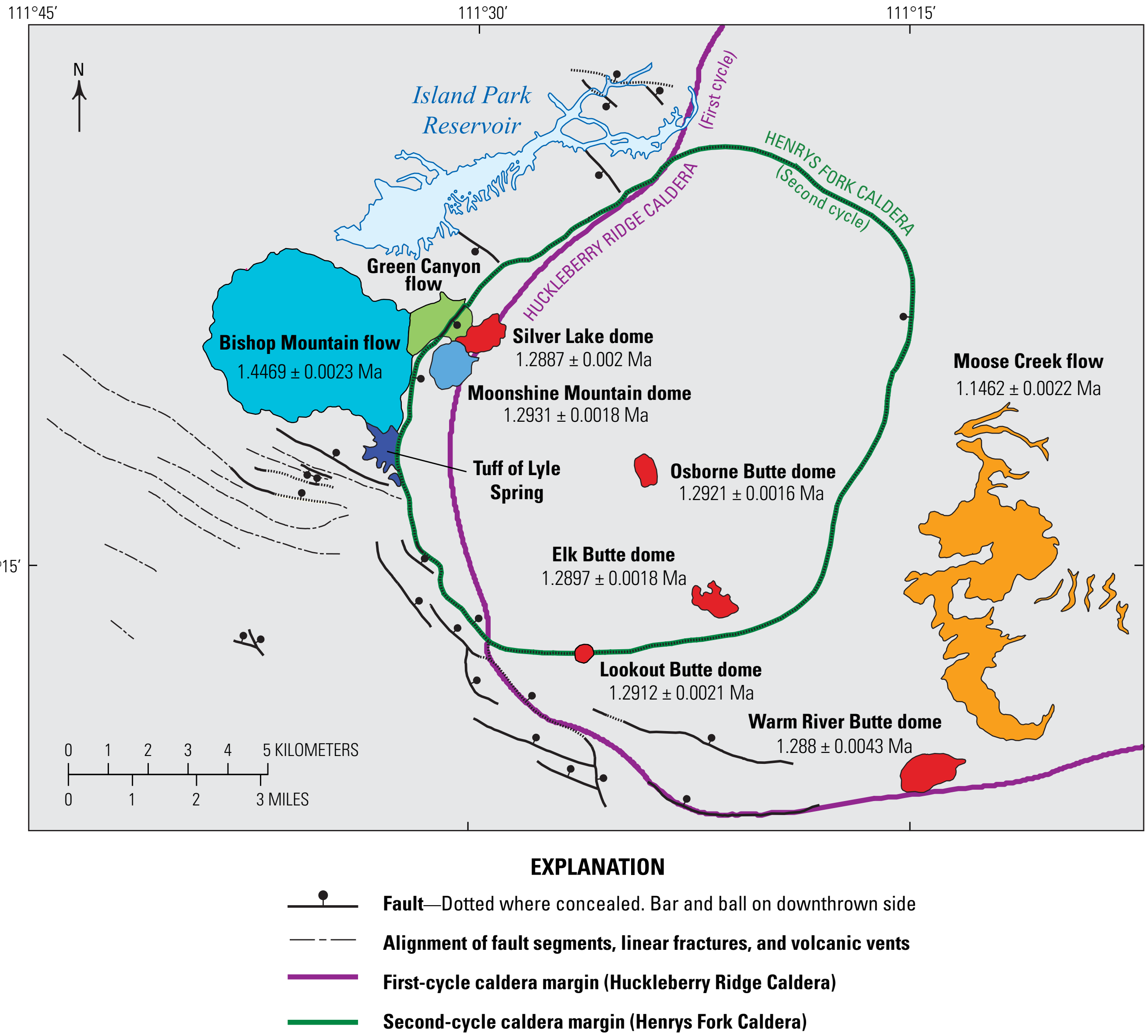


Figure 17. Simplified geologic map of Henrys Fork Caldera and vicinity; area of map shown in figure 16. The locations of pre-Mesa Falls Tuff rhyolites (Big Bend Ridge Rhyolite; blues and green) and post-Mesa Falls Tuff rhyolites (Island Park Rhyolite; red) are indicated. The Moose Creek flow (orange), which is part of the Mount Jackson Rhyolite series, is also included. The vent for the Moose Creek flow is thought to be near the margin of the third-cycle caldera, Yellowstone Caldera, to the east. New $^{40}Ar/^{39}Ar$ ages and their 2σ uncertainties (in million years, Ma) are shown below unit names.

Work is currently underway to apply modern, high-precision $^{40}Ar/^{39}Ar$ dating and paleomagnetic analysis to the Central Plateau Member rhyolites to assess whether these large-volume rhyolite flows (as large as 70 cubic kilometers) tend to erupt in clustered events or are separated in time by thousands of years.

Bathymetric and Geologic Mapping of Lewis and Yellowstone Lakes

A high-resolution multi-beam echo sounder survey, which uses sonar to map lakebeds and seabeds, has resulted in a new, state-of-the-art bathymetric map, in addition to the first geologic map, of Lewis Lake, the third largest lake in Yellowstone National Park. The multi-beam echo sounder data from Lewis Lake included over 1.8 billion points, enabling a vertical resolution of <10 centimeters. Working with researchers from the University of Illinois under a grant from the National Science Foundation, YVO staff assisted with the geologic interpretation and found that at least three, and possibly four, post-caldera rhyolites are present in Lewis Lake as well as several areas of focused hydrothermal venting. The study also produced new bathymetric maps of selected hydrothermally active areas in Yellowstone Lake, including “Deep Hole” (fig. 18)—the deepest part of Yellowstone Lake and the site of a hydrothermal field where the hottest fluids, at 170 °C, discharged from anywhere in the national park were measured.

Geothermal Studies

The 10,000+ on-land thermal features of the Yellowstone region range in temperature from just a few degrees Celsius above the normal background temperature to well above boiling (as hot as 138 °C). Studies of thermal features are accomplished by ground-based monitoring (including both occasional observations and continuous temperature monitoring), thermal infrared remote sensing observations from satellite and aircraft, and proxy measurements of chloride in Yellowstone National Park’s rivers (see sidebar on monitoring thermal changes on p. 26–27).

