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Yellowstone Volcano Observatory

2020 Annual Report

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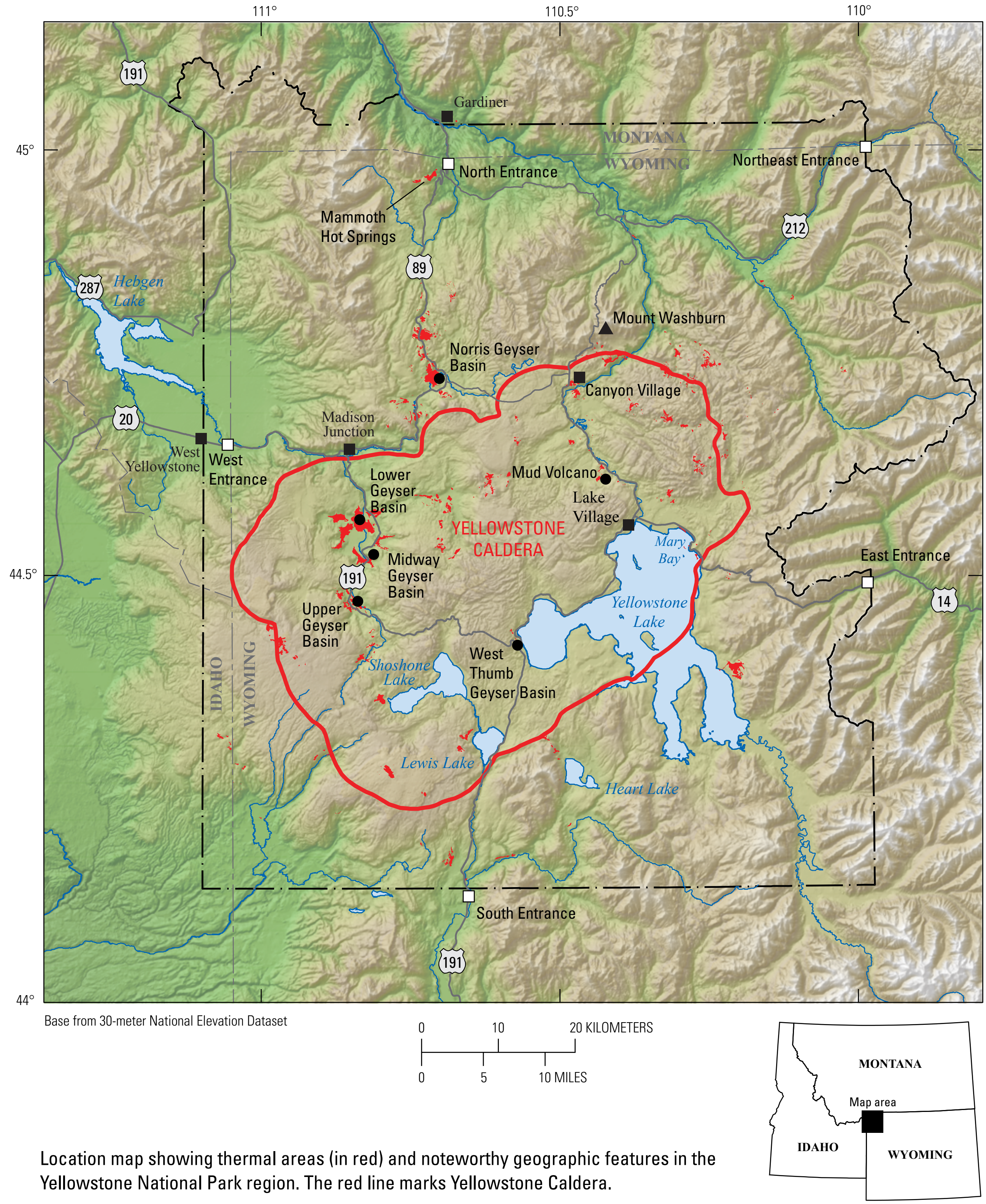

Location map showing thermal areas (in red) and noteworthy geographic features in the Yellowstone National Park region. The red line marks Yellowstone Caldera.

Cover. Photograph of Excelsior Geyser Crater in Midway Geyser Basin by Paula Hayes on Unsplash.

Facing page. Photograph of Fishing Cone in West Thumb Geyser Basin by Laura Nyhuis on Unsplash.

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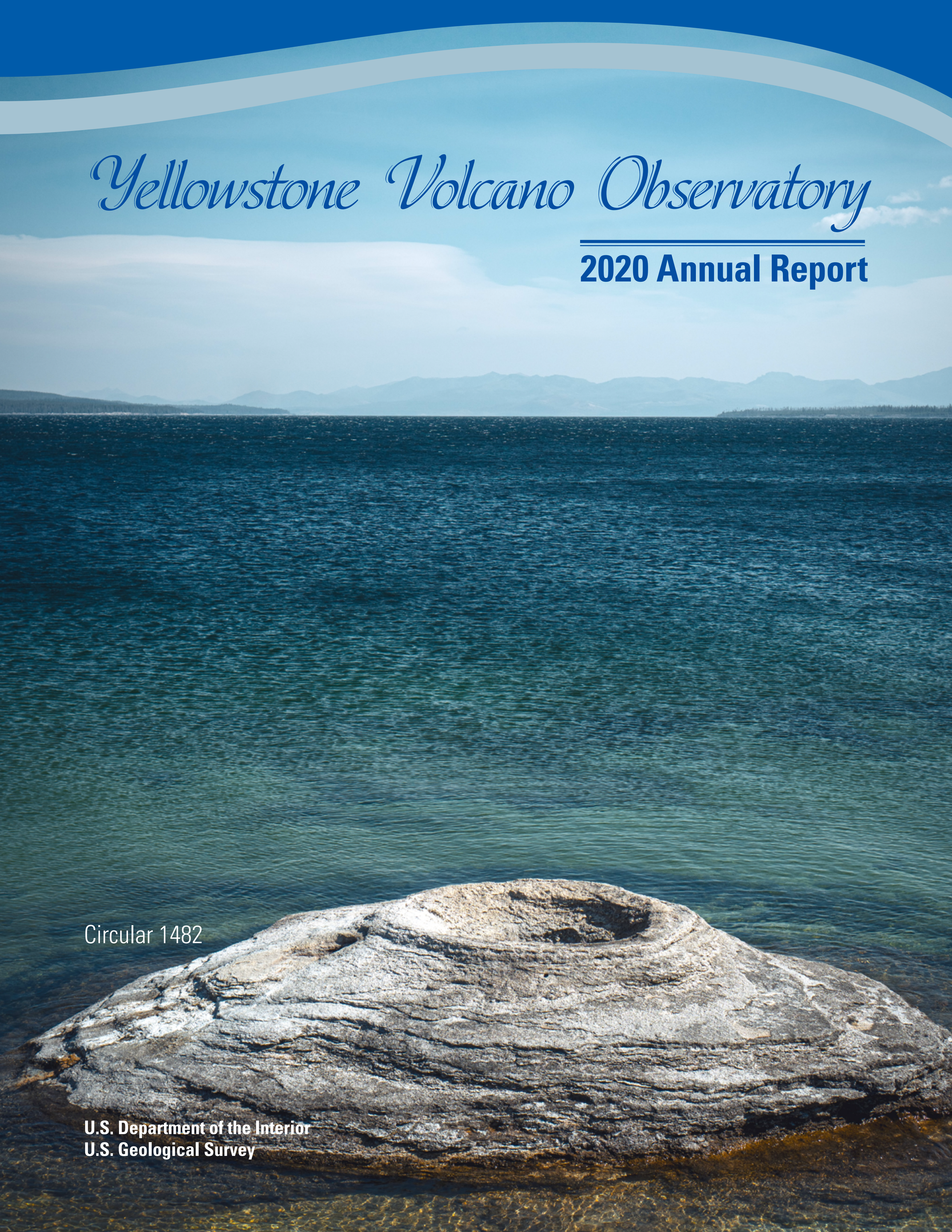

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U.S. Geological Survey, Reston, Virginia: 2021

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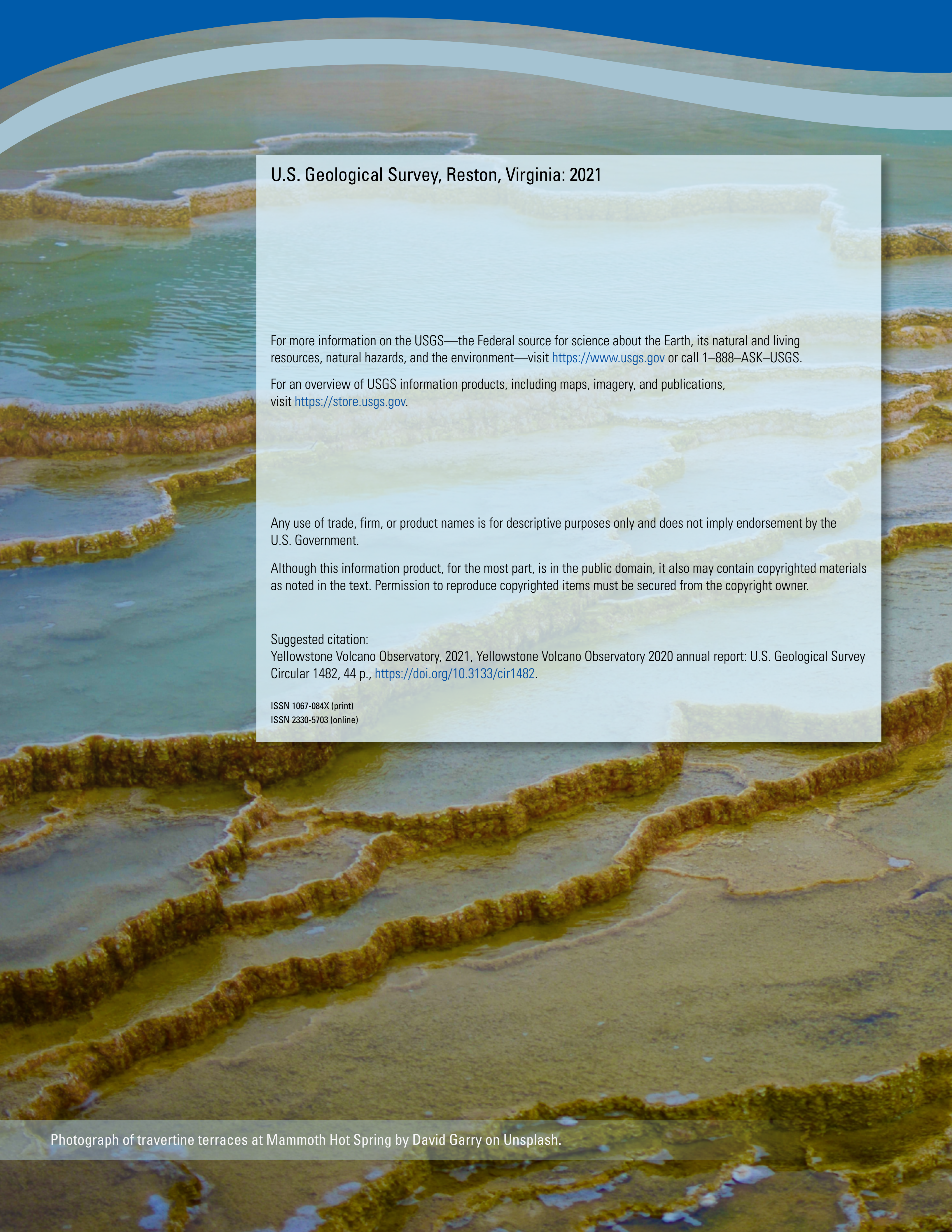

Photograph of travertine terraces at Mammoth Hot Spring by David Garry on Unsplash.

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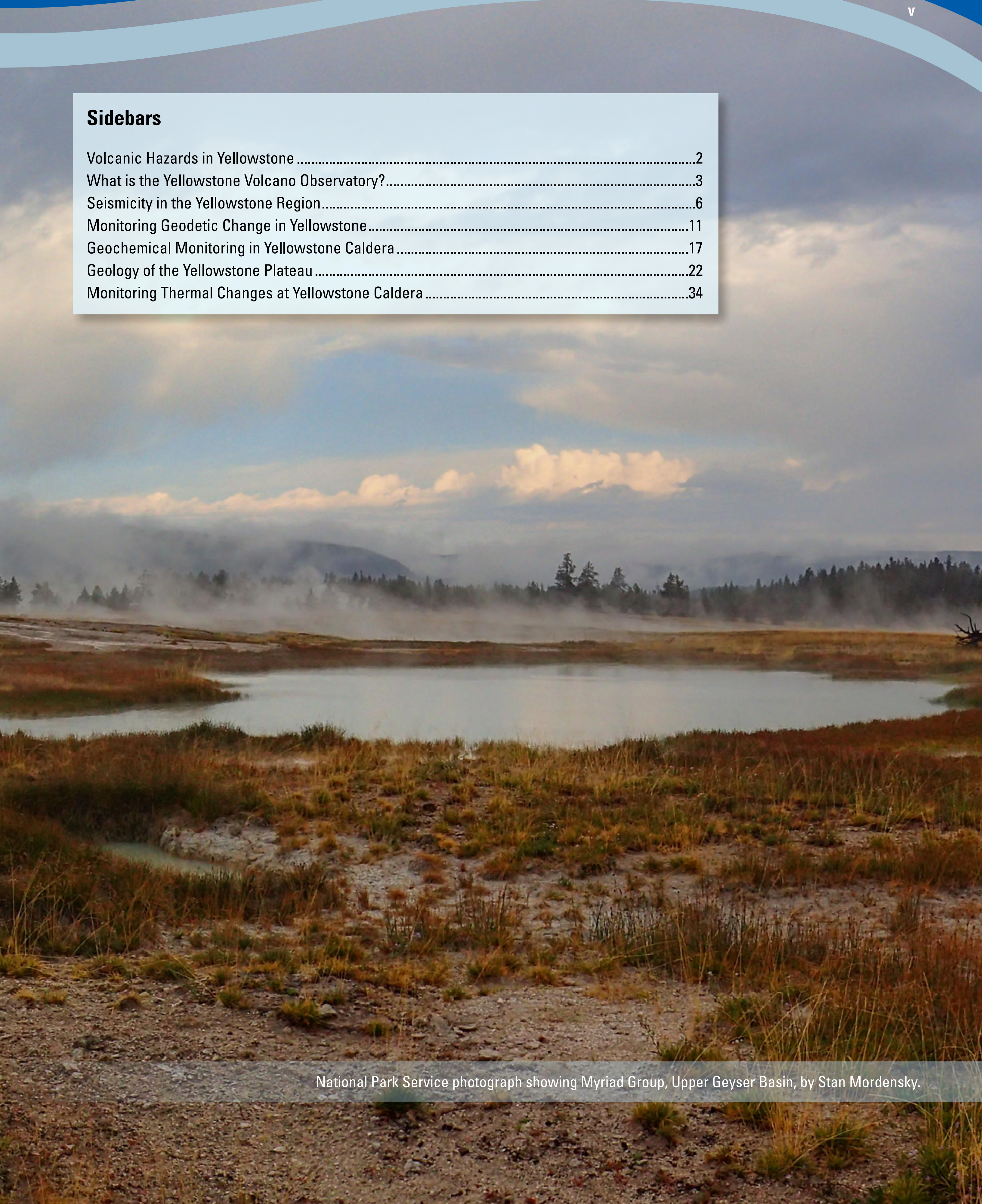

National Park Service photograph showing Myriad Group, Upper Geyser Basin, by Stan Mordensky.

National Park Service photograph showing Alum Creek by Annie Carlson.

Yellowstone Volcano Observatory

2020 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). YVO is a collaborative consortium made up of the U.S. Geological Survey (USGS), Yellowstone National Park, University of Utah, University of Wyoming, Montana State University, 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 2020, focusing on the Yellowstone volcanic system. Highlights of YVO research and related activities during 2020 include

- An active-source seismic experiment to image the top of Yellowstone's magma reservoir and quantify the amount of magma at that depth,
- Semipermanent Global Positioning System (GPS) array deployment, including a new site near Mary Mountain, from May to October,
- Studies of hydrothermal activity in the southwest portion of Yellowstone National Park,
- Numerous geological studies, including characterization of hydrothermal explosion craters, updating existing maps, and refining the ages of Yellowstone volcanic units,
- Investigation of a dormant period at Old Faithful Geyser that may be related to regional drought 800–650 years ago, and
- Development of a publicly available online map interface that displays a variety of geospatial data for Yellowstone National Park.

Steamboat Geyser, in Norris Geyser Basin, continued the pattern of frequent eruptions that began in 2018 with 48 water eruptions in 2020, matching the record for a calendar year that was set in 2019. Giantess Geyser, in the Upper Geyser Basin, erupted for the first time in 6 years in August 2020 and experienced a second eruption in September. The variation in activity at Steamboat and Giantess Geysers is typical for Yellowstone, where many geysers experience alternating periods of frequent and infrequent eruptions.

Patterns of both seismicity and deformation in 2020 were similar to those in 2019. Total seismicity—1,722 located earthquakes—was elevated compared to the 1,218 earthquakes located in 2019, but still well within the historical average of about 1,500–2,500 earthquakes per year. Deformation patterns during 2020 showed trends that were similar to previous years. Overall subsidence of the caldera floor, ongoing since late 2015 or early 2016, continued at rates of a few centimeters (1–2 inches) per year, and minor subsidence of Norris Geyser Basin that began in 2018 slowed during 2020 and stopped by the end of the year.

Throughout 2020, the aviation color code for Yellowstone Caldera remained at "green" and the volcano alert level remained at "normal."

YVO Activities

As with life in general around the globe, YVO activities were severely limited by the Coronavirus Disease 2019 (COVID-19) pandemic. The YVO biennial coordination meeting, scheduled for May 2020, was canceled. In addition, a scientific conference focusing on the time scales and hazards associated with the style of volcanism in the southwestern United States, planned for March 2020 in Flagstaff, Arizona, was postponed until 2022. Field work was also curtailed, and Yellowstone National Park itself did not fully open until June 2020. As a result, a number of field projects

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[1]This report was prepared jointly by members of the Yellowstone Volcano Observatory consortium, including Michael Poland, Daniel Dzurisin, Dakota Churchill, Lauren Harrison, Shaul Hurwitz, Jennifer Lewicki, Blaine McCleskey, Lisa Morgan, Pat Shanks, Mark Stelten, Wendy Stovall, R. Greg Vaughan, and Charles Wicks of the U.S. Geological Survey, Jefferson Hungerford, Stan Mordensky, and Mollie Pope of the National Park Service, Jamie Farrell of the University of Utah, David Mencin of UNAVCO, James Mauch and Erin Campbell of the Wyoming State Geological Survey, and Madison Myers and Natali Kragh of Montana State University. Seth Moran and Liz Westby of the U.S. Geological Survey reviewed the report.

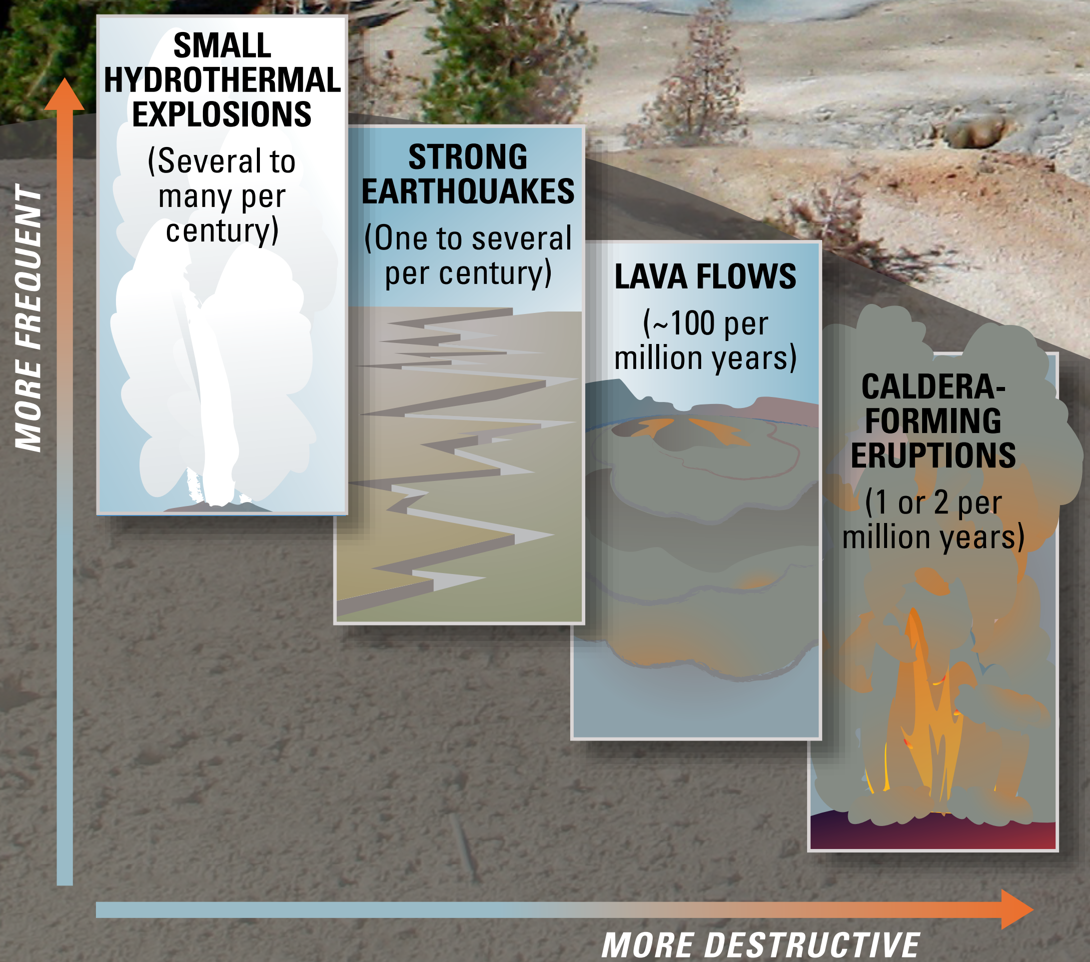
Volcanic Hazards in Yellowstone

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. This combination creates a diversity of hazards, but the most catastrophic events—large volcanic explosions—are also the least likely to occur.