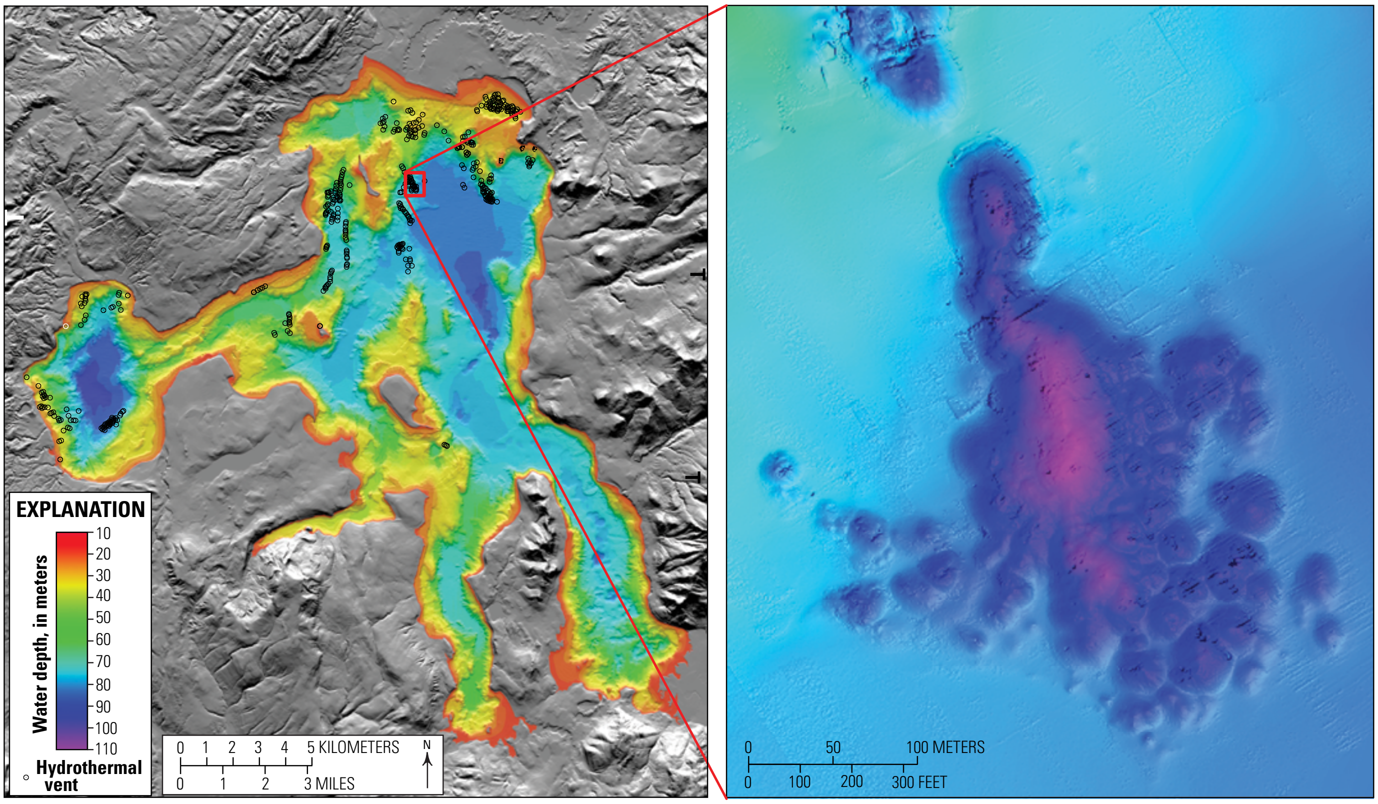
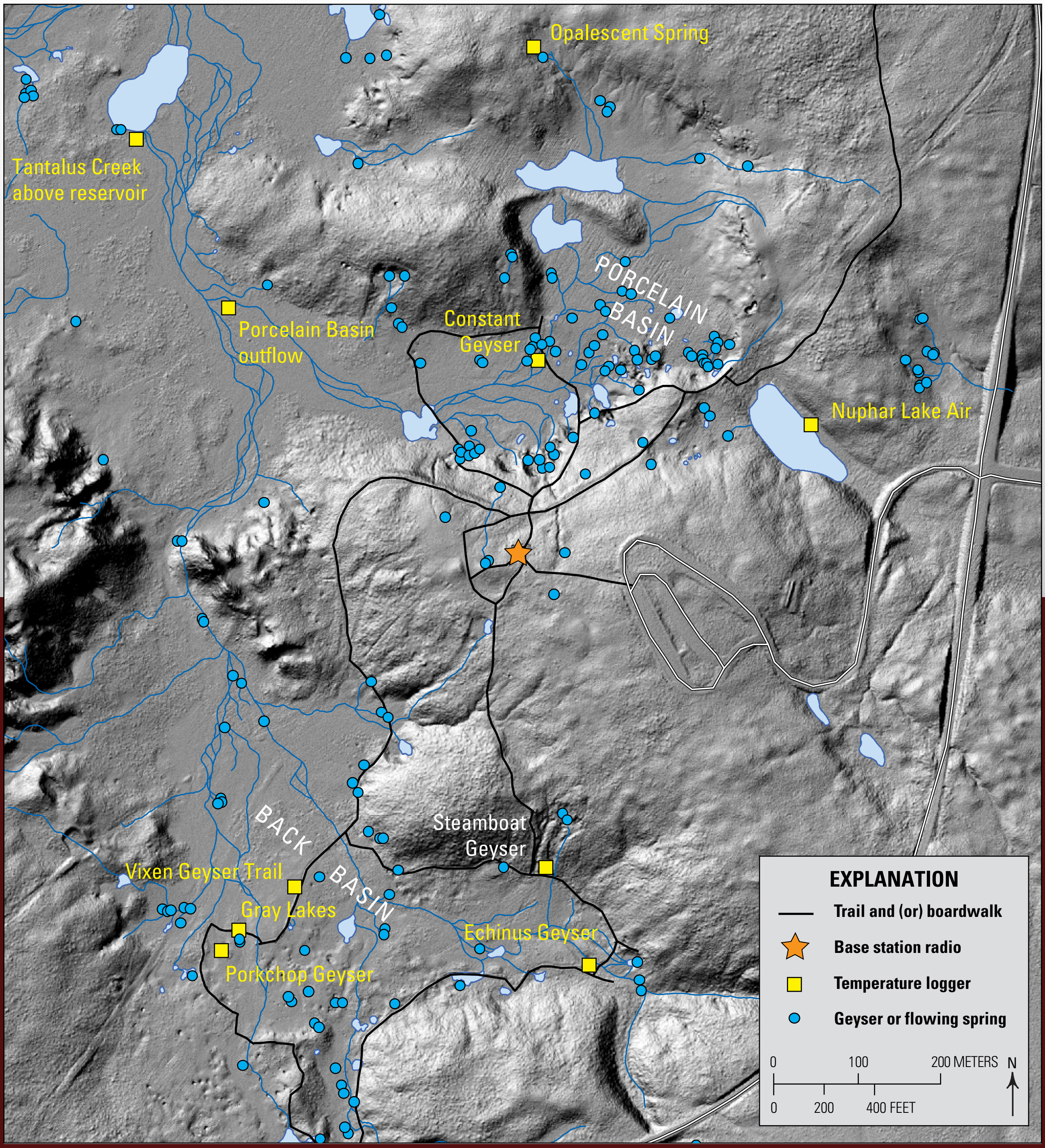


Figure 18. *Left*, High-resolution bathymetric map of Yellowstone Lake showing the location of hydrothermal vents (black dots) on the lake floor. Adapted from U.S. Geological Survey Scientific Investigations Map 2973 (Morgan and others, 2007). *Right*, Zoomed-in area of the ultra-high-resolution (25 centimeter) bathymetric map of an area known as “Deep Hole.” The data for Deep Hole were collected by the Woods Hole Oceanographic Institution’s autonomous underwater vehicle in July 2016 (see Sohn and others, 2017).

Sidebar Monitoring Thermal Changes at Yellowstone Caldera

A lot of heat is released from Earth's surface in the Yellowstone area. The evidence of this heat flow includes thermal features like hot springs, geysers, mud pots, and fumaroles. Tracking the temperatures and sizes of thermal areas is critical for monitoring Yellowstone Caldera's hydrothermal activity and also for understanding and preserving these spectacular features. The task is challenging, however, given that there are more than 10,000 individual thermal features spread out over a large and mostly inaccessible area within Yellowstone National Park.

Some specific thermal features are continuously monitored with temperature sensors, such as at Norris Geyser Basin. There, thermal probes are connected via radio links so that data within the thermal-monitoring network can be viewed at all times. These thermal probes have proven useful for detecting geyser eruptions when

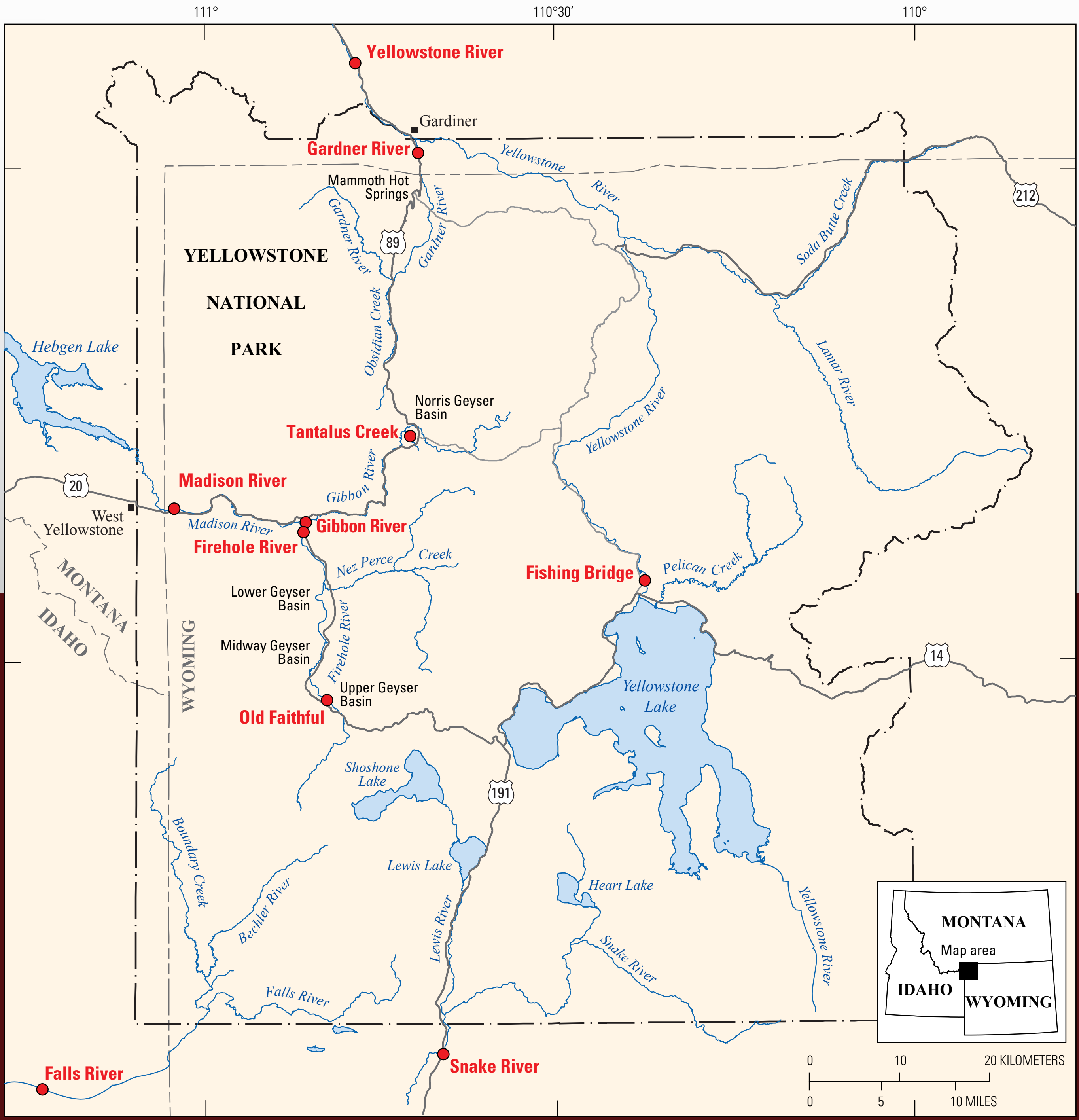


Base from 2009 EarthScope lidar dataset

Map of temperature measurement sites in Norris Geyser Basin.

visual observations are impossible (owing to weather or time of day).

Temperature probes can only be used to measure the output of a few specific features. To look at overall thermal output of Yellowstone, other techniques are employed—for instance, tracking the chemistry of Yellowstone area's major rivers. Since the hot water from thermal features ultimately ends up in rivers, changes in river chemistry are used to track overall hydrothermal activity. The most useful chemical indicator is the chloride composition of the river water, because hydrothermal water has a high concentration of chloride. In fact, nearly all (95 percent) of the chloride in Yellowstone rivers comes from thermal features. Thus, monitoring the chloride flux in the major rivers in Yellowstone National Park provides an overview of hydrothermal activity. River water samples were once collected periodically and manually to measure chloride, but