Over the past 2.1 million years, Yellowstone volcano 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 last of which erupted 70,000 years ago.

Tectonic extension of the western United States is responsible for large and devastating earthquakes in the Yellowstone region along 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 craters found throughout the park. At least 25 explosions that left craters greater than 100 meters (about 300 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).

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 nine 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 nine 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. Scientists from these two organizations analyze and provide data to the public as well as conduct research into active tectonic and volcanic processes in the region. Yellowstone National Park 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 and Montana State University support 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 of Guardian Geyser and Porcelain Basin in Norris Geyser Basin by Deb Bergfeld, U.S. Geological Survey.

were postponed or limited in scope. Nevertheless, critical field surveys and instrument maintenance were completed as needed to maintain monitoring networks and continue valuable scientific research projects.

In more positive news, Montana State University (MSU) became the ninth member of the YVO consortium in 2020! MSU is located in Bozeman, Montana, about 90 minutes from the north entrance to Yellowstone National Park. For years, researchers at MSU have used Yellowstone as a natural laboratory to test important scientific hypotheses and to teach classes, taking advantage of the rich biodiversity, hydrothermal activity, and geology. As part of YVO, MSU scientists will contribute to a better understanding of Yellowstone through their mapping of eruptive units, as well as work on the hydrothermal system and the unique biology of thermal areas.

YVO was also excited to welcome Dr. Lauren Harrison to the team in 2020. Lauren is a Mendenhall post-doctoral fellow with the U.S. Geological Survey based at Menlo Park, California. The objective of Lauren's current research at Yellowstone is to develop a robust methodology to date past hydrothermal explosions and to investigate the conditions of hydrothermal basins at the time of these events. The goal of the work is to provide a greater understanding of what causes hydrothermal explosions and to estimate the probability of similar activity in the future. Lauren is no stranger to the region, having obtained her B.S. degree from the University of Wyoming and completed a summer internship in Yellowstone National Park.

Seismology

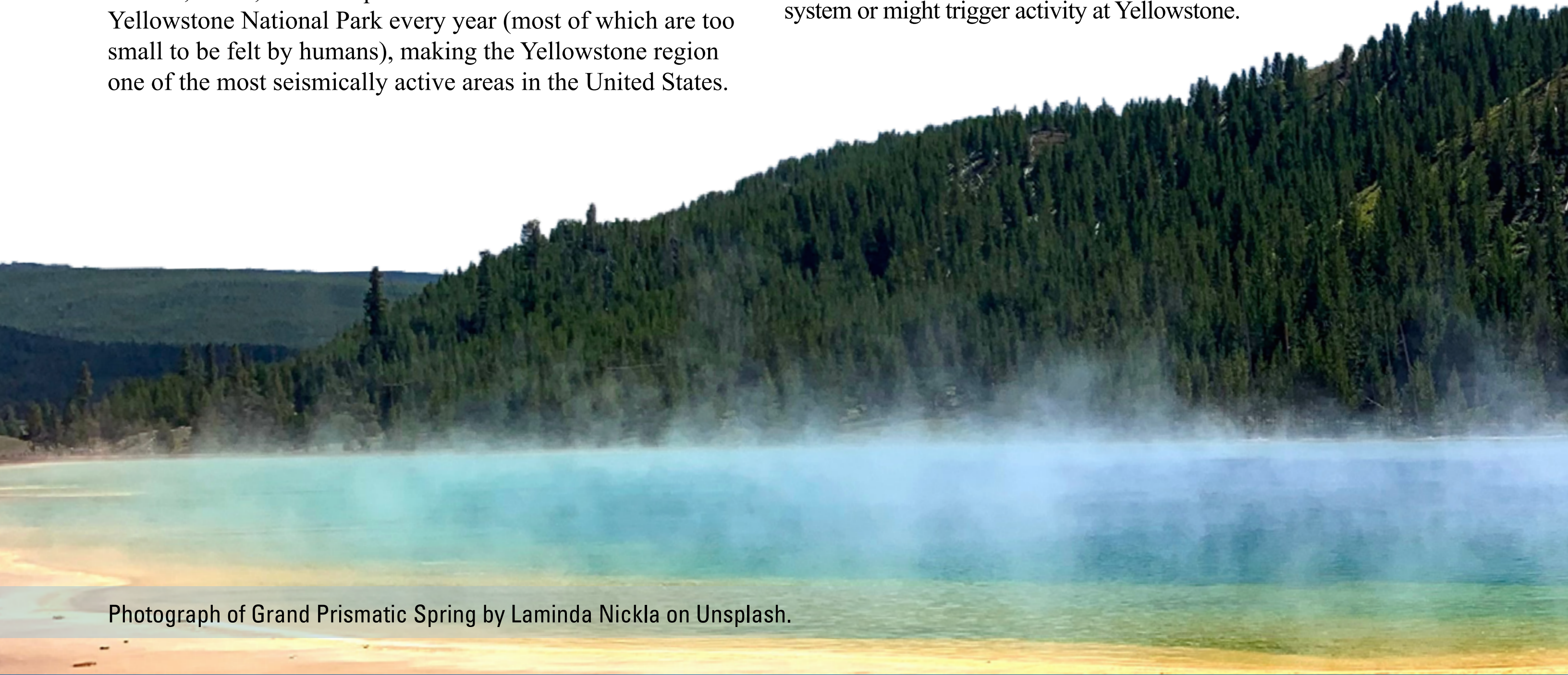
Earthquakes have been monitored in the Yellowstone area since the 1970s (see sidebar on seismicity on p. 6–7). The Yellowstone Seismic Network is maintained and operated by the University of Utah Seismograph Stations, which records data from 46 stations in the Yellowstone region. On average, about 1,500–2,500 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.

Overall Seismicity in 2020

During 2020, the University of Utah Seismograph Stations recorded 1,722 earthquakes in the Yellowstone region (fig. 1), including three that were felt (meaning that people reported some shaking). The largest events of the year were three magnitude 3.1 earthquakes, which occurred on March 31 at 9:36 a.m., May 29 at 4:39 a.m., and November 25 at 5:58 a.m. local time. All three events occurred in the area between Hebgen Lake, Montana, and Norris Geyser Basin in Yellowstone National Park—a region of abundant historical seismicity.

Of the total number of recorded earthquakes, 887 (about 52 percent of all the earthquakes that were large enough to be located in 2020) occurred as part of 26 swarms, which are defined as the occurrence of many earthquakes in the same small area over a relatively short period. Swarm activity is common in Yellowstone and typically includes nearly half of all earthquakes that take place in the region. The largest swarm in 2020 included 123 events during September 10–16 on the south boundary of the Yellowstone Caldera between Heart Lake and West Thumb. The second largest swarm of the year occurred December 1–4 and comprised 110 events on the eastern margin of Yellowstone Caldera, near the center of Yellowstone Lake. Three other swarms, of 102 events (May 29–June 4), 88 events (May 8–16), and 68 events (February 17–24), occurred in the region between Hebgen Lake and Norris Geyser Basin.

There were two noteworthy earthquakes in 2020 in the intermountain west outside of the Yellowstone region—a magnitude 5.7 event just west of Salt Lake City on March 18 and a magnitude 6.5 event in central Idaho on March 31, both of which were followed by strong and long-lived aftershock sequences. The earthquakes were related to slow extension of the Basin and Range Province in the western United States and were unrelated to the Yellowstone volcanic system. Neither earthquake caused changes in seismic or hydrothermal activity in the national park. Nevertheless, YVO answered many questions from concerned citizens who feared the earthquakes were related to the volcanic system or might trigger activity at Yellowstone.



Photograph of Grand Prismatic Spring by Laminda Nickla on Unsplash.

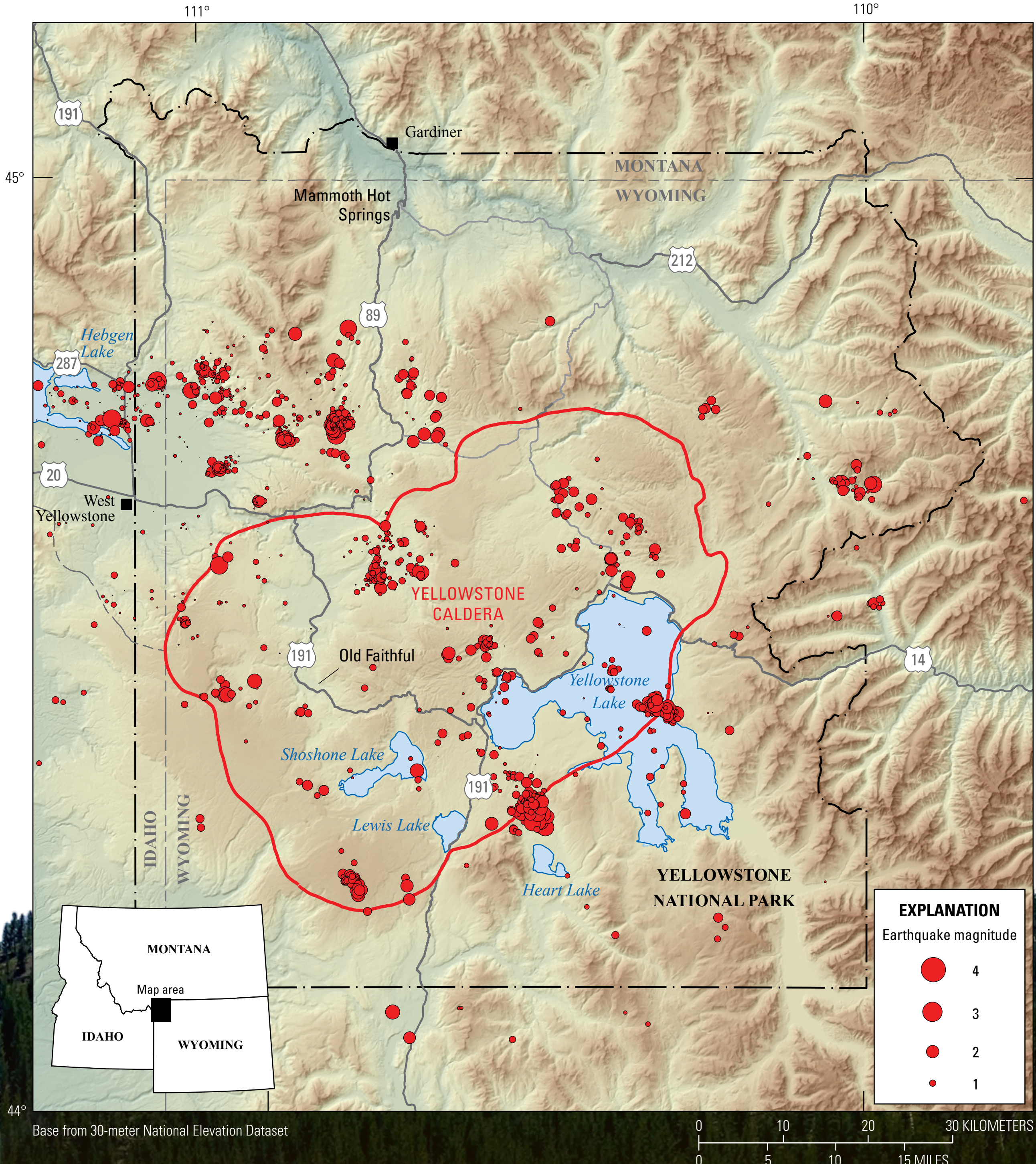
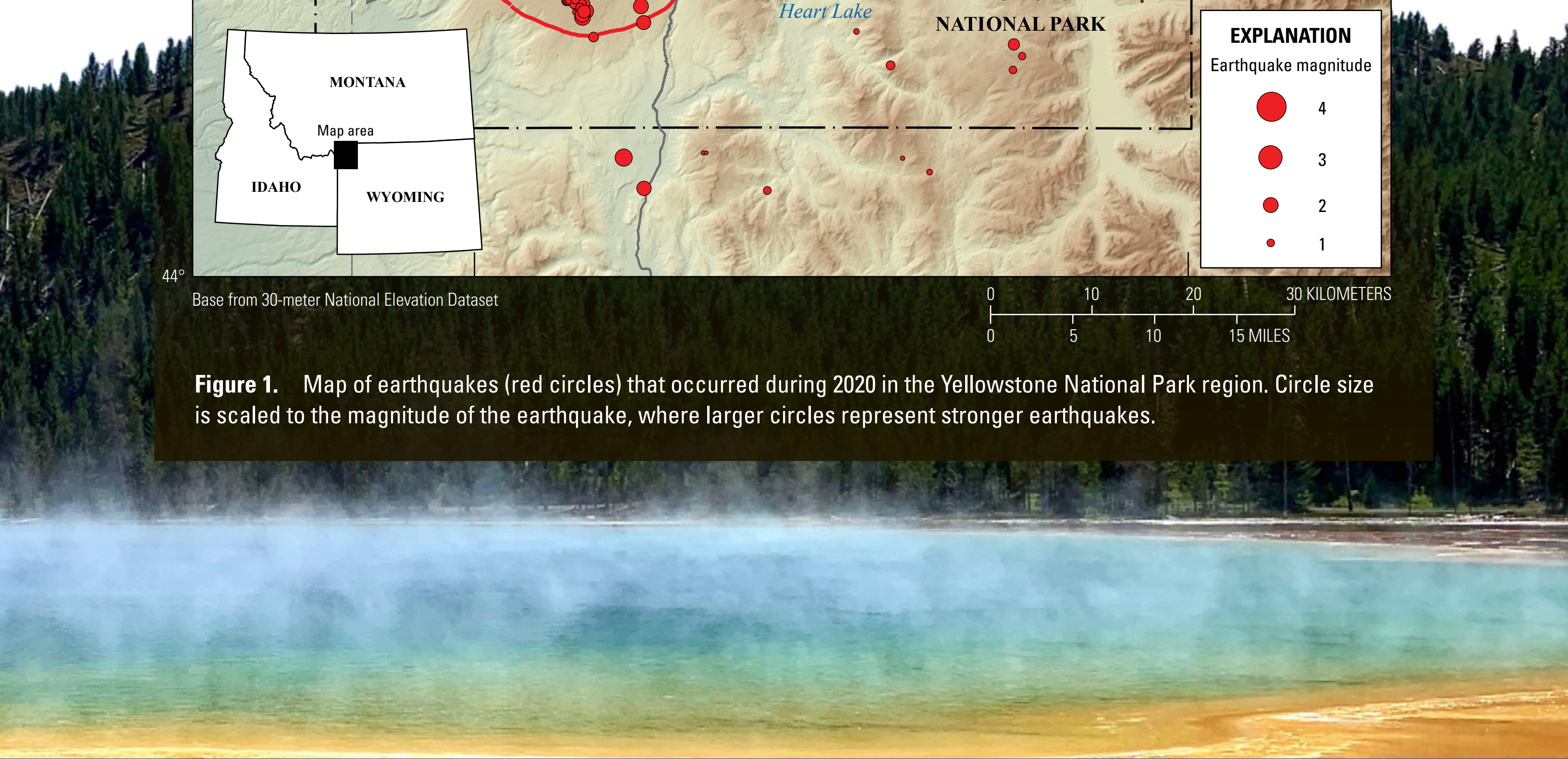


Figure 1. Map of earthquakes (red circles) that occurred during 2020 in the Yellowstone National Park region. Circle size is scaled to the magnitude of the earthquake, where larger circles represent stronger earthquakes.



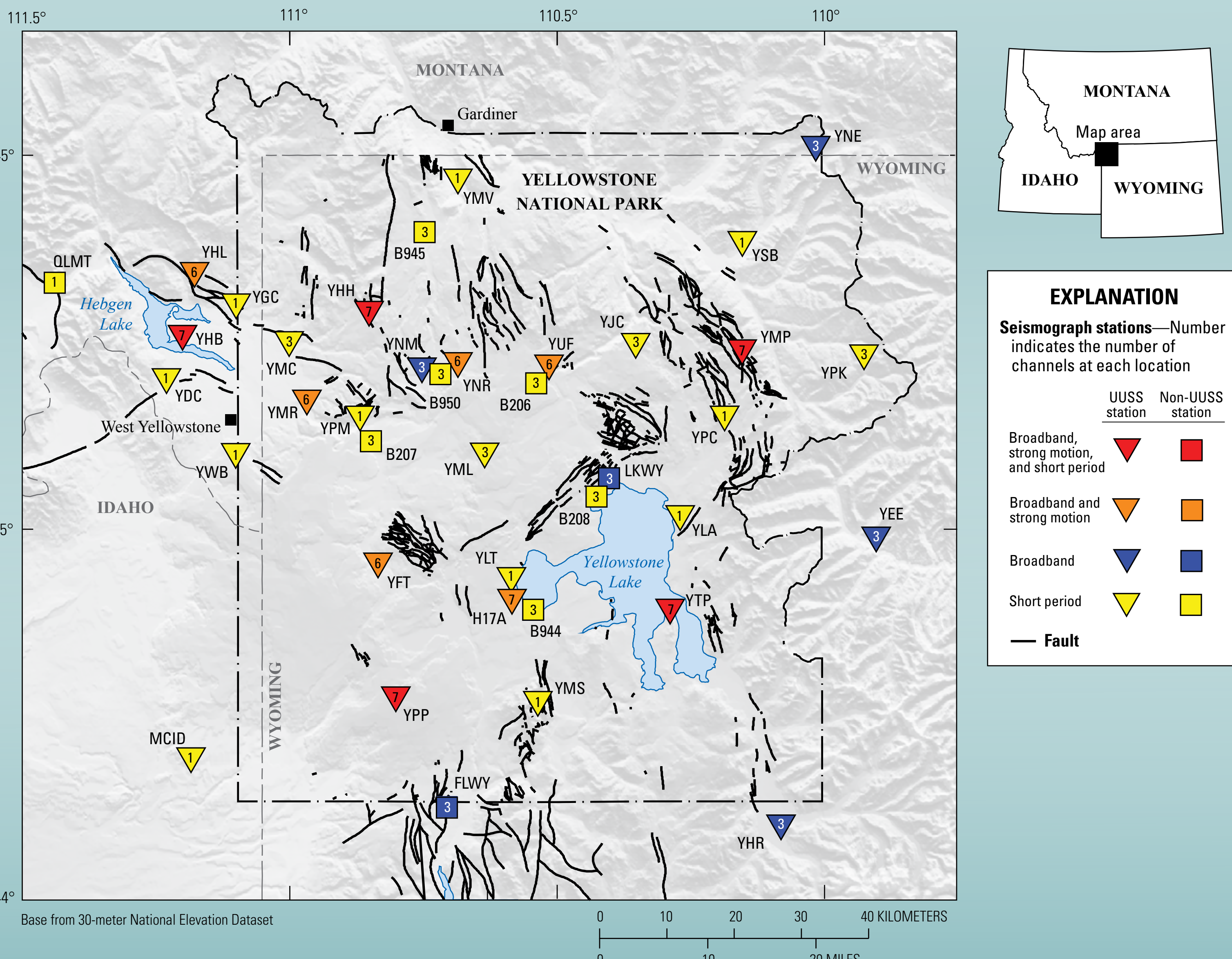
SIDEBAR

Seismicity in the Yellowstone Region

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 stations installed in the seismically and volcanically 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 or antennas get covered in