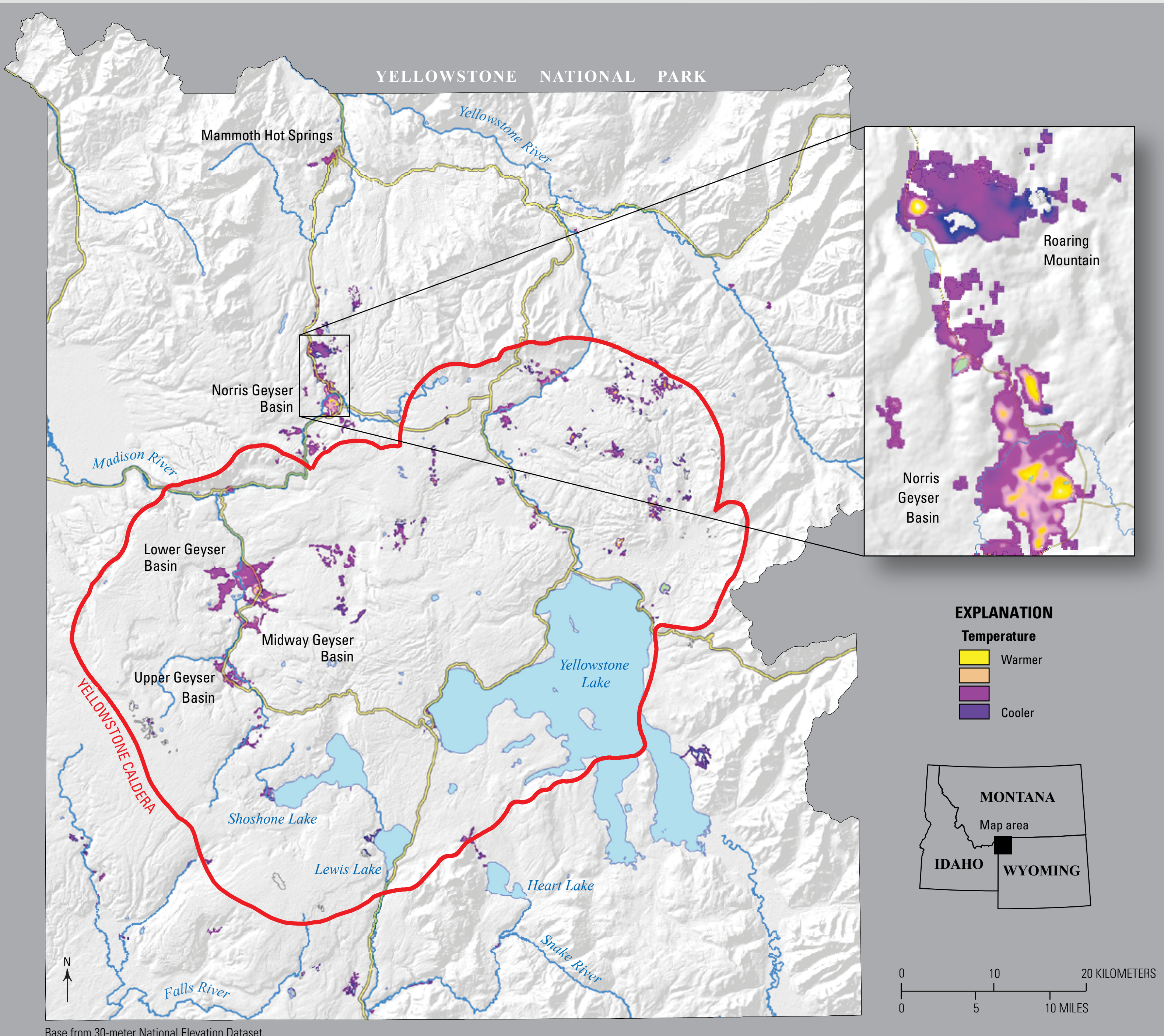


Map showing river chemistry monitoring sites (red dots) in Yellowstone National Park.

Sidebar Monitoring Thermal Changes at Yellowstone Caldera

now measurements of specific conductance (a proxy for chloride) are collected continuously by automated monitoring stations on all the park's major rivers.

Another method for obtaining broad views of Yellowstone Caldera's thermal output is to use satellites, which measure surface temperature and detect changes over time. One of the advantages of satellite-based thermal infrared remote sensing is that researchers can view nearly all of the thermal areas in the park at once. Unfortunately, this broad view comes at a cost—thermal infrared satellite images tend to have low spatial resolution, with pixels that are 90 meters (about 300 feet) on a side. Nevertheless, thermal infrared images of Yellowstone National Park have enough detail to make maps of temperature anomalies, which are especially useful in areas that are not easily accessible.



Satellite thermal infrared temperature anomaly map of Yellowstone National Park's thermal areas based on a Landsat-8 image from April 20, 2017. The warmest areas (yellow) are 20–30 °C (68–86 °F) above background; the cooler areas (purple) are 2–3 °C (36–37 °F) above background. By comparing maps like this for different times, scientists assess changes in thermal areas over time and estimate the total heat output from Yellowstone Caldera.

Overall Patterns

Thermal infrared energy is emitted by all objects that have a temperature greater than absolute zero (−273.15 °C or −459.67 °F). This energy can be detected by sensors on the ground, on airplanes, or on orbiting satellites and the measurements can be converted to temperature, providing a means for mapping changes in the temperature of Earth's surface over space and time. Analysis and interpretation of thermal infrared remote-sensing data for characterizing Yellowstone region's thermal areas has been ongoing since about 2005. High spatial resolution (1-meter pixels) airborne thermal infrared surveys of selected areas were completed once or twice per year from 2005 to 2015 using a FLIR SC640 broadband (8–12 micrometer) thermal infrared camera flown on a fixed-wing aircraft about 1,800 meters above ground level. Satellite-based thermal infrared data with 90–100-meter pixels, which is sufficient to map and quantify most of Yellowstone Caldera's thermal areas, have been acquired since 2000 with the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and, since 2013, with the Landsat-8 Thermal Infrared Sensor. Because the overwhelming majority of surface heating during the day is from the sun, nighttime acquisition of thermal infrared remote sensing data is best suited to evaluate the geothermal component of surface temperature, geothermal radiant heat flux, and geothermal radiative power output. In 2017, Landsat-8 acquired 16 nighttime scenes over the Yellowstone area; 11 scenes were cloudy to mostly cloudy—therefore unusable—and 5 scenes were clear to mostly clear and could be analyzed to calculate heat flux from Yellowstone National Park. Additionally, ASTER acquired 10 nighttime scenes over Yellowstone National Park; 6 of these scenes were cloudy to mostly cloudy and 4 were clear to mostly clear.

Analyses of the 2017 satellite thermal infrared data are generally consistent with previous results. The thermal areas with the highest temperatures above background (in °C), highest geothermal radiant emittance (in watts per square meter), and highest geothermal radiative power output (in megawatts) include Sulfur Hills, Upper Geyser Basin, Midway Geyser Basin, Lower Geyser Basin, Norris Geyser Basin, and Hot Spring Basin. An example of a satellite thermal infrared temperature image from 2017 is shown in figure 19. Summation of the geothermal radiative power output of all of Yellowstone National Park's thermal areas based on that temperature map is about 1.3 gigawatts, which is roughly equivalent to the power generated by a large nuclear reactor.

Analyses of high-resolution (1-meter pixel) airborne thermal infrared data were also conducted in 2017. The focus was on numerous nighttime thermal infrared datasets collected over Norris Geyser Basin from 2008 to 2015. Nighttime image frames were mosaicked into calibrated and georeferenced temperature maps. By comparing temperature maps from different seasons and calculating temperature difference images, both seasonal and longer term changes became apparent. Many features in Norris Geyser Basin show alternating seasonal temperature change patterns (fig. 20). Some of these changes are expected—for example, warming over summer months and cooling over winter months—but there were some thermal features that showed the opposite trend. These changes could be associated with fluctuating quantities of groundwater interacting with the shallow hydrothermal system. Alternatively, they could be an artifact of steam blocking the view of the thermal areas. More frequent high-resolution data acquisition campaigns in the future would improve our understanding of thermal area dynamics at the local scale.

Chloride Flux Measurements

Monitoring the chloride flux in the major rivers that drain Yellowstone National Park provides a holistic view of the thermal output from the underlying magma chamber because most of the chloride in Yellowstone National Park rivers comes from hydrothermal water heated by the magma reservoir. The USGS and the National Park Service have collaborated on chloride flux monitoring of the rivers in the park since the 1970s, typically by collecting water samples, but owing to funding restrictions, winter conditions, and the great distances between sites, the number of samples collected annually was limited.

Beginning in 2010, the USGS installed stations to automatically measure specific conductance (a measure of how well water conducts an electrical current), which can be used as a proxy for chloride concentration. The use of specific conductance probes at the various monitoring sites enables a more consistent estimation of chloride flux and can be used to identify changes in river chemistry as a result of geyser eruptions, rain events, or changes in thermal inputs as a result of earthquakes or other natural events. In 2017, continuous specific conductance measurements (every 15 minutes) were made at monitoring sites along the Madison, Firehole, Gibbon, Snake, Gardner, and Yellowstone Rivers, and a new station at Falls River was installed. No major changes were recorded by the conductance measurement stations in 2017, suggesting that overall thermal output at Yellowstone Caldera has been steady throughout the year.

Norris Geyser Basin Temperature Network

To better document changes in water flow and heat discharge from different parts of Norris Geyser Basin, a 10-station telemetered temperature network was installed in 2010. The sensors are located in various stream channels and thermal features within the basin, and they record temperatures every 2 minutes. Data from the network can reveal the changing patterns of geyser eruptions and thermal output.

Echinus Geyser in Norris Geyser Basin has historically been very predictable. By 1998, however, Echinus Geyser entered a period of quiescence punctuated by occasional erratic eruptions. During October 7–November 10, 2017, Echinus Geyser experienced a period of semiregular eruptions (about every 2 to 3 hours)—the first time such activity had occurred since November 2015 (fig. 21). During this recent eruptive cycle, the eruptions typically lasted 3 to 4 minutes and water drained significantly after each eruption with respect to previous levels (fig. 22).

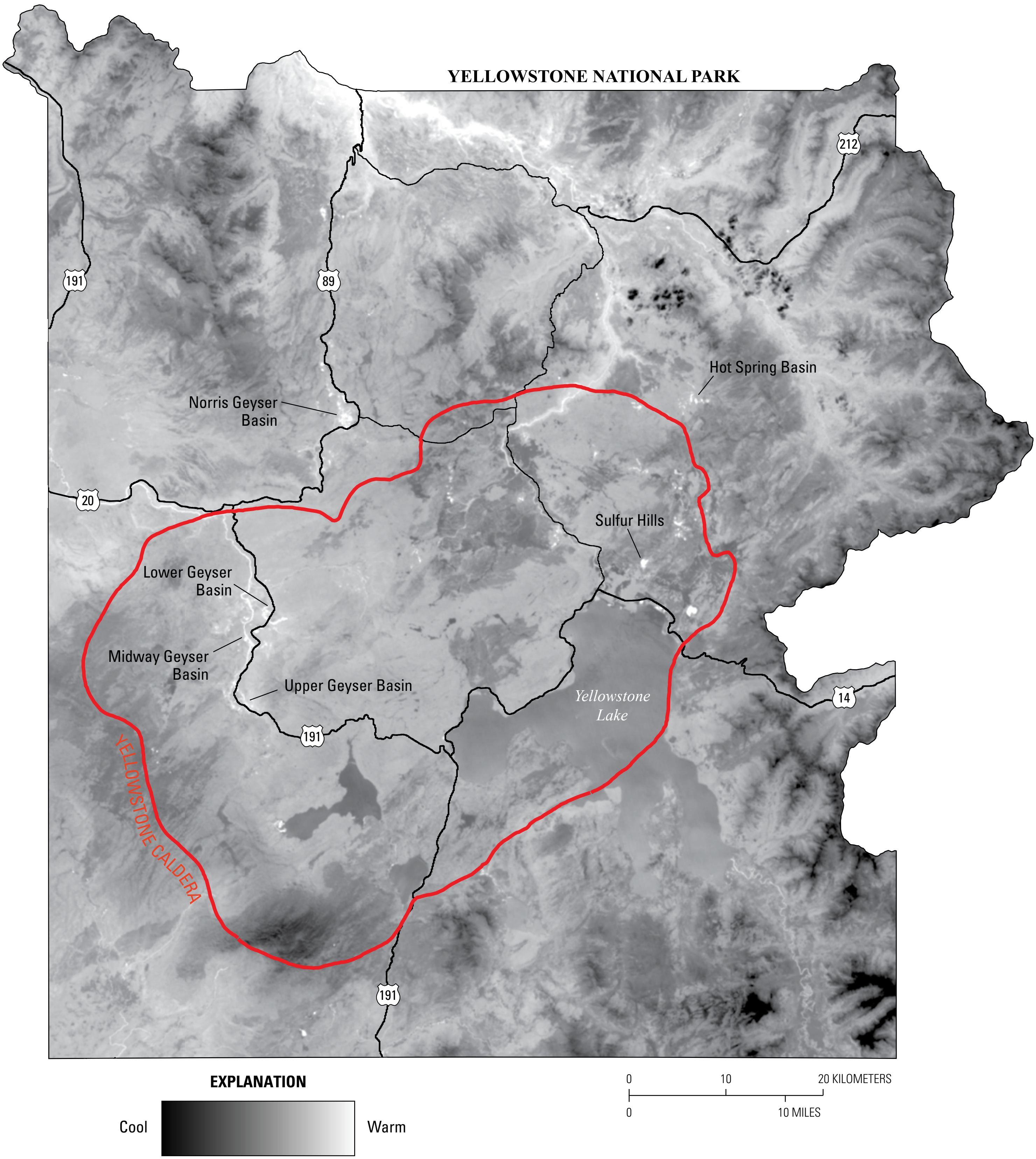


Figure 19. Satellite thermal infrared temperature image of Yellowstone National Park based on a Landsat-8 image from April 20, 2017. Satellite-based thermal infrared imagery shows areas of ground that are warmer versus cooler, and it can be used to estimate the total heat output from the Yellowstone magmatic system. The warmest areas (lightest in shade) in this image are 20–30 °C above background.