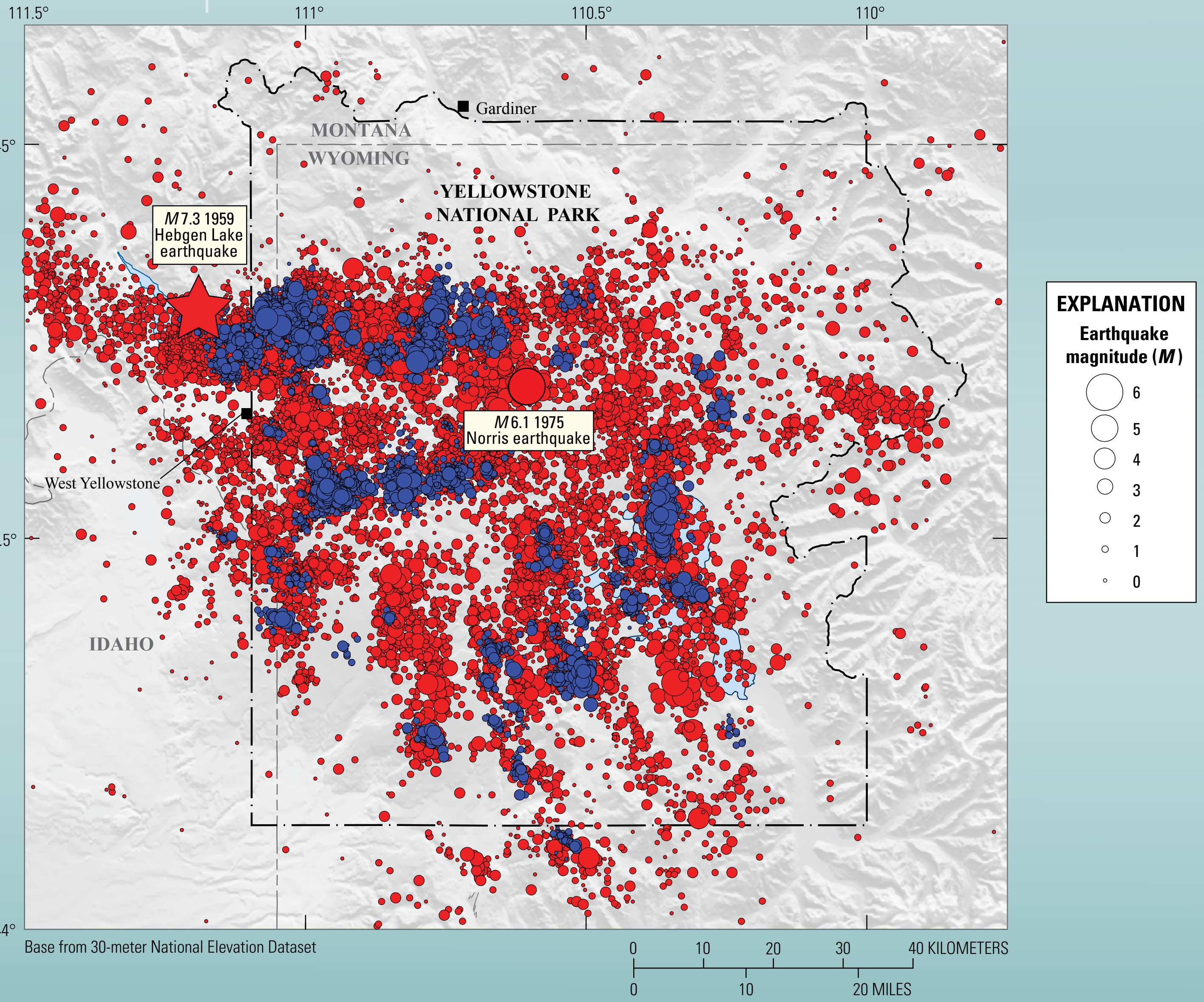


Map of seismometer station locations operated by the University of Utah Seismograph Stations (UUSS) and other agencies. Map view shows the Yellowstone earthquake catalog region.

snow and ice. Sometimes seismometers that go offline during the winter cannot be accessed until the following spring.

Since 1973, more than 50,000 earthquakes have been located in the Yellowstone region. More than 99 percent of those earthquakes are magnitude 2 or below and are not felt by anyone. Since 1973, 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 394 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. Though they can occur anywhere in the region, they are most common in the east-west band of seismicity between Hebgen Lake and 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.

Seismic Studies of the Yellowstone Magma Reservoir

In August 2020, the University of Utah and the University of New Mexico, in collaboration with Yellowstone National Park, deployed 648 seismometers throughout Yellowstone National Park (fig. 2) as part of a research project funded by the National Science Foundation. The purpose of the project was to use seismic data to better constrain the amount of melt (liquid magma) present at the top of the previously imaged Yellowstone magma reservoir. The seismic array was mostly deployed along the road system throughout Yellowstone National Park, with two lines of especially dense station spacing crossing the 631,000-year-old caldera. The instruments recorded continuous seismic data for about 1 month and then were removed.

Three types of data were collected during the month-long deployment:

1. Signals from earthquakes—both small local earthquakes and large worldwide earthquakes—that occurred while the seismic array was deployed, including the largest seismic swarm of the year during September 10–16,
2. Ambient seismic noise, or the background seismic "hum" of the Earth, that is largely produced by waves in the oceans and is occurring all the time, and
3. Seismic data from a vibroseis truck (fig. 3) that provided a source of low-frequency energy in multiple locations along two lines that cross the caldera.

The data will be used to construct high-resolution images of the shallow crust beneath the surface within Yellowstone Caldera, including the top of the magma reservoir and the overlying hydrothermal system. In addition, the array will make it possible to locate small earthquakes that would otherwise go undetected by the Yellowstone Seismic Network alone. This will provide a more complete view of where seismicity is occurring and on what geological structures (like faults), and how those structures may or may not be related to the volcanic system.

Geodesy

Geodesy is the scientific discipline focused on changes in the shape of Earth's surface, called deformation. At Yellowstone, deformation is caused by a combination of magmatic, tectonic, and hydrothermal processes. Ground motion is measured using networks of GPS[2] stations, borehole tiltmeters and strainmeters, and a satellite-based remote-sensing technique called interferometric synthetic aperture radar (InSAR) (see sidebar on monitoring geodetic change on p. 11–13). Changes in Earth's gravity field, which can indicate subsurface mass changes caused by movement of magma or groundwater, for example, also fit within the purview of geodesy. Geodetic data are used to develop models of subsurface sources of gravity change and deformation that provide insights into the physical processes responsible for changes measured at the surface.

[2]In this report, we use GPS as a general and more familiar term for Global Navigation Satellite Systems (GNSS), even though GPS specifically refers to the Global Positioning System operated by the United States.

Overall Deformation in 2020

Subsidence of the floor of Yellowstone Caldera continued during 2020 at rates of 2–3 centimeters (about 1 inch) per year, and the rate of minor subsidence near Norris Geyser Basin continued to wane (fig. 4). Caldera subsidence was a continuation of the trend that, except for a brief period of uplift in 2014–2015, has persisted since 2010. A period of rapid uplift in the Norris Geyser Basin area that began in late 2015 or early 2016 stalled in late 2018 and was followed by a minor amount of subsidence, which continued to slow in 2020. Net change in elevation since early 2018 has been less than a few millimeters.

In 2020, there were five borehole tiltmeters and four borehole strainmeters operational within Yellowstone National Park. These exceptionally sensitive instruments are most useful for detecting short-term changes in deformation (for example, owing to earthquakes or sudden fluid movements). Because their signals can drift over periods of weeks to months and show trends that are not related to deformation, tilt and strain data are less useful for measuring long-term (months to years) deformation patterns. The tiltmeter and strainmeter networks did not detect any meaningful changes during 2020.

Continuous GPS Results

Throughout 2020, surface deformation measured by 15 continuous GPS stations in Yellowstone National Park mostly followed trends established during previous years. Stations inside Yellowstone Caldera subsided at rates of 2–3 centimeters (about 1 inch) per year, following patterns that have been ongoing since late 2015 or early 2016 (see fig. 4, especially stations OFW2, WLWY, and HVWY). The subsidence appears to have stalled and may have even reversed during the summer months (May–August), but subsidence resumed after that time. This seasonal variation is observed during most summers and is probably related to groundwater recharge or other environmental factors, not to the volcanic system. Regardless, the change was too small to affect the overall caldera deformation pattern observed since 2015.

At Norris Geyser Basin, 2020 was uneventful with no ground deformation above the detection threshold of a few millimeters (less than 0.25 inches). Uplift that began in late 2015 or early 2016 paused in late 2018 (see 2018 YVO annual report [YVO, 2021a]) and gave way to slow subsidence in September 2019. By the end of 2019, 2–3 centimeters (about 1 inch) of subsidence had accumulated, but that trend stopped in 2020.

Station coordinates and daily time series plots for Yellowstone continuous GPS stations are available at https://earthquake.usgs.gov/monitoring/gps/YellowstoneContin.

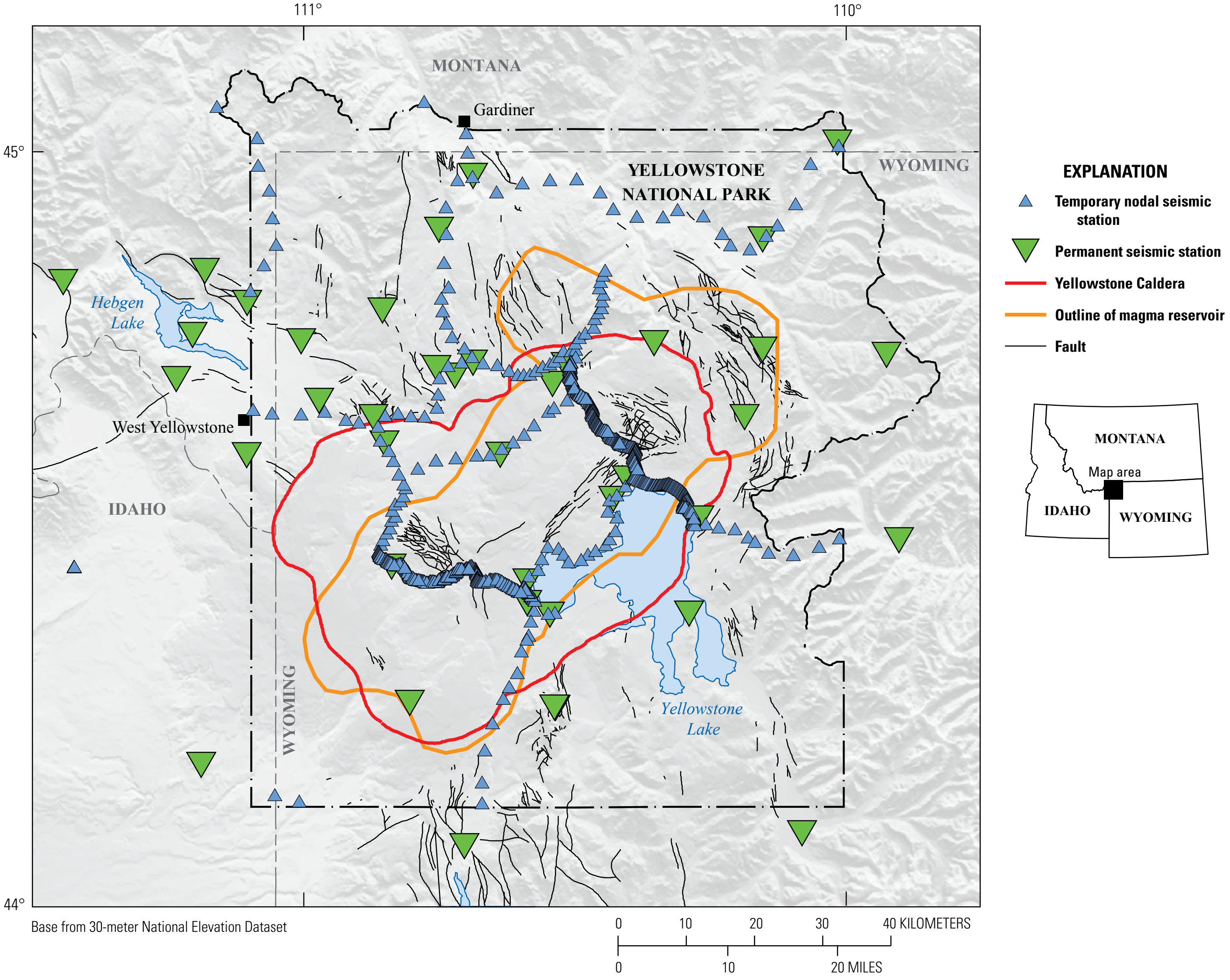
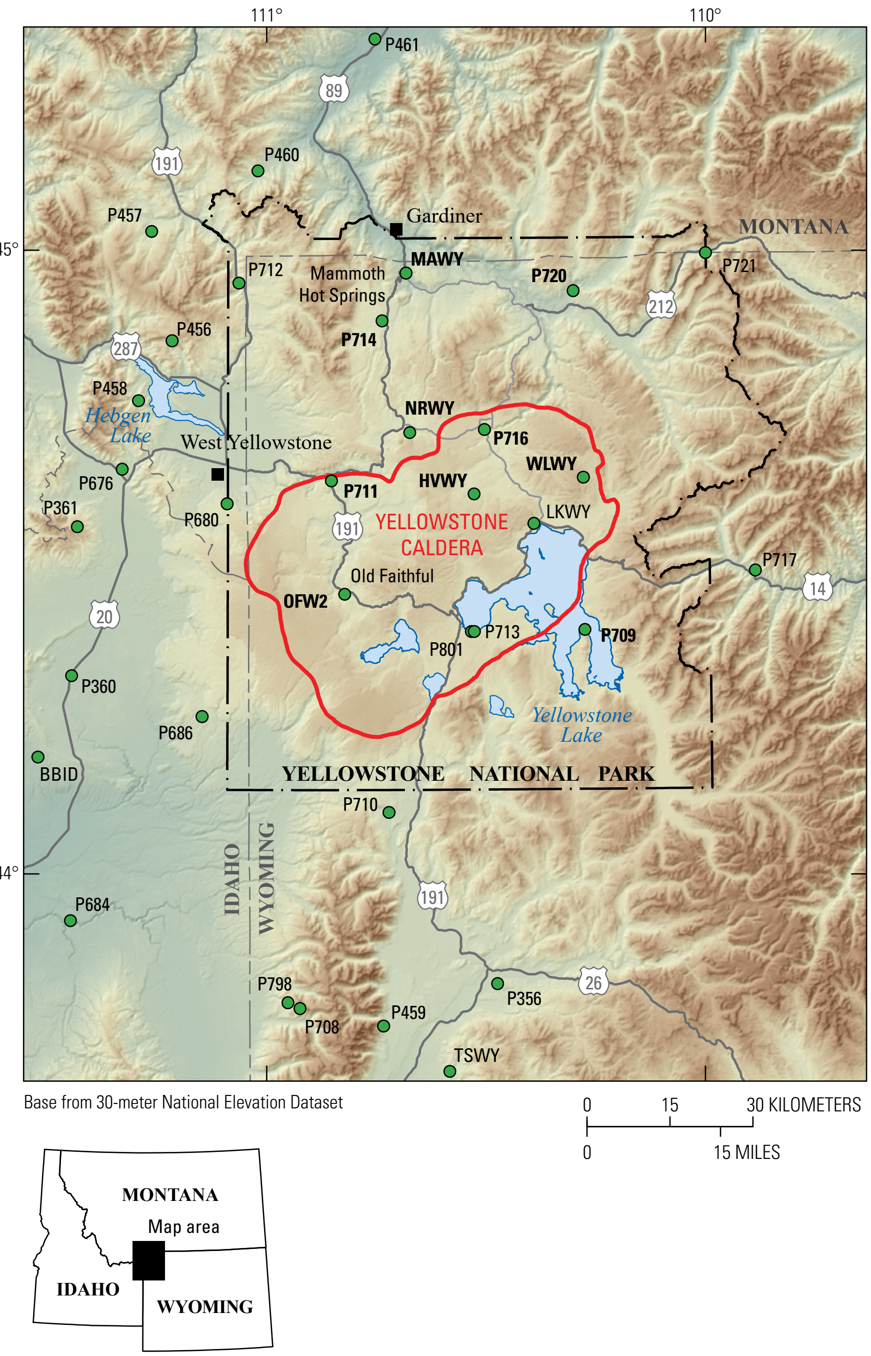


Figure 2. Map of permanent (inverted green triangles) and temporary (blue triangles) seismometers that recorded seismic signals during the August–September 2020 seismic experiment.

Figure 3. Vibroseis truck used to generate small amounts of low-frequency seismic energy that was recorded on temporary and permanent seismic stations (fig. 2) and that will be used to better understand the characteristics of the magma reservoir beneath Yellowstone Caldera. This seismic energy is not harmful to people or wildlife, and the work was done at night to minimize impacts on traffic. Photograph by Jamie Farrell, University of Utah, September 2020.



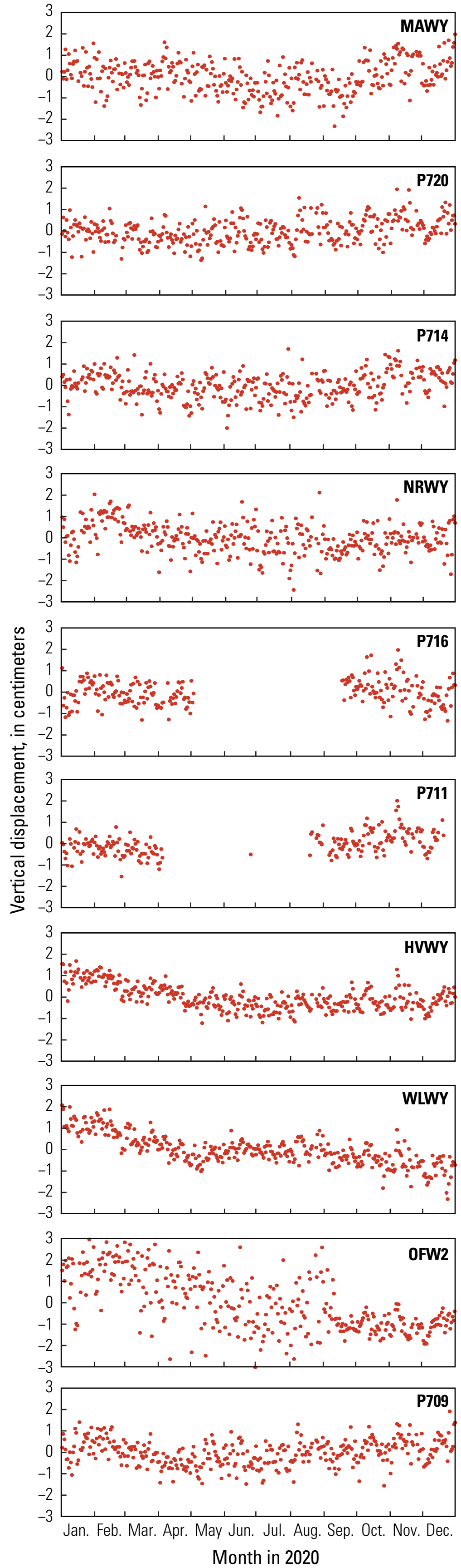


Figure 4. Map of Global Positioning System (GPS) stations showing the deformation observed in Yellowstone National Park in 2020. Vertical displacement (up or down movement of the ground) throughout the year is plotted for 10 selected GPS stations (green dots) located around the national park. The vertical axis of all plots is in centimeters (1 centimeter is equal to about 0.4 inches), and downward trends indicate subsidence and upward trends indicate uplift. General trends during 2020 are subsidence within Yellowstone Caldera (exemplified by stations WLWY, HVWY, and OFW2), and less than a few millimeters of vertical motion elsewhere, including at Norris Geyser Basin (station NRWY). Gaps during time series indicate periods when GPS stations were not operational.