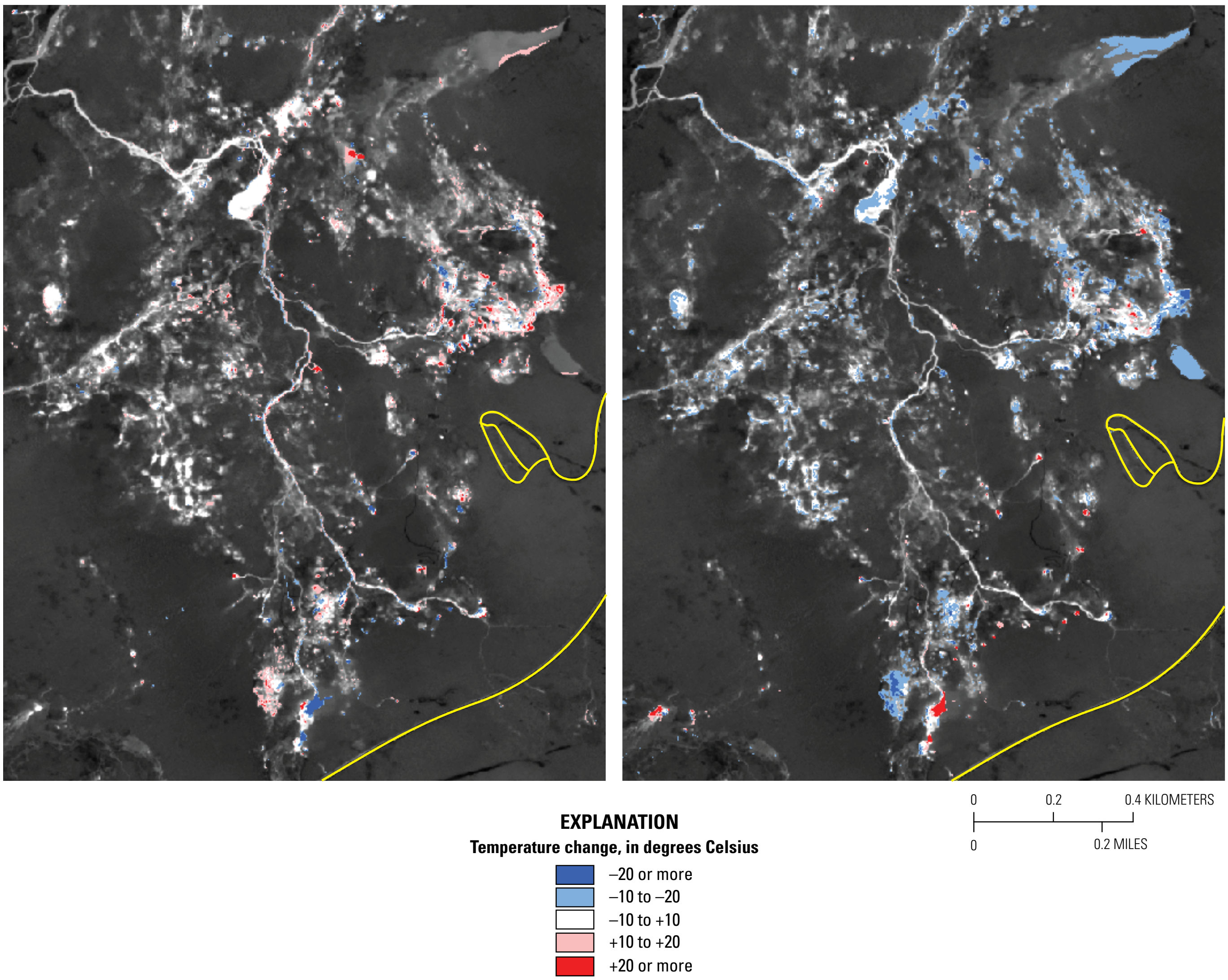


Figure 20. These two images show temperature changes in Norris Geyser Basin. *Left*, Temperature change over the summer season from April to October 2013. *Right*, Temperature change over the winter season from October 2013 to March 2014. Reds indicate areas of temperature increase and blues indicate areas of temperature decrease over the time span. Yellow lines are roads. Data from Carr and Vaughan (2017).

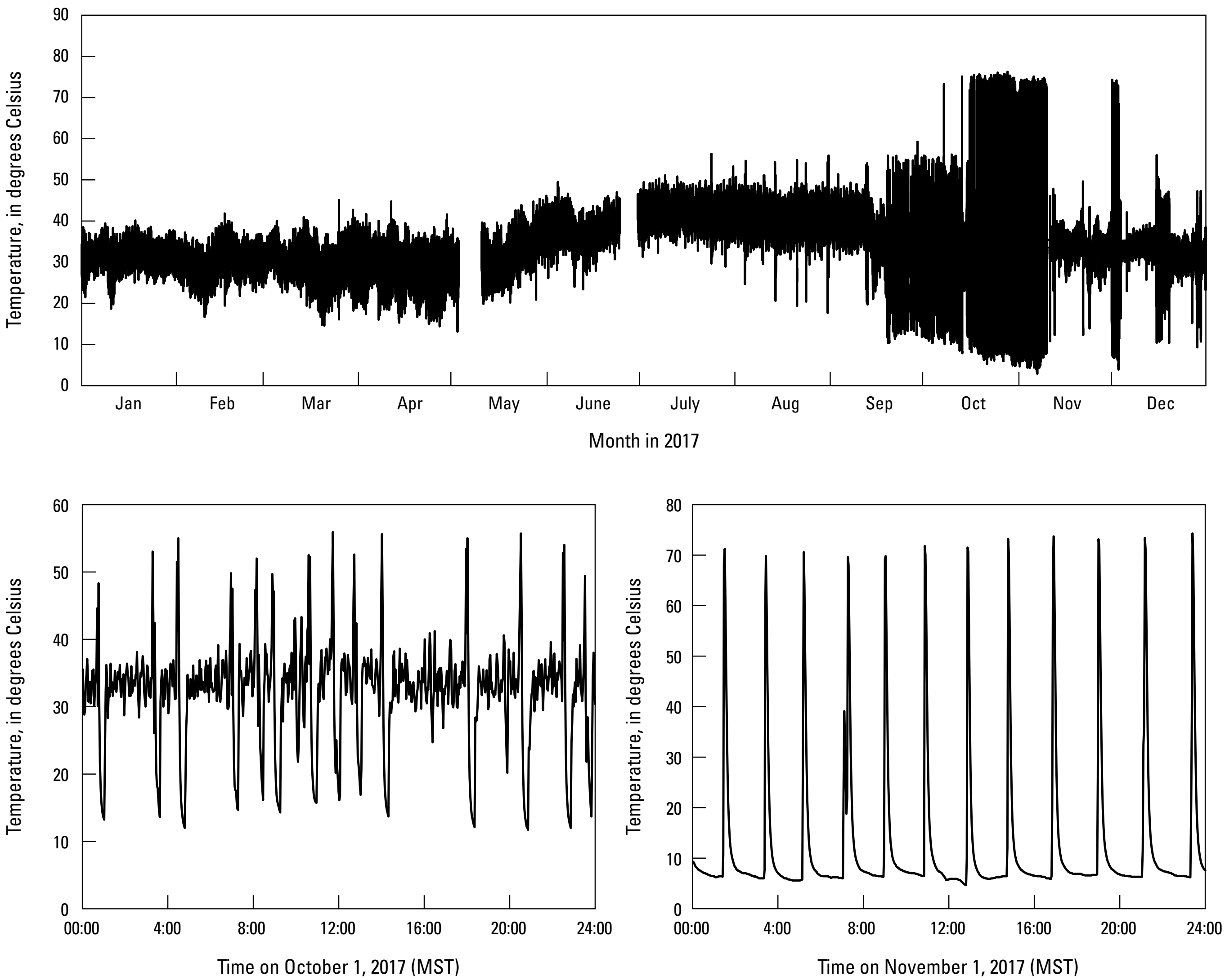


Figure 21. Time series of temperatures measured at the outflow channel of Echinus Geyser in Norris Geyser Basin. The fluctuations in September–November, and especially October–November, indicate semiregular eruptions of the geyser. MST, mountain standard time.

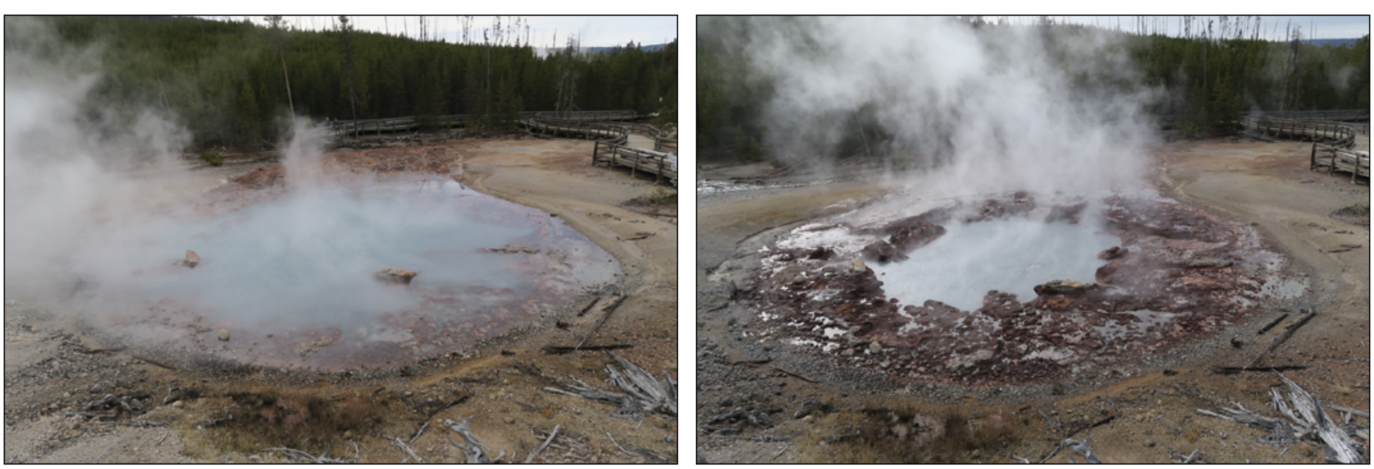


Figure 22. Photographs of Echinus Geyser on October 31, 2017, taken 2 minutes before (left) and 4.5 minutes after (right) an eruption. National Park Service photographs by Behnaz Hosseini.

Eruptions of Giant Geyser

Eruptions of Giant Geyser in the Upper Geyser Basin were documented three times in 2017—July 7 at 3:30 p.m., October 9 at 8:11 p.m., and November 3 at 1:02 p.m. (fig. 23; all times in Mountain Standard Time [MST]). The first two eruptions lasted 1–1.5 hours and the third had an unknown duration. These were the first known eruptions of Giant Geyser since September 28, 2015.

Mapping Travertine Growth at Mammoth Hot Springs

Over the past several years, the Yellowstone Center for Resources has conducted numerous helicopter overflights of thermal areas, collecting images using both thermal-infrared and visible-light cameras. Daytime visible-light images were collected at oblique angles from a helicopter over Mammoth Hot Springs from 2009 to 2016. These overlapping image sequences were processed using the Photoscan Pro structure-from-motion image processing software to make orthorectified mosaics and 1-meter-resolution digital elevation models (DEMs). DEMs from 2013 and 2016 were compared to test whether surface elevation changes could be detected. Figure 24 shows that elevation increases of as much as 2 meters over this three-year period were detected in the outflow region downslope from what is locally known as “Palette Springs,” most likely indicating travertine growth in this area.

When these images were acquired, they were not intended to be processed into DEMs, and were therefore not ideal for elevation-change analysis. This test, however, demonstrates the great potential for generating DEM difference datasets to characterize small-scale elevation changes at thermal areas, even with non-ideal imagery.

Figure 23. Giant Geyser, in the Upper Geyser Basin, in eruption on November 3, 2017. National Park Service photograph by Phil Officer.

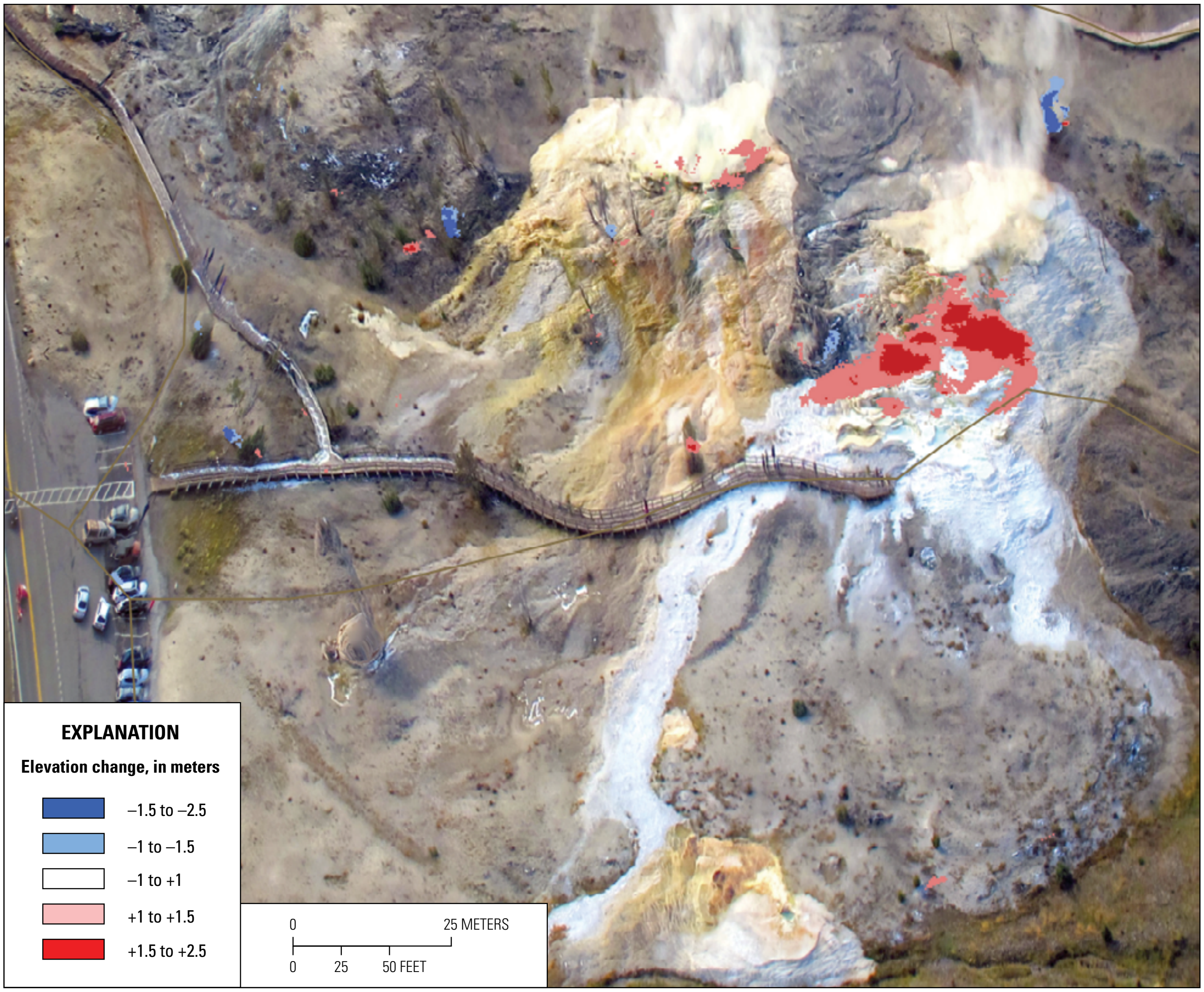


Figure 24. Digital elevation model difference image of Mammoth Hot Springs from 2013 to 2016 draped over an orthomosaic image from September 2013. The more than 2-meter elevation increase in the outflow region downslope from the spring locally known as Palette Springs (red colors) is interpreted as travertine growth. Data from Carr and Vaughan (2017).

Hydrothermal Dynamics of Yellowstone Lake

Several YVO researchers played an active role in the Hydrothermal Dynamics of Yellowstone Lake (HD-YLAKE) project during 2017. Project HD-YLAKE, which began in 2016 and will continue through 2018, is funded by the National Science Foundation, with support from the U.S. Geological Survey and the National Park Service. The project seeks to understand how the Yellowstone Lake hydrothermal system responds to geological and environmental changes by observing how the temperature and composition of the hydrothermal fluids, the heat flow of the system, and the microbial communities inhabiting the vent fields evolve over time. The field strategy uses a two-pronged approach: (1) geophysical and geochemical monitoring of the active system and (2) analyses of sediment cores to study the postglacial (~15,000-year) history of hydrothermal activity beneath the lake.