Monitoring Geodetic Change in Yellowstone

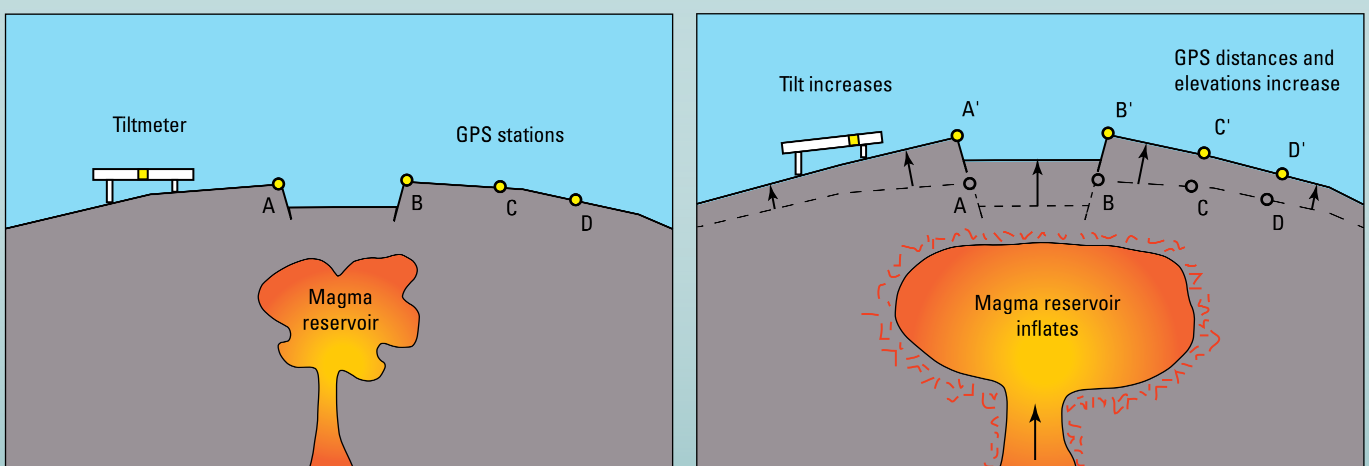
Subtle changes to the shape of a volcano's surface, called deformation, can be caused by the accumulation, withdrawal, or migration of magma, gas, or other fluids (typically water) beneath the ground, or by movements in Earth's crust owing to motion along faults. Typically, this deformation is very small in magnitude—a few centimeters (inches) or less—and so can only be detected and monitored using very sensitive instruments. Changes in the amount of material beneath the ground also result in variations in gravity at the surface. Combining measurements of gravity change with deformation can help scientists determine the type of fluid that is accumulating or withdrawing—for example, magma versus gas.

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 and what type of 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. Yellowstone Caldera presents a complicated situation because deformation may be caused by magma, water, or gas as well as non-volcanic processes such as fault or landslide motion.

A variety of techniques are used to monitor ground deformation in the Yellowstone region. UNAVCO 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 and so cannot track long-term ground deformation. This is where GPS, the backbone of the Yellowstone deformation monitoring network, comes into play. There are 15 continuously recording GPS stations within Yellowstone National Park and many more in the surrounding region. Data from these sites are used 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 deforms owing to local processes, such as subsurface fluid accumulation and withdrawal or 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/dai.

Semipermanent GPS sites are temporary stations that are deployed from late spring to early fall to densify the number of instruments measuring deformation in the Yellowstone area. Compared to continuous GPS, semipermanent GPS stations are less expensive and less intrusive on the landscape, and they are portable enough to be deployed in areas that might be off limits to a continuous GPS installation. Disadvantages of semipermanent GPS are that the data are intermittent whereas continuous GPS data are collected year round, and semipermanent GPS data are not telemetered—they are available only after the stations have been retrieved. Used together, however, the two approaches complement one another by providing precise ground deformation data from more than 30 sites in and around Yellowstone National Park.

Satellite measurements, called interferometric synthetic aperture radar (InSAR), can also be used to take a broad snapshot of deformation. Two

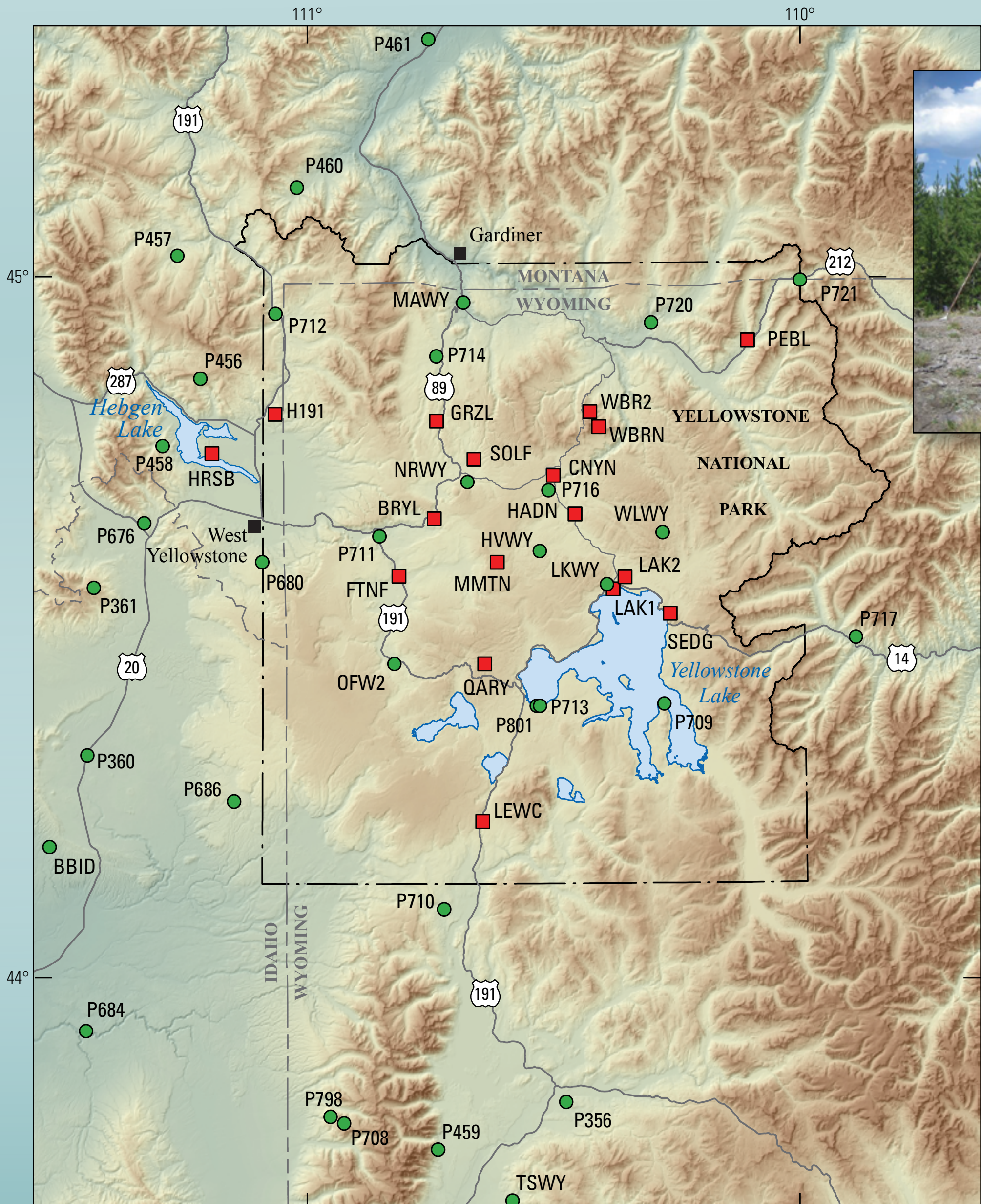


Schematic cartoon showing how the ground changes shape as magma accumulates beneath the surface. GPS, Global Positioning System.

Monitoring Geodetic Change in Yellowstone

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; using InSAR, it is possible to track ground deformation even in bad weather and at night. Although less precise than GPS, InSAR has the advantages of showing the entire pattern of surface deformation as a spatially continuous image, and the technique does not require access to, or installations in, the study area. Disadvantages are that current InSAR satellites have repeat times measured in days (whereas GPS data are continuous), InSAR only shows deformation in one direction (line-of-sight of the satellite) compared to the three-dimensional deformation given by GPS, and InSAR data are not usable during winter in the Yellowstone region because most of the surface is covered with snow.

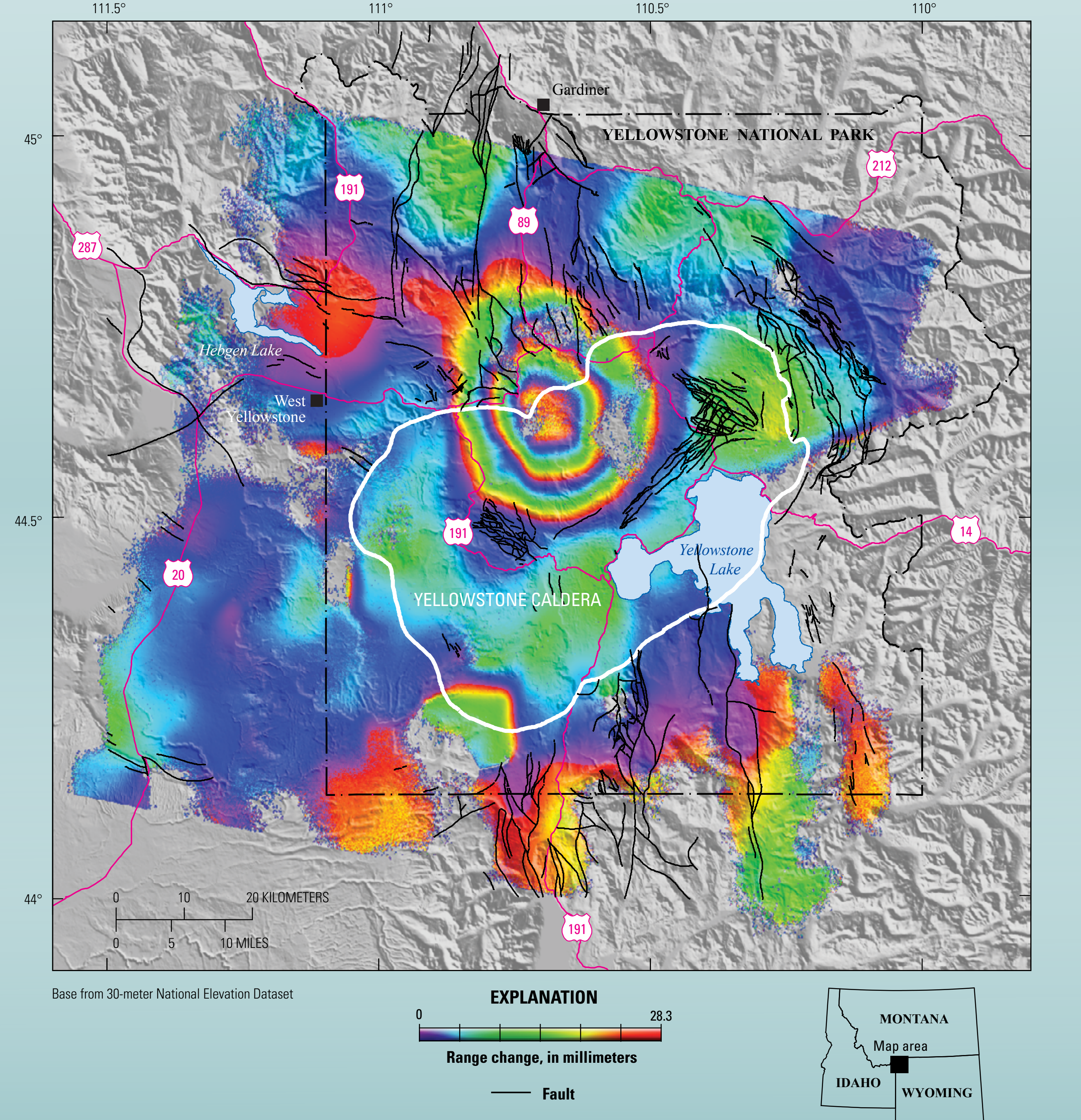
Measurements of changes in Earth's gravity field are another means to study processes that occur underground, hidden from sight. For example, gravity will increase slightly if more magma accumulates in a shallow reservoir, or if porous rock fills with groundwater. By combining



Base from 30-meter National Elevation Dataset

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

gravity measurements (which can record changes in subsurface mass) with deformation (which can indicate changes in subsurface volume), it is possible to calculate the density of the fluids that are driving the changes seen at the surface. High-density fluids are likely to be magma, whereas low-density fluids may be water or gas.



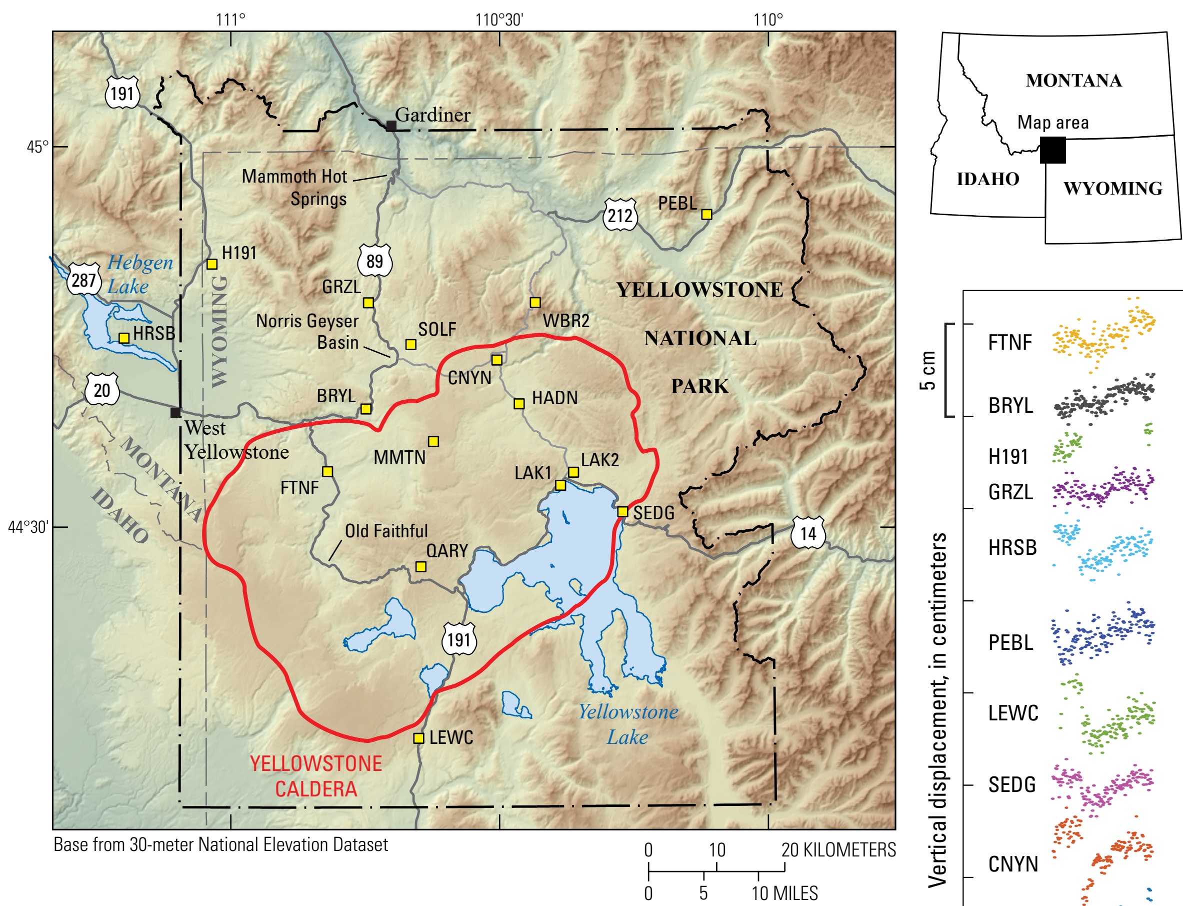
Map of past ground deformation in the Yellowstone region. This image was created using data from satellite passes in 1996 and 2000. The image shows 125 millimeters (about 5 inches) of uplift centered near the north rim of Yellowstone Caldera, about 10 kilometers (6.2 miles) south of Norris Junction.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

Semipermanent GPS Results

In 2020, the Yellowstone semipermanent GPS network comprised 16 stations in the park and one in the adjacent Hebgen Lake Ranger District of Gallatin National Forest (fig. 5). Fifteen of the 17 stations were deployed in late May; a station high on Mount Washburn and a new backcountry station on Mary Mountain were deployed in mid-July. The Mount Washburn and Mary Mountain stations were retrieved in late August to avoid the possibility of them being stranded by early snowfall. The other 15 stations were retrieved in early October. The temporary deployments are designed to complement the permanent GPS network and to take advantage of generally benign summertime conditions to collect data while avoiding harsh Rocky Mountain winters. For more information on the semipermanent GPS technique, see the sidebar on monitoring geodetic change (p. 11–13).

Both semipermanent GPS and continuous GPS stations record not only ground deformation caused by volcanic and tectonic processes, but also unrelated short-term signals. These include seasonal effects, like changes in lake and groundwater levels that cause variable loading of the surface, as well as noise that occurs when a GPS antenna is covered with snow or ice, which is especially common near the start or end of an annual deployment. Such signals are easier to identify on records from continuous GPS stations than from semipermanent GPS stations, which are deployed for only part of the year. For this reason, unless the deformation rate is unusually high, data from semipermanent GPS stations are best compared from year to year, ignoring trends during any one year.

In 2019–2020, most semipermanent GPS stations away from Yellowstone Caldera recorded only seasonal effects or weather-related noise, with little net change from 2019 to 2020. Only sites near the Sour Creek resurgent dome on the east side of Yellowstone Caldera, including HADN, LAK1, and LAK2, show resolvable deformation—namely subsidence



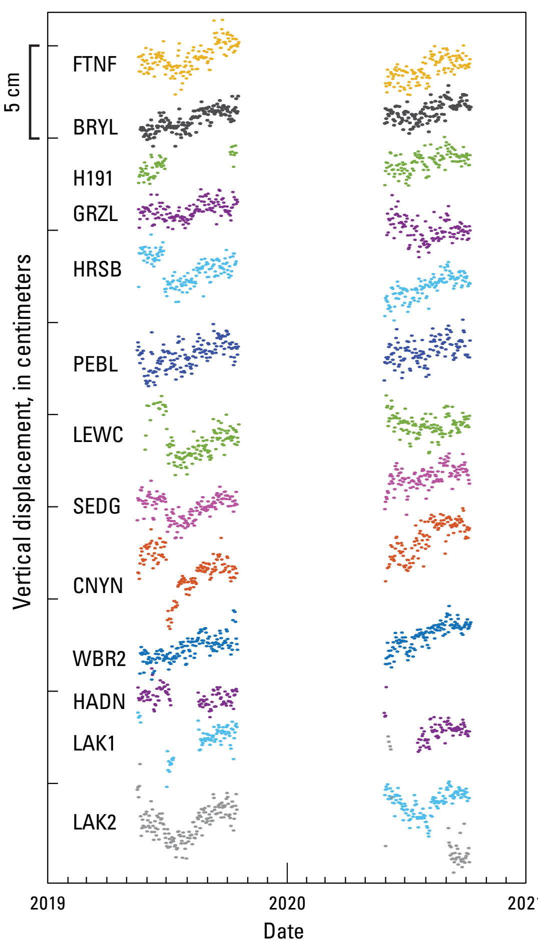


Figure 5. Map of semipermanent Global Positioning System (GPS) stations showing changes observed in Yellowstone National Park from 2019 to 2020. Vertical displacement (up or down movement of the ground) is plotted for 13 selected semipermanent GPS stations (yellow squares on map) located around or just outside the park. The distance between tick marks on the vertical axis is 5 centimeters (cm) (about 2 inches). Downward trends indicate subsidence and upward trends indicate uplift. See text for discussion of trends.