In 2016, using the research vessel (RV) *Annie* and the submersible remotely operated vehicle (ROV) *Yogi*, a network of pressure-temperature gages, heat-flow equipment, and seismometers was deployed on the lake floor, sediment cores were collected from lake beds, and samples were taken of hydrothermal fluids and microbial material (fig. 25). Work in 2017 included analysis of these data and samples, as well as deployment of a full-scale network of monitoring instrumentation, including 10 lake-bottom seismometers and 2 chemical sensors. One of the main areas of interest is the deepest part of the lake (at depths of about 110 meters), where hydrothermal fluids discharge at temperatures as high as 170 °C—the hottest hydrothermal vent fluid temperatures yet measured in Yellowstone National Park. Monitoring equipment on the lake floor will be recovered in August 2018.

Analysis is continuing of the eight sediment cores, the longest of which is 11.5 meters in length. They were collected in 2016 from six different geologic environments in the northern basin of Yellowstone Lake, including hydrothermal areas, old

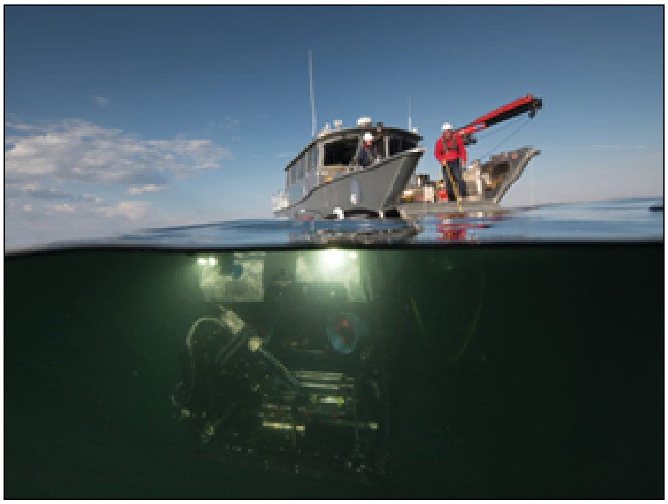


Figure 25. *Left*, The research vessel *Annie* and the submersible remotely operated vehicle *Yogi* deployed. *Right*, Lake bottom seismometers awaiting deployment from the deck of research vessel *Annie*.

hydrothermal explosion craters, and areas prone to landslides. Preliminary examination reveals that many of the cores contain multiple hydrothermal explosion deposits, tephra layers, landslide deposits, possible turbidite layers, and faulted sections (indicating the occurrence of strong earthquakes). One prominent tephra is found in most of the cores, and its variable depth in individual cores suggests different rates of sediment accumulation in different areas of Yellowstone Lake. Looking at the stratigraphy present in the eight cores across the northern basin provides a geologic cross-section and insight into the large hydrothermal system beneath the lake floor. The cores have been scanned for geophysical and geochemical parameters, and analyses are underway to determine their chemical compositions. Geochemical analyses of pore-fluid samples from the cores will provide insight into the fluid chemistry below the lake floor and constrain the nature and lateral extent of hydrothermal fluids in sediments surrounding the vent fields. Analyses of tephrochronology and diatom populations, pollen, and charcoal preserved in the cores will provide evidence of the response of the lake to past climate, hydrothermal, and geologic changes.

Communications and Outreach

During 2017, in addition to the regular monthly updates of Yellowstone activity that are issued on or about the first of each month, information statements were issued on June 15, June 19, and July 18, all for the purpose of describing seismicity associated with the Maple Creek earthquake swarm (including the June 15 magnitude 4.4 event, which was the largest Yellowstone area earthquake of the year). Information about Yellowstone Caldera was also posted to @USGSVolcanoes Twitter and Facebook sites; the posts were routinely among the most viewed for any volcano or volcanic region. Research at YVO was featured as a USGS "top story" when a report on geyser eruptions, written by USGS hydrologist Shaul Hurwitz and University of California, Berkeley, professor Michael Manga, was profiled on the main USGS website (https://www.usgs.gov/news/complex-dynamics-geyser-eruptions).

In June 2017, YVO began streaming data from a webcam located near Lake Village, just north of Yellowstone Lake (fig. 26). The first YVO mobile camera was installed in 2010 on Lake Butte, where it provided a striking view of Yellowstone Lake through a grove of fire-charred tree trunks (the site was frequented by wildlife). In 2012, the system was moved to Biscuit Basin, where it remained until 2017. The current image from the Yellowstone Lake webcam can be viewed at https://volcanoes.usgs.gov/volcanoes/yellowstone/multimedia_webcams.html.

Figure 26. View toward Yellowstone Lake from a webcam near Lake Village on June 28, 2017, at 1:30:03.124 p.m. local time, shortly after the camera was activated.

Finally, Yellowstone National Park was the site of a major field excursion associated with the 2017 International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) scientific assembly. The IAVCEI meeting happens only once every four years at a different location around the world, and in 2017 the meeting took place in Portland, Oregon. Prior to the 2017 meeting, the most recent IAVCEI meeting held in the United States was in New Mexico in 1989. The post-meeting Yellowstone National Park excursion was co-led by YVO scientists Lisa Morgan, Pat Shanks, Jamie Farrell, and Jake Lowenstern. Field-trip guides from the IAVCEI meeting published by the USGS and describing geological excursions in the Yellowstone region can be downloaded from https://doi.org/10.3133/sir20175022 (chapters P and Q).

Summary

The most noteworthy event of 2017 in the Yellowstone region was the June–September Maple Creek earthquake swarm, which was the second longest and second most energetic seismic sequence ever recorded in the vicinity of Yellowstone National Park. The swarm was not associated with any other changes, however. Deformation patterns that have been ongoing since 2015 continued, including subsidence of Yellowstone Caldera and uplift in the Norris Geyser Basin area, both at rates of about 3 centimeters (about 1 inch) per year. Hydrothermal activity remained at background levels with no significant changes in gas or thermal emissions. Besides the Maple Creek earthquake swarm, all indications of volcanic and hydrothermal activity in the Yellowstone region were at background levels.

Many research efforts were substantially advanced by YVO scientists and collaborators during the year, including investigations of hydrothermal areas beneath Yellowstone Lake, the geological makeup of Yellowstone Lake and Lewis Lake, the eruptive history of lavas during the second caldera cycle, evolution of the temperature and topography of hot spring regions over time, the seismic characteristics of the Upper Geyser Basin, and the chemistry of gases and waters from various areas around Yellowstone National Park. These studies build on decades of prior research and will likely improve understanding of the hydrothermal, magmatic, and tectonic systems associated with Yellowstone Caldera. As they are finalized, the results of these studies are planned to be published in academic journals, as well as highlighted in future editions of YVO's new weekly series of online articles, Yellowstone Caldera Chronicles, which can be accessed at https://volcanoes.usgs.gov/volcanoes/yellowstone/article_home.html.

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Photograph of columnar basalt at Sheepeater Cliffs, Yellowstone National Park. U.S. Geological Survey photograph by S.R. Brantley.

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