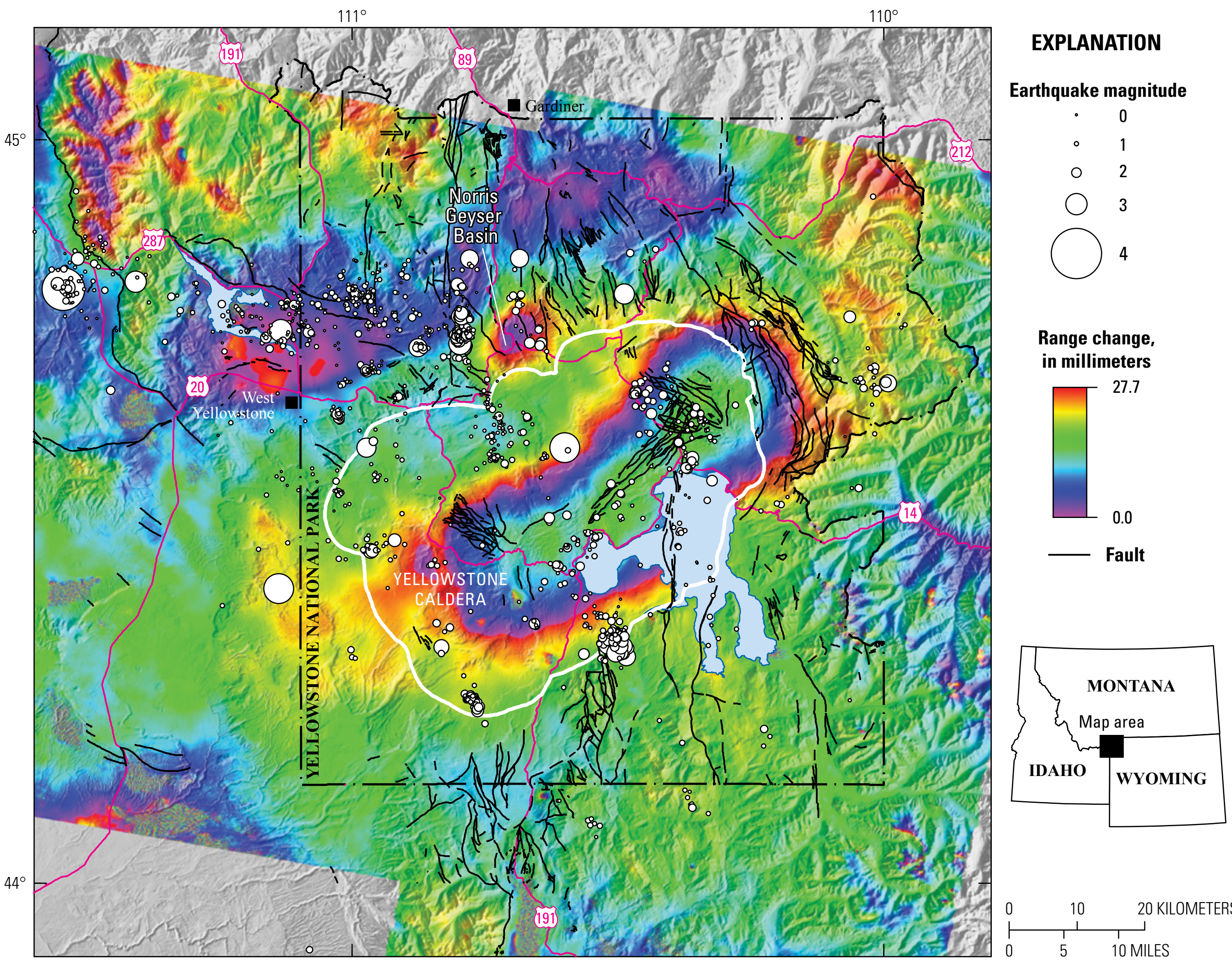
of 2–3 centimeters (about 1 inch). This motion is consistent with that measured by continuous GPS (site WLWY in fig. 4) and InSAR (fig. 6). Sites LAK1 and LAK2 are both close to the shore of Yellowstone Lake and, in addition to caldera subsidence, the two stations recorded seasonal effects caused by changes in surface loading by lake water—subsidence when lake level rises, uplift when it falls (see 2017 YVO annual report [YVO, 2019]). A small amount of subsidence is also indicated at semipermanent GPS site GRZL, probably related to the subtle subsidence of the Norris Geyser Basin area in 2019–2020 that is recorded by continuous GPS (site NRWY in fig. 4) and InSAR (fig. 6).

Station coordinates and daily time series plots for Yellowstone semipermanent GPS stations are available at https://earthquake.usgs.gov/monitoring/gps/Yellowstone_SPGPS.

InSAR

Satellite InSAR uses data from radar satellites to map ground deformation by comparing satellite-to-ground distances at different times. Resulting images are called interferograms, and they show how much the surface moved during the time between satellite observations. For more information about the InSAR technique, see the sidebar on monitoring geodetic change (p. 11–13).

A radar interferogram for the period from September 28, 2019, to October 4, 2020, revealed a deformation pattern consistent with that indicated by GPS observations—subsidence of the caldera by a maximum of about 3 centimeters (slightly more than 1 inch) and a small amount of subsidence—about 1.5 centimeters (less than 1 inch)—in the area around Norris Geyser Basin (fig. 6).



Base from 30-meter National Elevation Dataset

Figure 6. Interferogram created from data collected on September 28, 2019, and October 4, 2020, by the Sentinel-1 satellite system. Colored fringes indicate a change in distance (called range change) between the satellite and ground surface that is caused by surface deformation. In this interferogram, the fringes indicate subsidence (an increase in the range between the ground and the satellite) of as much as 3 centimeters (slightly more than 1 inch) in the central part of Yellowstone Caldera, and less subsidence of a small area near Norris Geyser Basin during the period spanned by the images. By the end of the year, Global Positioning System (GPS) data show the Norris Geyser Basin subsidence had essentially stopped. Fringes that correlate with topography in the northwest corner of the image are caused by atmospheric artifacts. White circles show earthquakes that occurred during the time spanned by the interferogram. Circle size scales with magnitude, with the largest about magnitude 3.5.

Yellowstone Lake Level Measurements

Prior to 2017, the water level in Yellowstone Lake was determined by occasional measurements at Bridge Bay marina or inferred from a streamgage on the Yellowstone River at the lake outlet near Fishing Bridge. A pressure-depth gage was installed in 2017 at the Grant Village dock (see 2017 YVO annual report), enabling lake-level measurements to be made at 1-minute intervals. Despite a station outage in early 2020, lake-level measurements during the year showed normal spring to summer lake-level increase owing to snowmelt influx, and then summer to fall decrease owing to outflow (fig. 7). The maximum variation in lake level over the course of the year was about 1.45 meters (4.75 feet).

As observed during previous time periods, a seiche was measured more or less continuously over the year (fig. 7 inset). Seiches are standing waves that cause short-term variations in the surface level of Yellowstone Lake, thus far observed to range from a few to 15 centimeters (peak-to-peak) (about 1–6 inches) during storms or atmospheric events, possibly driven by wind or other environmental variations. They are too subtle and slow to be noticed by the human eye, but they do change the distribution of water in the lake over time. Deformation patterns recorded by borehole strainmeters located throughout Yellowstone National Park reveal the presence of these seiches and have been used to provide insights into the structure of the subsurface—for example, the depth and viscosity of the magma reservoir beneath Yellowstone Caldera.

Geochemistry

Geochemical studies of Yellowstone's diverse and dynamic thermal features are aimed at better understanding the interface between its hydrothermal and magmatic systems, with the ultimate goal of investigating processes that are hidden from direct observation (see sidebar on geochemical monitoring on p. 17). Thermal features provide a window into Yellowstone's subsurface characteristics, and geochemistry is a powerful tool for illuminating those depths, as well as detecting gases possibly emanating from subsurface magma.

Summary of Geochemistry Activities in 2020

In 2020, YVO scientists continued with gas and heat emission measurements and also collected water samples in various areas for laboratory analysis. An eddy covariance system, installed in 2018 near Norris Geyser Basin, made continuous measurements of carbon dioxide (CO_2) and heat fluxes until an equipment failure in October 2020, but over the 2+ years of its deployment, the system measured remarkably consistent gas and heat emission rates that can be used as baseline data for analyzing future changes. Water samples were collected from Washburn Hot Springs, Hillside Springs, and Norris Geyser Basin to better understand the geological, geochemical, and biological processes that influence water chemistry. Finally, a multi-year study of the geochemistry of

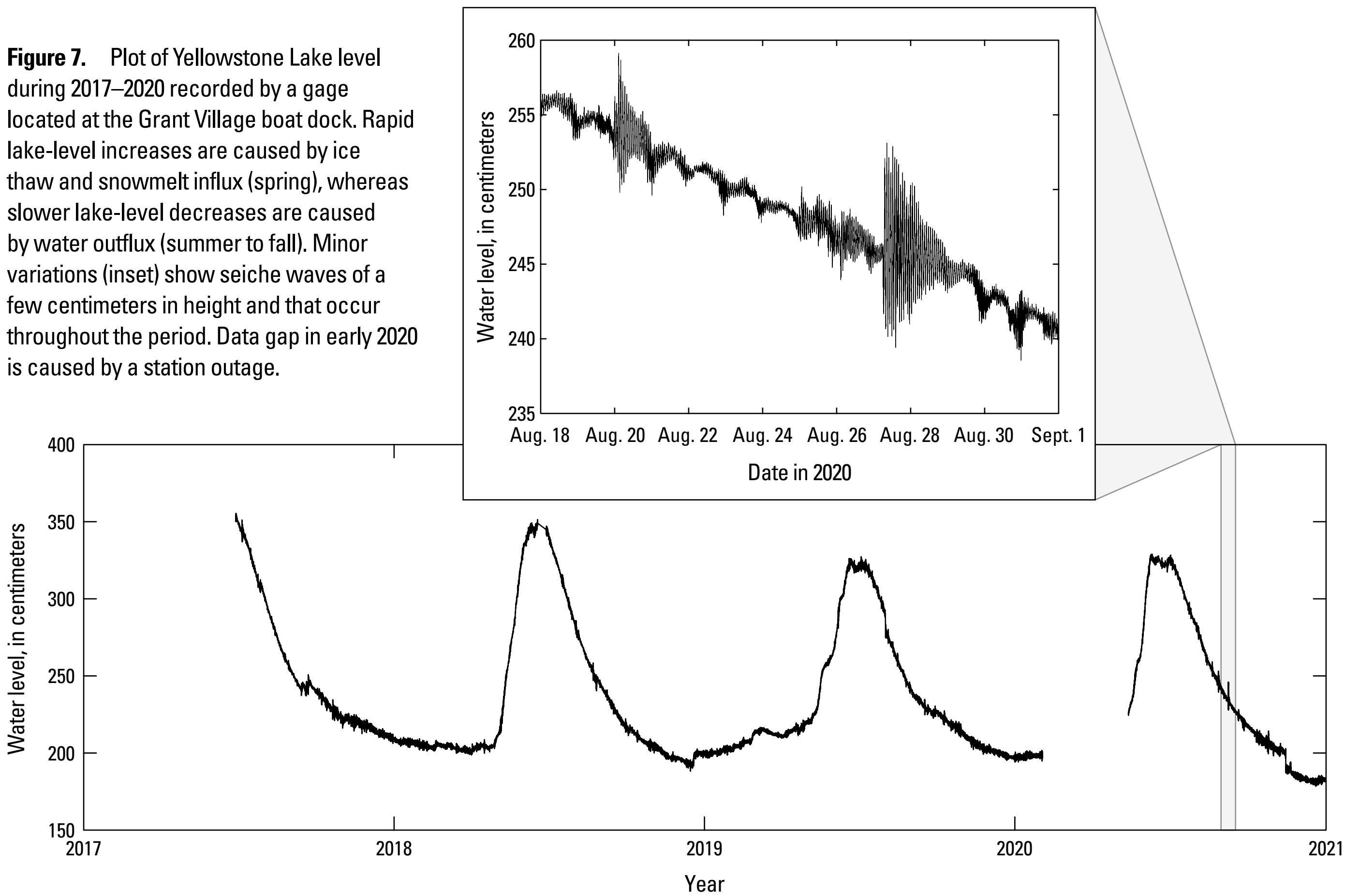


Figure 7. Plot of Yellowstone Lake level during 2017–2020 recorded by a gage located at the Grant Village boat dock. Rapid lake-level increases are caused by ice thaw and snowmelt influx (spring), whereas slower lake-level decreases are caused by water outflux (summer to fall). Minor variations (inset) show seiche waves of a few centimeters in height and that occur throughout the period. Data gap in early 2020 is caused by a station outage.

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 more than 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 are also possible. 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.

hydrothermal activity in the little-visited southwest portion of Yellowstone National Park was concluded, providing insight into the character of thermal contributions to rivers that drain the region.

Gas Emissions

In 2020, the multi-year study of temporal variations in gas and heat emissions continued in the area locally known as Bison Flat within Norris Geyser Basin. The project commenced in July 2018 (see 2018 YVO annual report) after an exploratory summer-only investigation in 2016 (Lewicki and others, 2017) and involved the use of an eddy covariance system—a micrometeorological technique that measures CO_2 on a half-hourly basis. The system also measures sensible heat flux (owing to changes in temperature with no change in phase) and latent heat flux (owing to changes in temperature associated with changes in phase [for example, evaporation]) emitted from ground areas upwind of the sensors.

Eddy covariance CO_2 flux measurements are plotted versus wind direction in figure 8*A* and were relatively high when wind was from the southwest, such that the sensor was directly downwind of several steam vents. Wheras eddy covariance CO_2 fluxes were highly variable on a half-hourly basis, the smoothed data, constructed using a 90-day window (chosen to reduce seasonal variations), was stable at around 175 grams per square meter per day (fig. 8*B*), similar to levels reported in 2018 and 2019 (see 2018 and 2019 YVO annual reports [YVO, 2021a,b]). The seasonally smoothed data were stable over the entire 2018–2020 timeframe (fig. 9*A*) and are also consistent with the mean eddy covariance CO_2 flux recorded at the site in 2016 (179 grams per square meter per day; Lewicki and others, 2017). Time series of half-hourly eddy covariance sensible, latent, and sensible plus latent heat flux measurements are shown in figure 10. Since the goal is to quantify the hydrothermal component of these heat fluxes, only fluxes measured during the nighttime (when solar effects are minimized) are used (red dots on fig. 10). The average values of nighttime sensible, latent, and sensible plus latent heat flux during 2020 were 85, 153 and 238 watts per square meter, respectively, similar to values from 2018 and 2019 (fig. 9*B*; see 2018 and 2019 YVO annual reports). This result demonstrates that latent heat flux was the dominant of the two components measured. Overall, the 2018–2020 record of eddy covariance CO_2 and heat flux will provide a baseline against which future changes can be assessed in the context of hydrothermal activity in Norris Geyser Basin, as well as caldera unrest.

Unfortunately, several eddy covariance equipment failures occurred in 2020, leading to large gaps in data collection. Although repairs were made during the summer, the station could not be revived after the failure of a critical component in October. All equipment will be recovered and refurbished in 2021 with the goal of redeploying the equipment in 2022. It also proved impossible to carry out a soil CO_2 flux grid survey and fumarole gas sampling at the study site in 2020, as had been done in 2018 and 2019, because of COVID-19 travel restrictions.

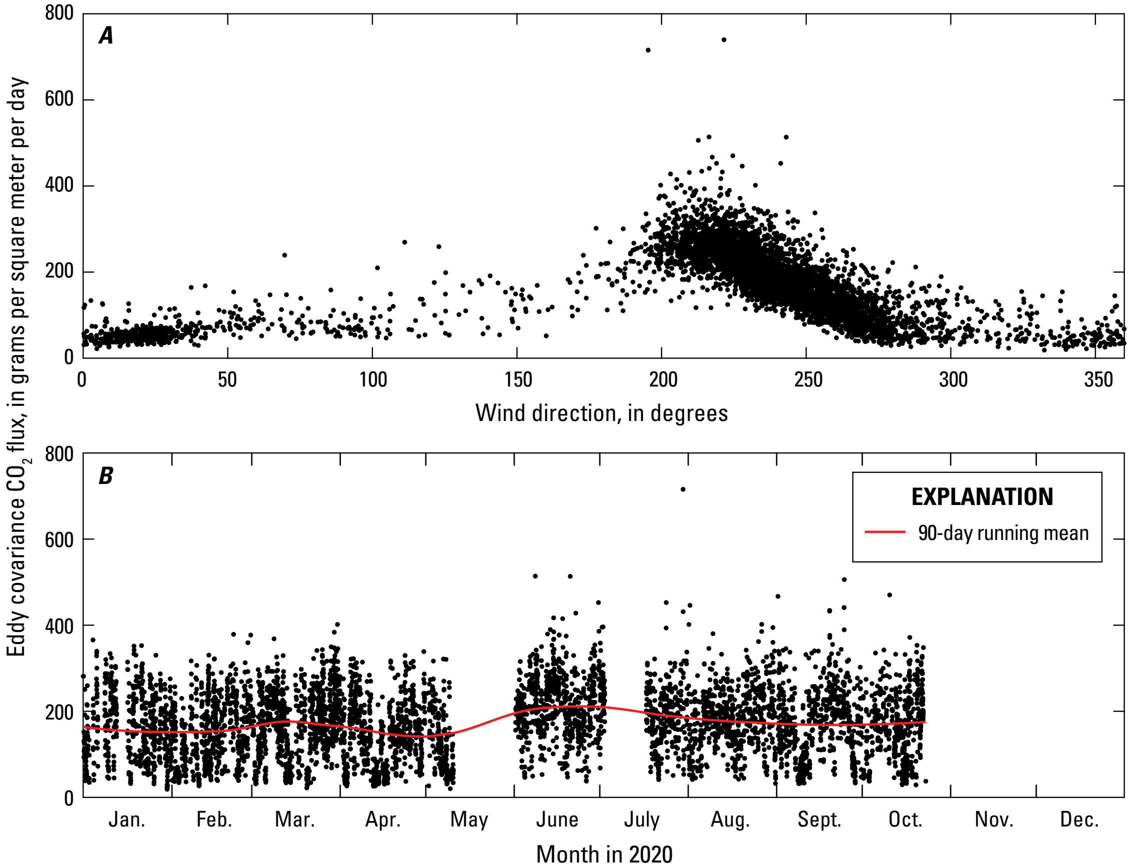


Figure 8. Plots of eddy covariance CO_2 flux versus wind direction (*A*) and time (*B*). CO_2 flux measurements are higher when the wind is from the southwest because gas vents are upwind of the station. Gaps in the timeseries data are when the station was not operating. Red line is data averaged using a 90-day (seasonal) window. The smoothed data show minor variations, and this baseline can be used to assess potential future changes.

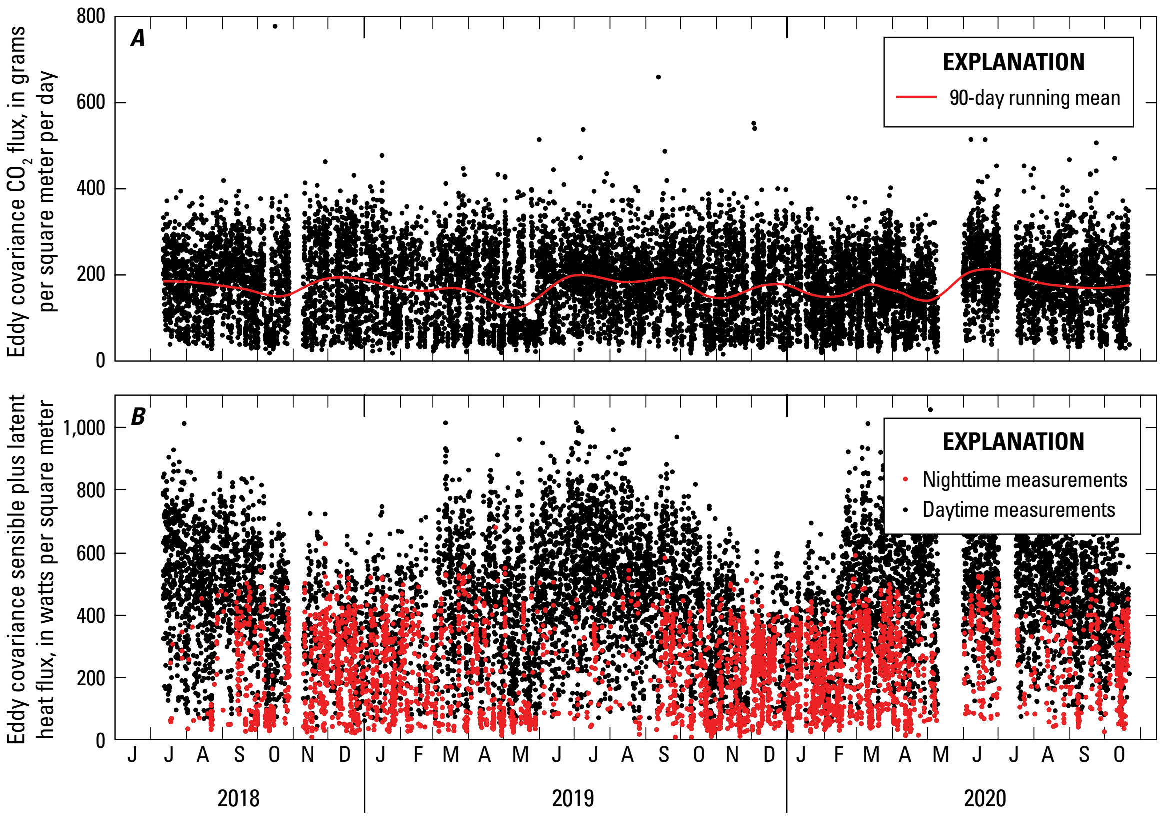


Figure 9. Time-series plots of eddy covariance CO_2 flux (*A*) and sensible plus latent heat flux (*B*) during 2018–2020. Red line in *A* is data smoothed using a 90-day (seasonal) window and indicates stable flux over the past 3 years. Red and black dots in *B* indicate nighttime and daytime measurements, respectively. Nighttime measurements were used to minimize the effects of solar heating.

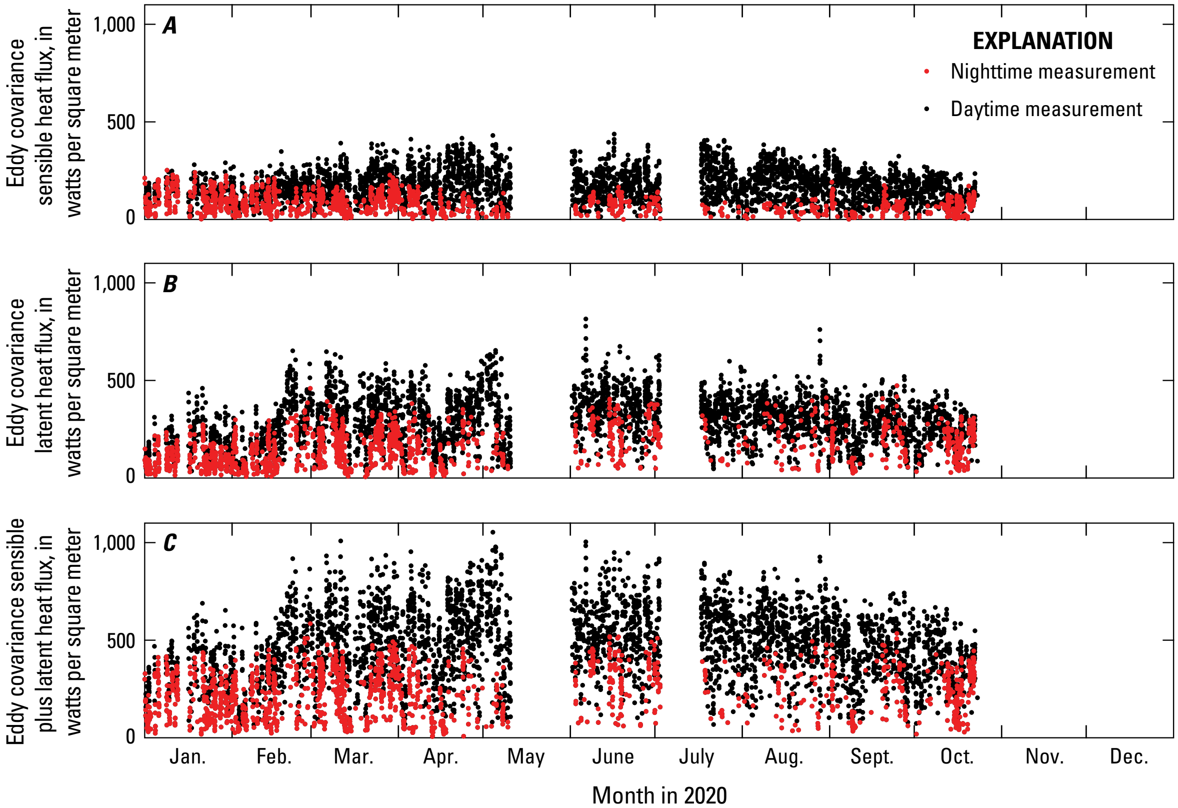


Figure 10. Time-series plots of eddy covariance sensible (*A*), latent (*B*), and sensible plus latent (*C*) heat fluxes. Red and black dots indicate nighttime and daytime measurements, respectively. Data indicate that latent heat flux was greater than sensible heat flux in this area.

Water Sampling

In the summer of 2020, scientists from the USGS and Yellowstone National Park sampled thermal waters at Hillside Springs, Washburn Hot Springs, and Norris Geyser Basin. The purpose of collecting water samples from each thermal area varied.

At Hillside Springs, the seasonal effects on thermal water chemistry are being investigated. As the name implies, the Hillside Springs thermal area (fig. 11*A*) is located on the side of a hill to the west of the Firehole River near Biscuit Basin (about 3.5 kilometers [2.2 miles] northwest of Old Faithful Geyser), and the spring water is thought to be a mixture of deep thermal water and shallow groundwater—a perfect site to investigate the seasonal effects of snowmelt on the shallow hydrothermal system.

At Washburn Hot Springs, the speciation and transformation of mercury and arsenic are the focus of sample collection. Waters from Washburn Hot Springs (fig. 11*B*) are different from most other thermal waters in Yellowstone, in that they contain very high concentrations of ammonium (NH_4^+) as a result of flowing through marine sedimentary rock. Little is known about the impacts and controls of NH_4^+ on the distribution of arsenic and mercury (both toxic in high concentrations) in Yellowstone.

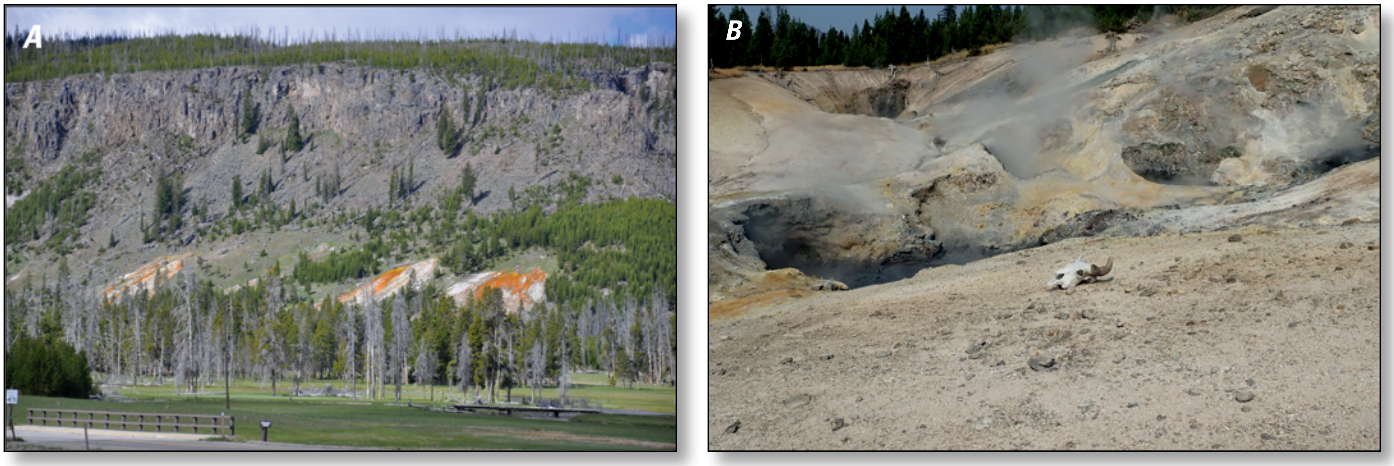


Figure 11. *A*, Hillside Springs as seen looking to the west from Artemisia Trail. Photograph by James St. John, Ohio State University at Newark, on June 3, 2013. *B*, Washburn Hot Springs as seen from Mount Washburn Spur Trail. U.S. Geological Survey photograph by Blaine McCleskey on September 6, 2020.

Norris Geyser Basin is one of the most dynamic and hottest areas in Yellowstone. The water chemistry of several features is monitored to document changes and to understand or infer how chemical variations in hydrothermal systems relate to a range of processes, such as deformation, geyser activity, heat output, and seismicity. At each sample site, a variety of field measurements were collected (including pH, specific conductance, and temperature), and water samples were taken for the determination of major cations, anions, trace metals, redox species (iron, arsenic, mercury), water isotopes, and tritium. Water samples collected in the summer of 2020 will be analyzed during the winter of 2020–2021, and data and interpretive reports are planned for 2021.

Hydrothermal Activity in Southwest Yellowstone National Park

In the past two decades, USGS and Yellowstone National Park scientists have studied hydrothermal activity across the Yellowstone Plateau volcanic field to improve understanding of the magmatic-hydrothermal system and to provide a baseline for detecting future anomalous activity. One of the last areas of the region to be systematically examined, because of its remoteness, was the southwestern part of Yellowstone National Park. Campaigns to collect water and gas samples were carried out over this large area in 2017 and 2018 (see 2017 and 2018 YVO annual reports), and data analyses have now been completed.

The chemical and isotopic composition of water and gas samples and Landsat 8 thermal-infrared satellite data suggest that most thermal activity in southwest Yellowstone is near the Yellowstone Caldera boundary. Springs and fumaroles (fig. 12) discharge from a variety of rock types, including some of the youngest rhyolite lava flows in the Yellowstone Plateau volcanic field. Gas compositions and helium isotope ratios of most samples resemble those in other parts of the volcanic field, and waters have meteoric (snow and rain) origins. Thermal waters from some areas have compositions that indicate mixing between thermal and nonthermal water compositions. The thermal water composition indicates temperatures of 160–170 degrees Celsius (°C) (320–340 degrees Fahrenheit [°F]), which is cooler than waters in Yellowstone's geyser basins. Heat discharged by springs and fumaroles originates from within the Yellowstone Caldera and is transported laterally by advection, mainly along the base of rhyolite lava flows that cover the inferred caldera boundaries (Hurwitz and others, 2020).

The Fall River drains southwest Yellowstone, but how much of the runoff from the region is influenced by geyser basins and thermal areas? Because the area receives considerable precipitation, river waters carry dissolved solids and solutes not only from thermal sources, but also from groundwater flowing through the rhyolite lava and ash-flow units that make up the regional geology. Specific conductance and discharge measurements indicate that every year the Fall River carries 11 percent of the chloride, 5 percent of the arsenic, 25 percent of the fluoride, and 19 percent of the silica that exits the Yellowstone Plateau volcanic field (McCleskey and others, 2020).

Approximately 11 percent of the Fall River chloride is from nonthermal waters, and a large proportion of fluoride and silica in the Fall River is derived from water-rock interaction in the shallow nonthermal groundwater system. Consequently, 73±3 percent of the annual total dissolved solid flux in the Fall River is from thermal sources. From synoptic sampling of river water and discharge measurements during low-flow conditions, it was determined that chloride, sodium, arsenic, rubidium, lithium, and boron are primarily (>89 percent) associated with thermal waters. The Bechler River is the primary source of most hydrothermal solutes in the Fall River, but the major source of arsenic is Boundary Creek (McCleskey and others, 2020).

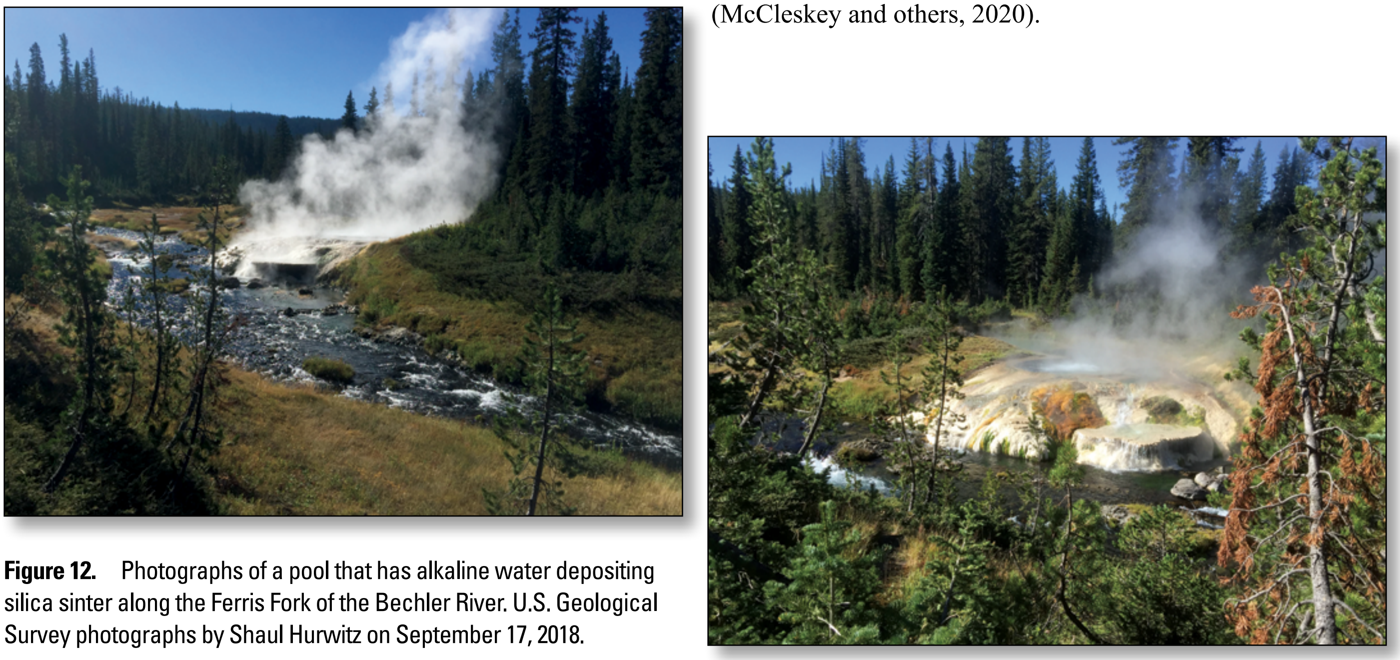


Figure 12. Photographs of a pool that has alkaline water depositing silica sinter along the Ferris Fork of the Bechler River. U.S. Geological Survey photographs by Shaul Hurwitz on September 17, 2018.

Geology

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

Summary of Geology Activities in 2020

Despite the pandemic, progress was made on a number of independent yet related laboratory- and field-based geologic studies. Laboratory work focused on age-dating rhyolite and basalt lava flows in Yellowstone National Park to better constrain the timing of post-caldera eruptions. Office work included updating geological maps of Yellowstone—both digitizing old printed maps and reconciling boundary problems on adjoining geological maps that were produced at different times and scales and by different geologists. Field work included investigating some of the boundary-problem issues, as well as investigating the characteristics of hydrothermal explosion craters in the Lower Geyser Basin.

Age Dating of Yellowstone Volcanism

During 2020, work on constraining the timing and composition of volcanism within the Yellowstone Plateau volcanic field continued. The goals of this work are to better constrain the timing and periodicity of (1) the most recent episode of rhyolite volcanism within the volcanic field that occurred from ~170,000 to 70,000 years before present, producing the Central Plateau Member rhyolites (fig. 13), and (2) basaltic volcanism throughout the volcanic field. To achieve this goal, YVO geologists applied modern, high-precision $^{40}Ar/^{39}Ar$ dating methods to the Central Plateau Member rhyolites and Yellowstone basalts to constrain their

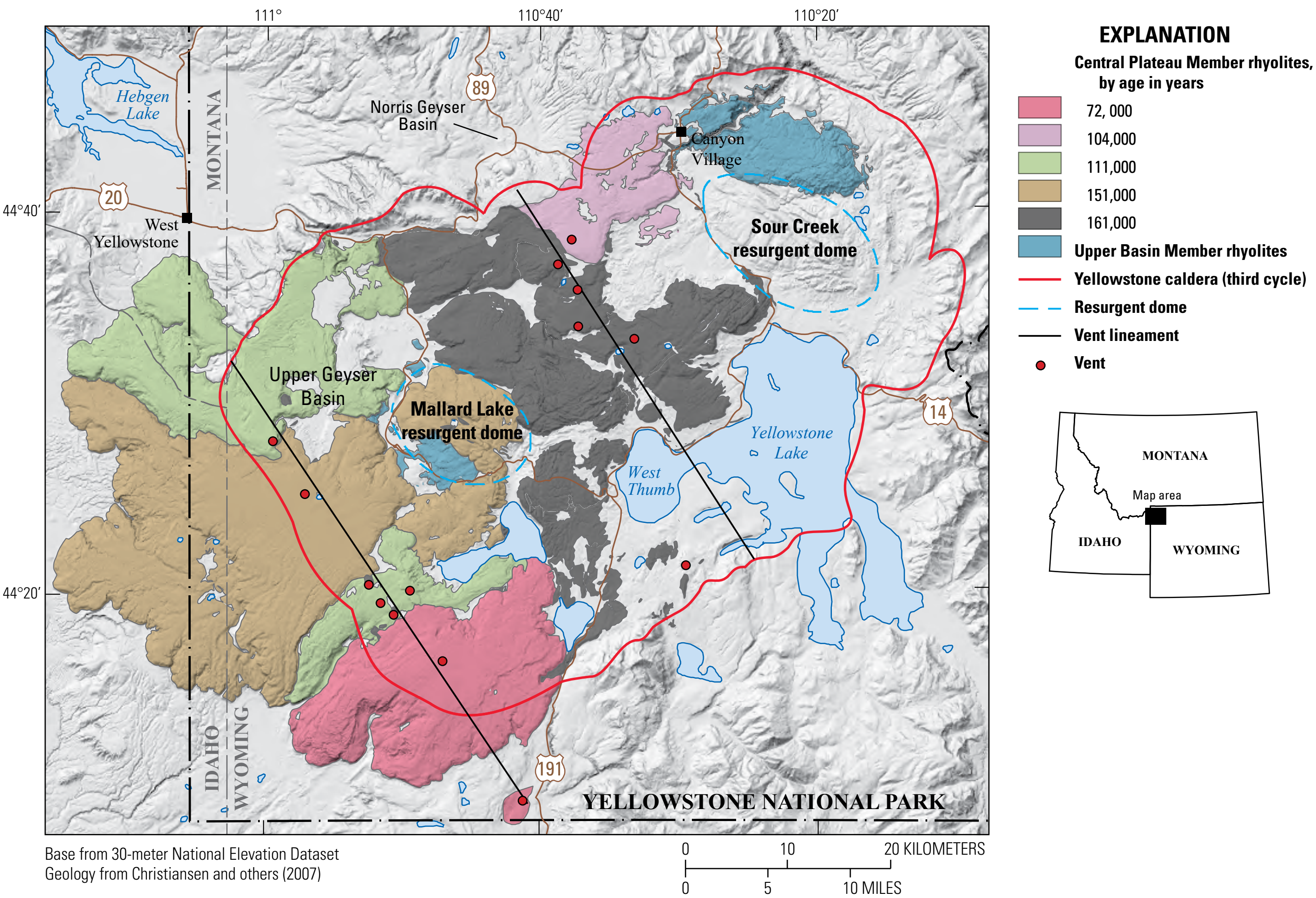
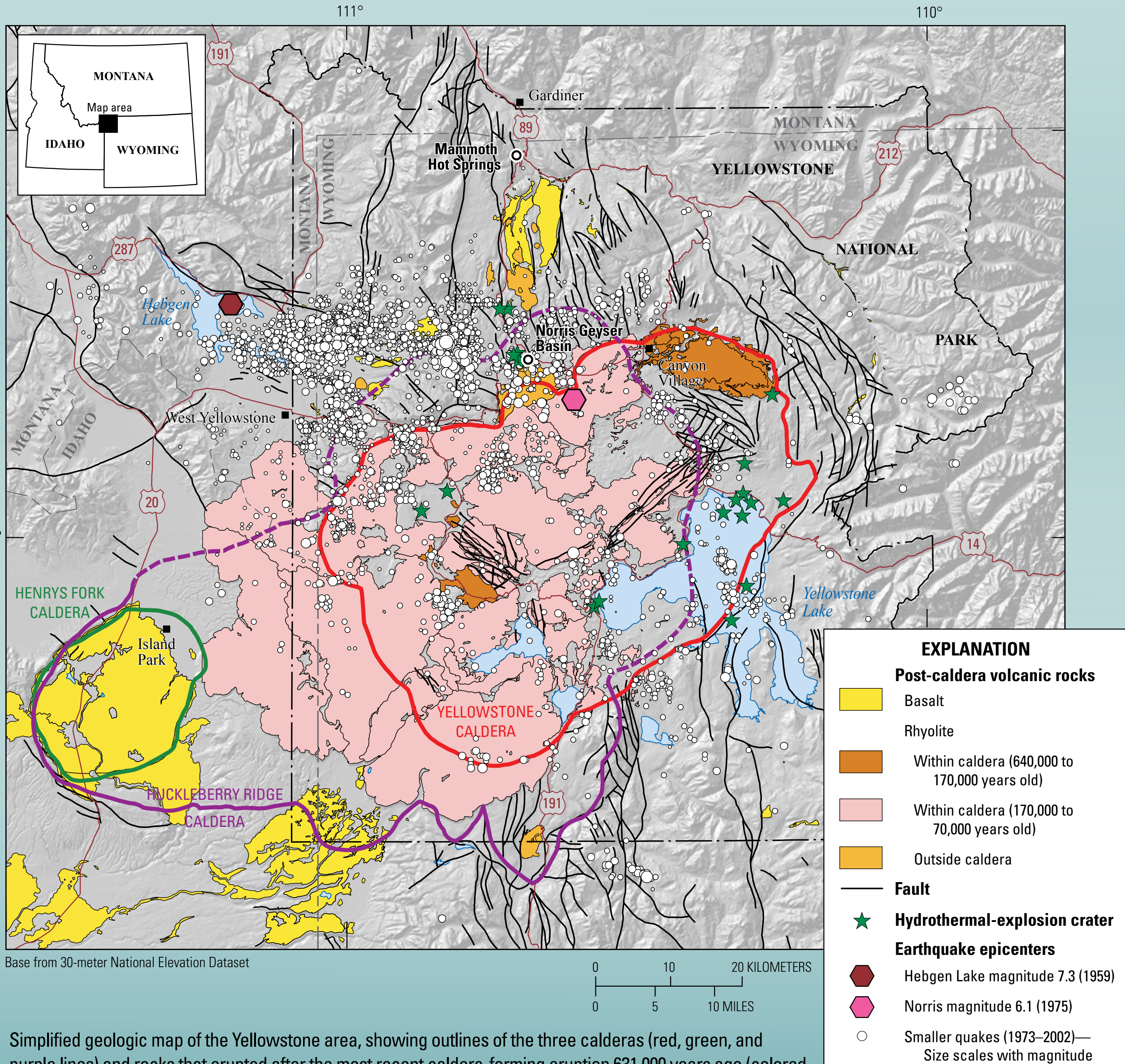


Figure 13. Shaded-relief map of Yellowstone Caldera showing the age and location of intra-caldera rhyolites that erupted after the Lava Creek Tuff. The Upper Basin Member rhyolites (blue) are the first episode of post-Lava Creek Tuff volcanism, occurring from approximately 630,000 to 255,000 years before present. The Central Plateau Member rhyolites erupted in a second episode and are shown by eruption age estimated via recent high-precision $^{40}Ar/^{39}Ar$ dating methods. The black solid lines represent structurally controlled vent zones from which the Central Plateau Member rhyolites erupted (individual vent locations shown as red dots).

Geology of the Yellowstone Plateau

The Yellowstone Plateau volcanic field developed through three volcanic cycles that span 2 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) wide 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

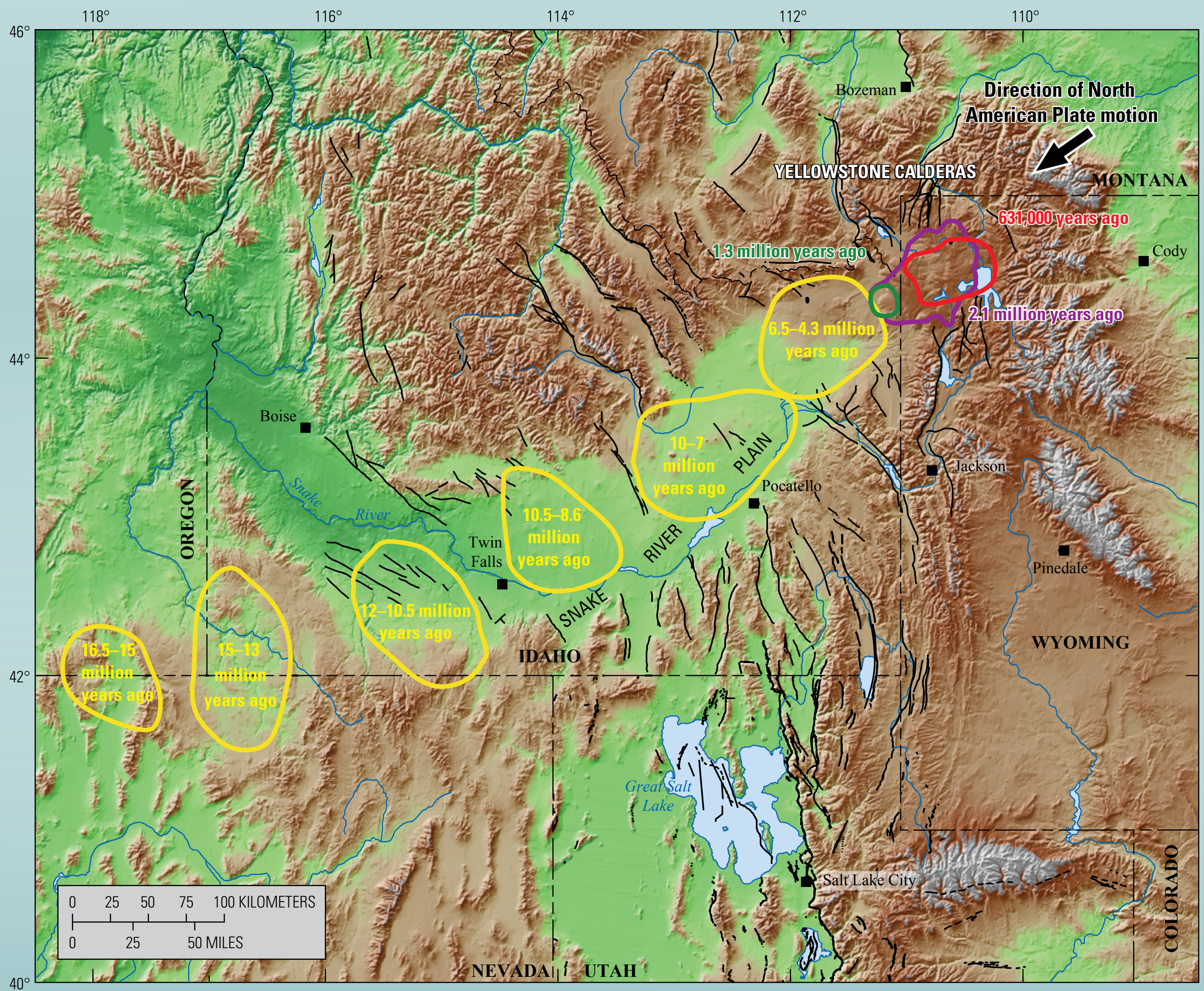


Simplified geologic map of the Yellowstone area, showing outlines of the three calderas (red, green, and purple lines) and rocks that erupted after the most recent caldera-forming eruption 631,000 years ago (colored areas). Modified from U.S. Geological Survey Fact Sheet 2005–3024 (Lowenstern and others,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

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

Before and after these caldera-forming events, eruptions in the Yellowstone area produced rhyolitic and basaltic rocks—including 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 170,000 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, from 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 the alignment of past calderas that have since been filled in by lava flows and sediments. Black lines show faults within the region. Modified from Smith and Siegel (2000) with permission.

eruption ages. Although the USGS Menlo Park argon laboratory was closed for much of the year owing to technical issues and COVID-19 restrictions, progress was made on dating the Central Plateau Member rhyolites. In total, six rhyolite samples were dated via single-crystal incremental heating of the mineral sanidine, where 15 to 20 sanidine grains were analyzed per sample.

These new data, along with data collected in 2018 and 2019, suggest that the Central Plateau Member rhyolites erupted in five pulses, at approximately 161,000, 151,000, 111,000, 104,000, and 72,000 years before present. During each of these eruptive pulses, as many as seven rhyolites may have erupted over a span of about 1,000 years or less. In 2021, YVO geologists plan to collaborate with scientists at University of California, Davis, to conduct lead isotope analyses of rhyolite glass from each of the seven rhyolite lava flows erupted during the 161,000-year-old pulse. These data will test whether the seven rhyolites that erupted during this time frame were derived from a common, interconnected magma body or from discrete, chemically distinct magma bodies.

No Yellowstone basalts were dated in 2020, but 16 basalt samples were prepared for $^{40}Ar/^{39}Ar$ dating that will take place 2021. In addition, basalt samples for future age determination have been retrieved from the USGS sample warehouse. Work will continue in 2021 to complete dating the Central Plateau Member rhyolites and Yellowstone basalts.

Updating the Geological Map of Yellowstone

In the 1960s and 1970s, a group of USGS mappers set out to determine what rocks form the Yellowstone Plateau volcanic field. Identifying the rocks that make up a region is not only useful from a resource management standpoint but also for reconstructing the geologic history of the park. Yellowstone National Park is very large (about the same size as Puerto Rico), making it impossible to cover the entire area completely. To make mapping more efficient, the park was split into 34 separate smaller sections (called quadrangles), which were then stitched together to make a complete map that was published in 1972.

The challenge, however, was that having multiple mappers working in different areas of the park commonly resulted in variable interpretations, names, and levels of detail, leading to areas where rock units are mismatched across map boundaries (fig. 14). This is not necessarily a problem at the reconnaissance scale, where details are less critical and mappers could agree on the characteristics of major map units, but it did present challenges in areas where more detail is present.

Starting in 2020, a team of geologists from Montana State University set out to address some of these challenges and increase the accuracy of the geologic map at a larger scale. Some of the problems they identified were readily fixed without having to visit the field, but the team also had to visit many areas where, for example, mapped contacts were offset by hundreds of meters across a boundary—perhaps not surprising, since there was no GPS in the 1970s to aid with the precise positioning of contacts on a map, nor geographic information systems that today are indispensable when generating maps. Many of the problematic boundaries are located in hard-to-access areas deep in the backcountry, requiring long hikes and overnight stays to reach sites and study issues.

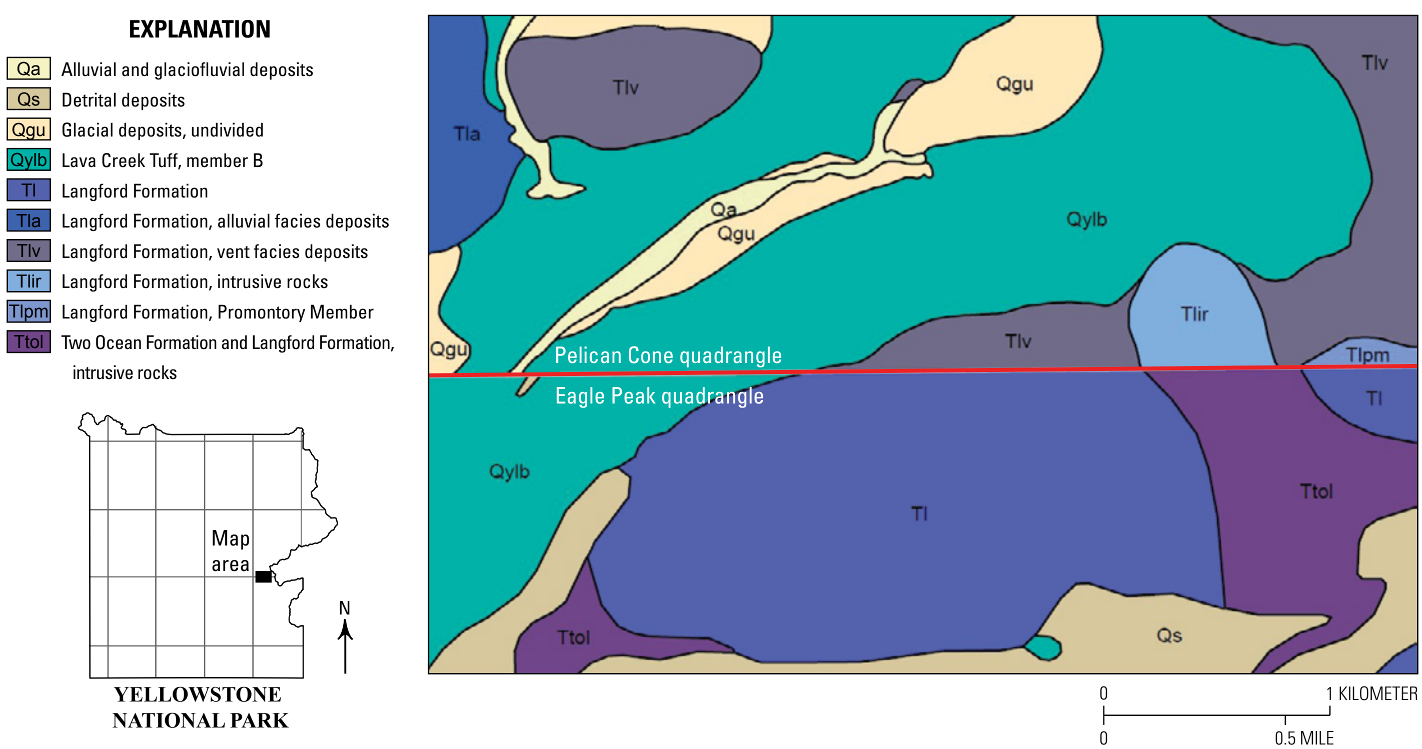


Figure 14. Map showing an example of a boundary problem between two geologic maps of Yellowstone National Park. Map area covers 12.6 square kilometers (4.8 square miles) and straddles the Pelican Cone and Eagle Peak 15-minute quadrangles (quadrangle boundary marked by red line). Grid on inset map of Yellowstone National Park shows 15-minute quadrangle boundaries.

During a 9-week period in the summer of 2020, Montana State University teams spent 30 days in the field examining boundary problems and collecting samples for geochemical analysis (fig. 15). The work also provided an opportunity to train undergraduate students in the practice of geologic mapping. Additional work and planning will occur during winter 2020–2021, and the team will visit the remaining areas that have boundary issues during summer 2021. The goal of the work is to produce an updated geological map of the Yellowstone Plateau volcanic field at 1:100,000 scale in time for the 150-year anniversary of Yellowstone National Park in 2022.

Figure 15. Montana State University undergraduate geology student Emma Kerins takes field notes while observing sedimentary rocks on Mount Everts in Yellowstone National Park. Photograph by Logan Bouley of Montana State University on July 16, 2020, used with permission.

Investigating Past Hydrothermal Explosions

Most visitors to Yellowstone National Park know of the rare caldera-forming eruptions that have blanketed the region in meters of ash three times in the past 2.1 million years. Less well known, however, and far more likely to pose a hazard to Yellowstone visitors, are hydrothermal explosions—forceful steam-driven eruptions that can expel rocks, mud, and boiling water (see sidebar on volcanic hazards on p. 2). Small hydrothermal explosions occur about every 2 years in Yellowstone National Park. A few human-observed explosive events include Excelsior Geyser in Midway Geyser Basin in the late 1800s, and Porkchop Geyser in Norris Geyser Basin in 1989. Large hydrothermal explosions, like those that produced Mary Bay and Turbid Lake on the north side of Yellowstone Lake, occur every few thousand years, can throw material up to 4 kilometers (2.5 miles), and produce craters as wide as 2 kilometers (1.25 miles) in diameter.

During September 19 to October 3, 2020, USGS and Yellowstone National Park scientists investigated the deposits associated with two major hydrothermal explosions in Lower Geyser Basin. The Pocket Basin and Twin Buttes explosion craters were first identified by USGS researchers Donald White and Patrick Muffler in the late 1960s from their large craters and surrounding breccia (broken fragments of rock cemented together) deposits. These craters were later recognized as amongst the largest and oldest in Yellowstone. Much is still unknown about the timing and triggers of these events as well as the behavior of the local hydrothermal system at the end of the last major glaciation (the Pinedale glacial epoch, approximately 22,000–13,000 years ago). The main goal of the 2020 research expedition was to document field relations between the hydrothermal breccia units and related geologic formations, characterize the hydrothermal breccia deposit, and sample datable materials in order to reconstruct the geologic history of Lower Geyser Basin.

Lower Geyser Basin is one of Yellowstone's largest thermal areas. The Pocket Basin explosion crater (fig. 16) is a 365 by 800 meter (approximately 2,000 by 2,600 feet) depression that has shallowly dipping inner slopes and an asymmetric hydrothermal breccia deposit ringing the crater. A smaller crater filled by a lake

Figure 16. Mosaic photograph of Pocket Basin taken from the northeast rim looking southwest into the crater. Pocket Basin is a U-shaped crater that is dissected on the southwest edge by the Firehole River, visible on the far-right side of the photograph. U.S. Geological Survey photograph by Lauren Harrison on September 24, 2020.

(Rush Lake) is located about 330 meters (1,080 feet) to the south of Pocket Basin and marks a potentially older explosion event. The Rush Lake breccia is characterized by fragments of rhyolite and is less altered than the Pocket Basin breccia, whose distinctive bleached fragments of red conglomerate, heavily altered rhyolite, and angular clasts of a laminated sandy unit thinly drape the northwest rim of Rush Lake. Both Pocket Basin and Rush Lake are located along parallel northeast-southwest lineaments delineated by vigorously active thermal features and low-lying, clay-altered marshy areas. Two boulders of Pocket Basin hydrothermal breccia, assumed to have been brought to the surface by the hydrothermal explosion, were sampled for cosmogenic exposure dating, which uses isotopes to measure the length of time that a rock has been exposed to cosmic rays at, or near, the Earth's surface and that could help reveal the timing of the explosion.

The Twin Buttes explosion crater (fig. 17) is located about 4 kilometers (2.5 miles) to the southwest of Pocket Basin. The crater is approximately circular with a circumference of about 645 meters (2,115 feet) and contains multiple smaller nested craters. Twin Buttes, which overlooks the crater, is composed of glacial deposits that contain opal-cemented, poorly bedded cobble and gravel conglomerates. The deposits surrounding Twin Buttes can be attributed to two sources: (1) a large hydrothermal explosion, whose deposits are best identified by variably altered angular breccia fall, and (2) a water-rich landslide that rafted large, meter-sized boulders far from their original position, creating a hummocky slope east of the explosion crater. The landslide is difficult to separate from the hydrothermal explosion because both events reworked the same units of preexisting glacial conglomerates, muddling the direct observation of geologic contacts. In fact, the two events may be linked. The landslide could have triggered catastrophic boiling of a confined hydrothermal system, resulting in the hydrothermal explosion. Alternatively, the hydrothermal explosion could have destabilized surrounding slopes enough to cause a landslide. Samples of landslide-emplaced boulders far from the main explosion crater and boulders emplaced by the hydrothermal explosion were collected for cosmogenic exposure dating to determine whether the two events were synchronous (fig. 18).

Lower Geyser Basin Mapping

Extensive geologic mapping has been conducted at different scales over the past 60 years at Yellowstone (see "Updating the Geological Map of Yellowstone" section above). In some areas, detailed mapping was conducted to better understand the geological history of a localized area. Many of these studies were conducted in the 1960s and 1970s, resulting in a series of published maps. For example, USGS geologists Patrick Muffler, Don White, Alfred Truesdell, and Bob Fournier mapped the Lower Geyser Basin of Yellowstone National Park to establish a basis for understanding the hydrothermal processes and explosions in the region. The mapping was published as USGS Miscellaneous Investigations Series Map I-1373 (Muffler and others, 1982). Patrick Muffler also created a more detailed map of the geology and thermal features of Pocket Basin, located within Lower Geyser Basin, using a 1:24,000 orthophotographic base. The

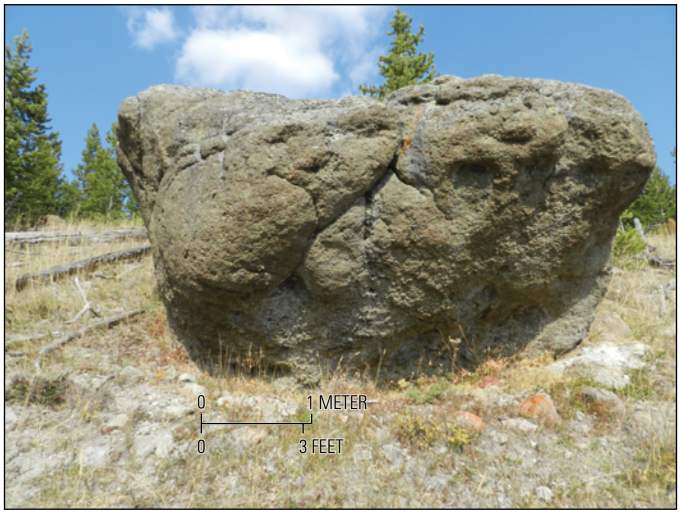


Figure 18. Photograph of a boulder associated with the Twin Buttes hydrothermal explosion crater that was sampled for cosmogenic isotope analysis. U.S. Geological Survey photograph by Lauren Harrison on October 2, 2020.

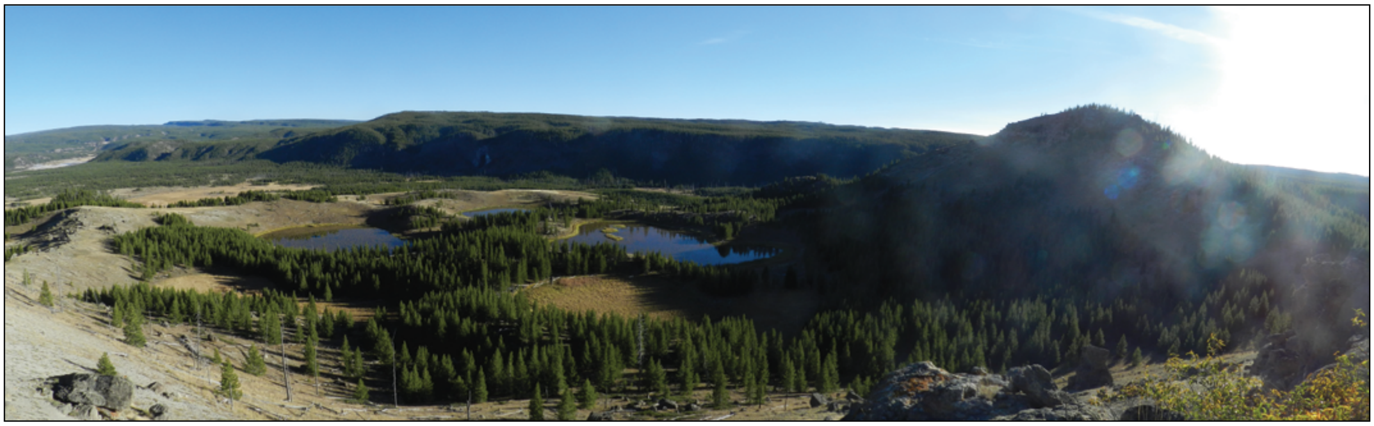


Figure 17. Mosaic photograph of Twin Buttes taken from the east butte looking south into the main crater. The lakes are smaller satellite craters within the main explosion crater, and the tall slope on the right side of the photograph is the western butte of Twin Buttes, composed of opal-cemented conglomerate. The forested ridge in the far distance is the flow front of the post-caldera West Yellowstone flow—a rhyolite lava flow that erupted about 114,000 years ago. U.S. Geological Survey photograph by Lauren Harrison on September 30, 2020.

mapped geology and hydrothermal features for the Pocket Basin map were compiled by A.L. Cook in 1979 but were available in hand-drawn form.

Recent work has converted the printed maps, unpublished field mapping, and some field observations into digital database products. The Lower Geyser Basin map (fig. 19) was scanned, georegistered, and digitized into a geodatabase at 1:24,000 scale by USGS geologist Laura Clor in 2012. In 2020, the geodatabase was updated to match existing USGS database standards, and the final product is expected to go out for peer review in early 2021. The Pocket Basin map (fig. 20) was also scanned, imported, and georeferenced. Sample descriptions were taken from the original field notebooks and appended to sample locations on the map. Like the Lower Geyser Basin map, the Pocket Basin map is also planned for peer review in early 2021.

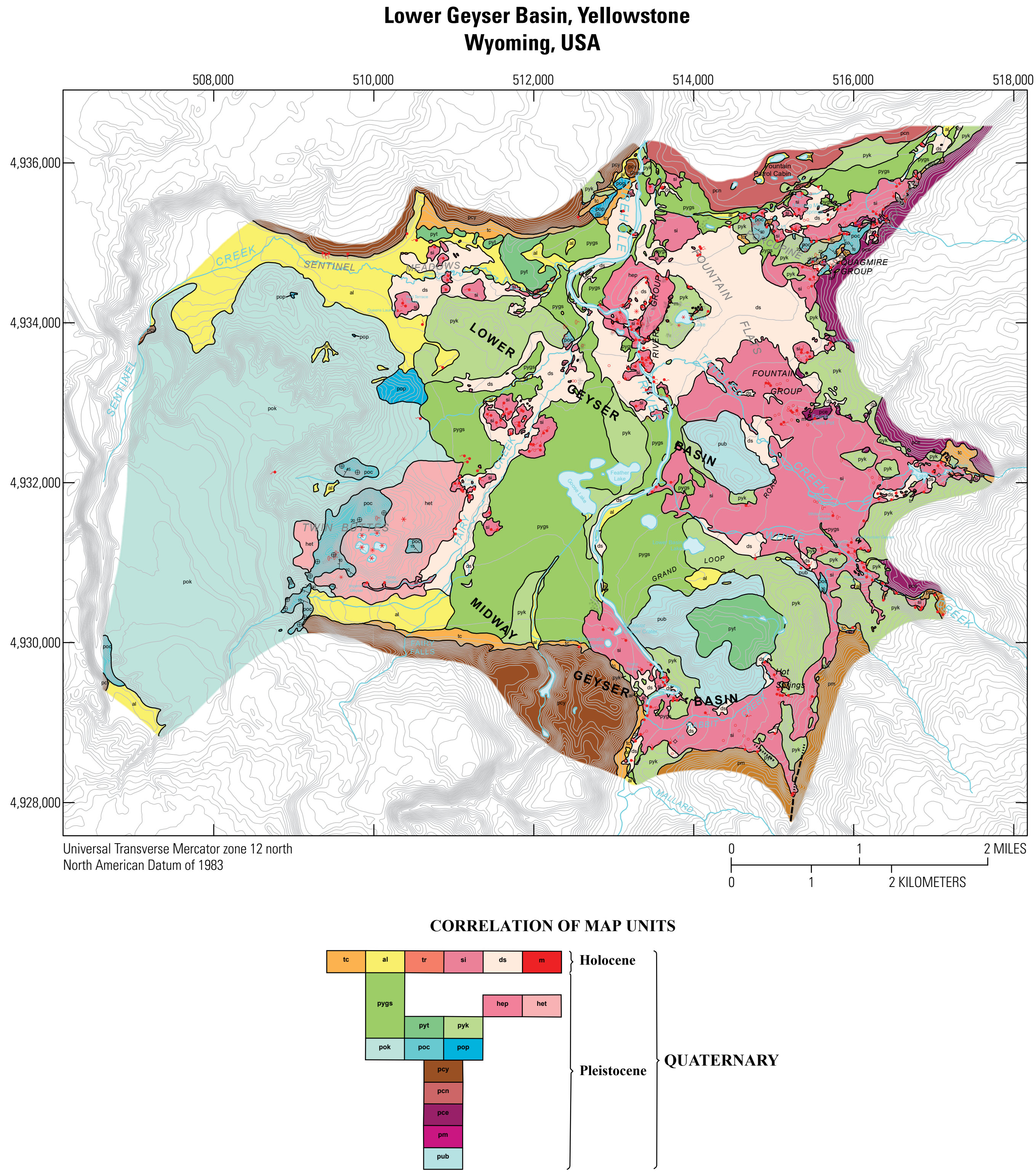


Figure 19. Image of a digitized geologic map of the Lower Geyser Basin originally published by Muffler and others (1982).

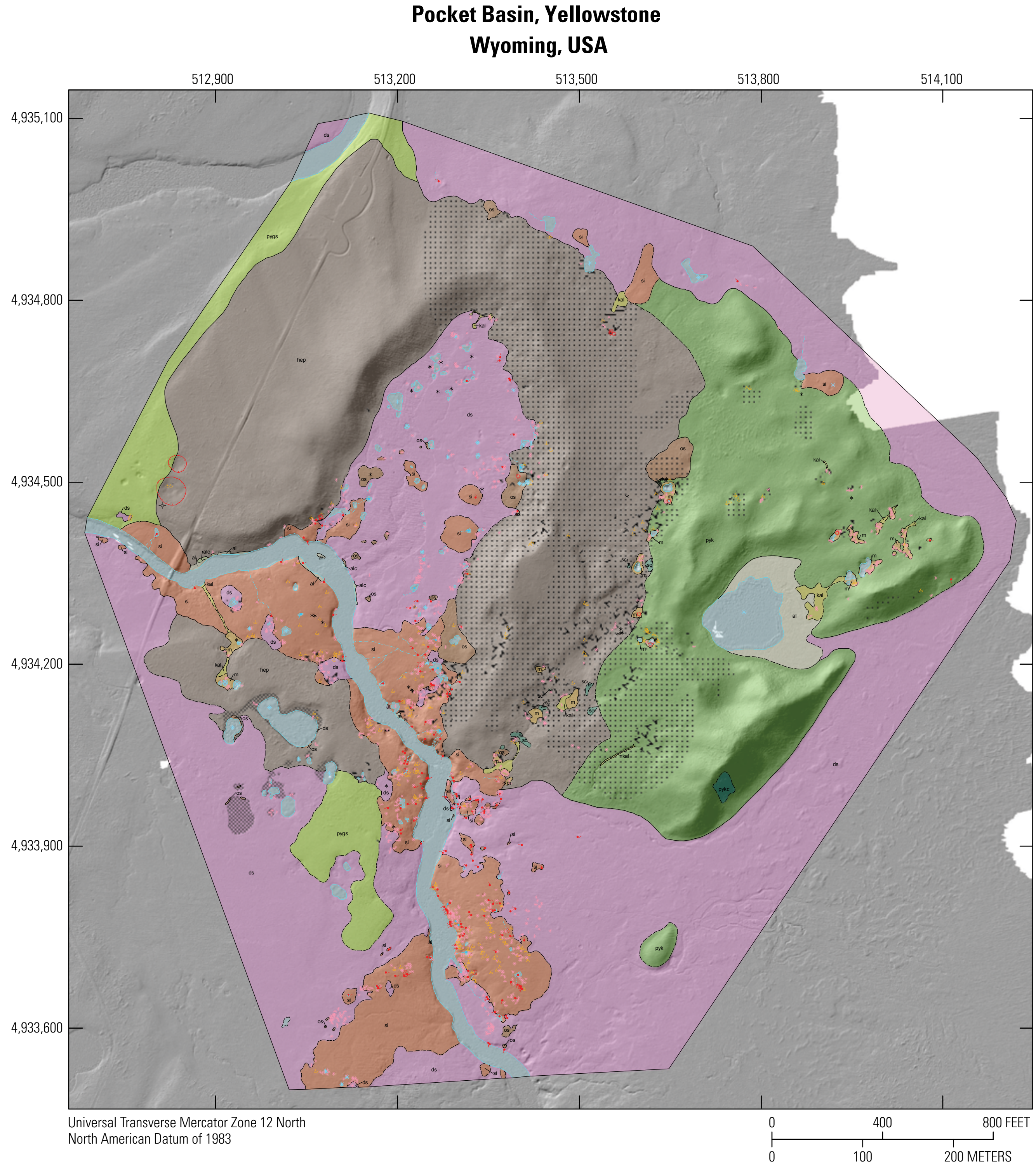
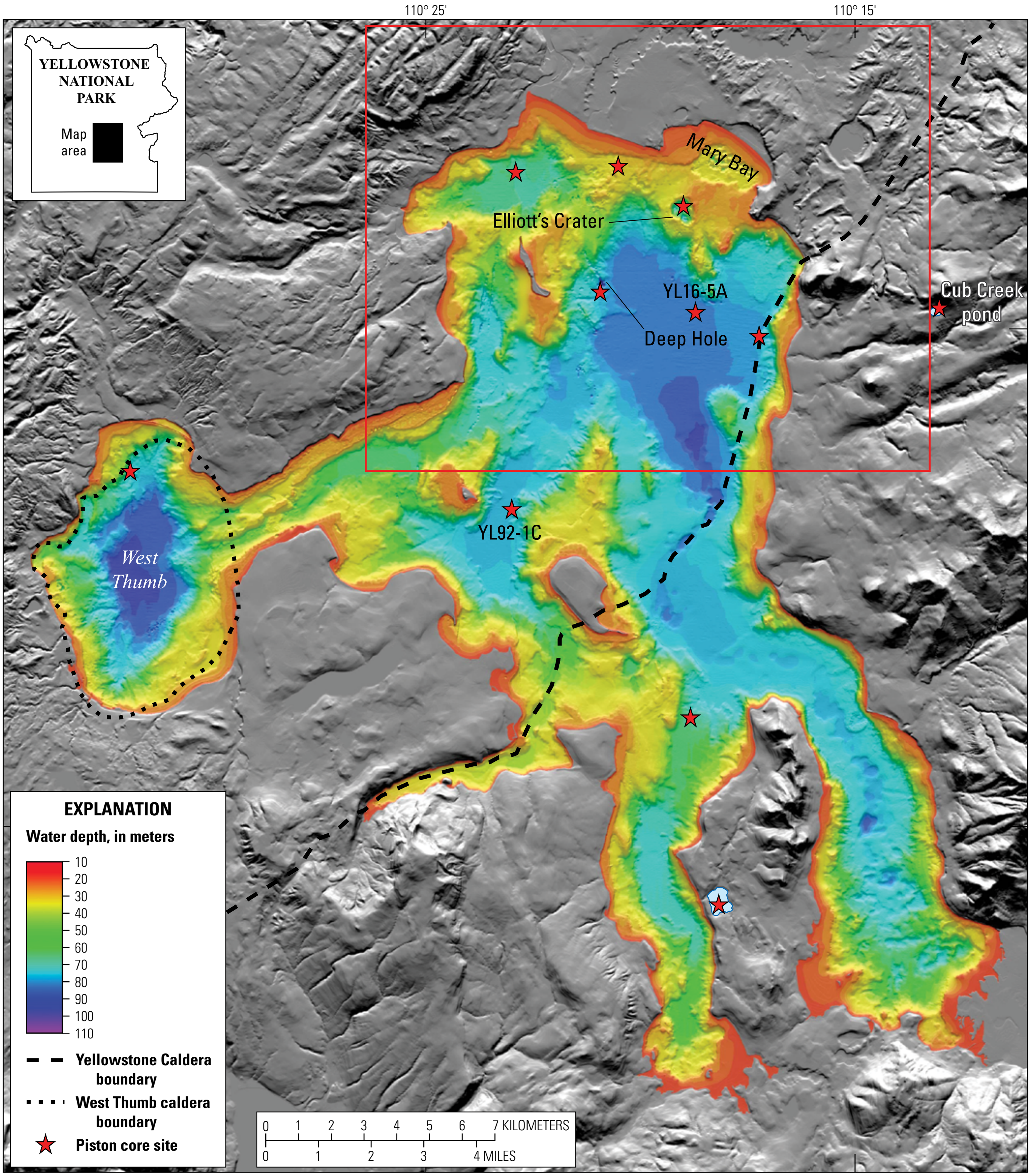


Figure 20. Image of a digitized geologic map of Pocket Basin, based on hand-drawn maps by P. Muffler and compiled by A.L. Cook.

Past geologic mapping of Yellowstone is an essential steppingstone on which the geologists of today can build to conduct even more advanced studies into the geologic history of the region. These new digital maps will serve as a critical resource for these investigations, including some of the work described above (see “Investigating Past Hydrothermal Explosions” section).

Yellowstone Lake Studies

Yellowstone Lake (fig. 21) is the largest high-altitude (>7,000 feet) freshwater lake in North America. It covers about 341 square kilometers (132 square miles) of Yellowstone National Park and hosts a variety of hot springs and



Base from U.S. Geological Survey Scientific Investigations Map 2973 by Morgan and others (2007)

Figure 21. Bathymetric map of Yellowstone Lake showing the locations of piston coring sites and the features informally named Deep Hole and Elliott's Crater. A portion of core YL92-1C (labeled on the map) is shown in figure 22. The red box outlines the area covered by the magnetic and bathymetric maps in figure 23.

hydrothermal areas beneath its surface. Long a subject of research, investigations of hydrothermal processes on the lake floor got a boost in 2015 with the start of the Hydrothermal Dynamics of Yellowstone Lake (HD-YLAKE) project, funded by the National Science Foundation with support from the USGS, National Park Service (Yellowstone National Park), Yellowstone Foundation, and Global Foundation for Ocean Exploration (Sohn and others, 2017). The project involves scientists from numerous institutions around the world and seeks to understand how Yellowstone Lake hydrothermal systems respond to geological and environmental changes by compiling observations of temporal changes in temperature and compositions of hydrothermal fluids, heat flow, seismicity, water-column processes, and microbial communities that inhabit the vent fields. The field strategy used a two-pronged approach: (1) geophysical and geochemical monitoring of the active hydrothermal system over a continuous 2-year period (with instruments deployed annually), and (2) analyses of sediment cores to study the postglacial (approximately 15,000-year) history of sedimentary, tectonic, and hydrothermal activity beneath the lake. Although funding for the project concluded in 2019, HD-YLAKE scientists continue to analyze data collected during the project.

Summary of Yellowstone Lake Studies in 2020

In 2020, scientific results from the HD-YLAKE project included studies of lake cores that contain evidence of past hydrothermal explosions, pollen analyses that examine vegetative responses to volcanic and hydrothermal disturbances, interpretations of multiscale high-resolution magnetic surveys of northern Yellowstone Lake, and geochemical analyses from the area informally known as Deep Hole—a 130 meter (427 feet) deep, 200 meter (656 feet) wide active geothermal vent field that hosts the hottest hydrothermal vent fluid temperatures (174 °C [345 °F]) yet measured in Yellowstone National Park. The Deep Hole was the HD-YLAKE active-venting focus site.

Explosion Deposits in Lake-Bottom Sediments

An important goal of the HD-YLAKE project has been to understand the characteristics, distribution, depositional processes, and triggers of large hydrothermal explosions in and around Yellowstone Lake. Analyses of 13 piston cores (fig. 21) from all parts of Yellowstone Lake and two piston cores from Cub Creek pond, 4 kilometers (2.5 miles) due east of Yellowstone Lake, reveal details of multiple hydrothermal explosions, with age constraints provided by interbedded ash from past eruptions in the Cascade Range (fig. 22)—the eruptions of Mount Mazama (Crater Lake) 7,700 years ago and Glacier Peak 13,700 years ago. All but one of the 15 piston cores contain either one or both Cascade Range ash deposits and at least one Yellowstone-sourced hydrothermal explosion deposit. Two extensive explosion deposits were found at depth throughout the Yellowstone Lake basin and came from the approximately 8,000-year-old sublacustrine Elliott's Crater hydrothermal explosion (discovered by USGS multibeam bathymetric mapping in 1999) and the approximately 13,000-year-old Mary Bay hydrothermal explosion crater on the north side of Yellowstone Lake (Morgan and others, 2009). A few small-volume hydrothermal explosion events also are identified in the piston cores.

The two extensive explosion deposits reveal details of the explosion processes and indicate the following: (1) the explosion deposits are distinct from other lake sediments in their physical characteristics, trace element composition, magnetic susceptibility, and density; (2) the ejecta from these explosions are extensively altered, suggesting that pervasive hydrothermal activity occurred prior to the explosions; (3) physical sorting of the deposits in the piston cores indicates the explosion ejecta settled through the water column; (4) the large (>800 meter [2,625 feet] in diameter) crater-producing hydrothermal explosion events generated multiple explosion pulses, separated by decades to hundreds of years; (5) the intensity of the explosions from a specific crater decreased over time; and (6) the distribution and cumulative thickness of the deposits suggests that some explosions are directional (Morgan and others, 2009).

Vegetation Response to Volcanic and Hydrothermal Disturbances, Near and Far

Given the prevalence of volcanic and hydrothermal activity affecting the Yellowstone region, how does the ecosystem react? Schiller and others (2020) used variation in pollen records to examine the vegetation response to sudden emplacement of rhyolite lava flows, tephra deposition, and hydrothermal explosions in the northern Rocky Mountains and the greater Yellowstone ecosystem. The study utilized HD-YLAKE piston core YL16-5A from the north-central basin of Yellowstone Lake, cores from Cub Creek pond, and known pollen records from cores in other regional lakes and ponds. Results indicate that

1. The Pleistocene rhyolite lava flows in the central greater Yellowstone ecosystem created infertile landscapes that have shaped vegetation since rhyolite emplacement. Nutrient-poor, well-drained soils developed on these flows and supported low-diversity grassland during late-glacial time and forests dominated by lodgepole pine forests in interglacial periods.

2. Ash layers from eruptions of Cascade Range stratovolcanoes are commonly preserved in lake-sediment records in the northern Rocky Mountains, and associated pollen records show enhancement of steppe vegetation relative to pine forests for years to decades after these ash deposits are emplaced.

3. Large hydrothermal explosions in Yellowstone have resulted in vegetation changes that indicate tree mortality after deposition of explosion debris, followed by recovery in a matter of years.

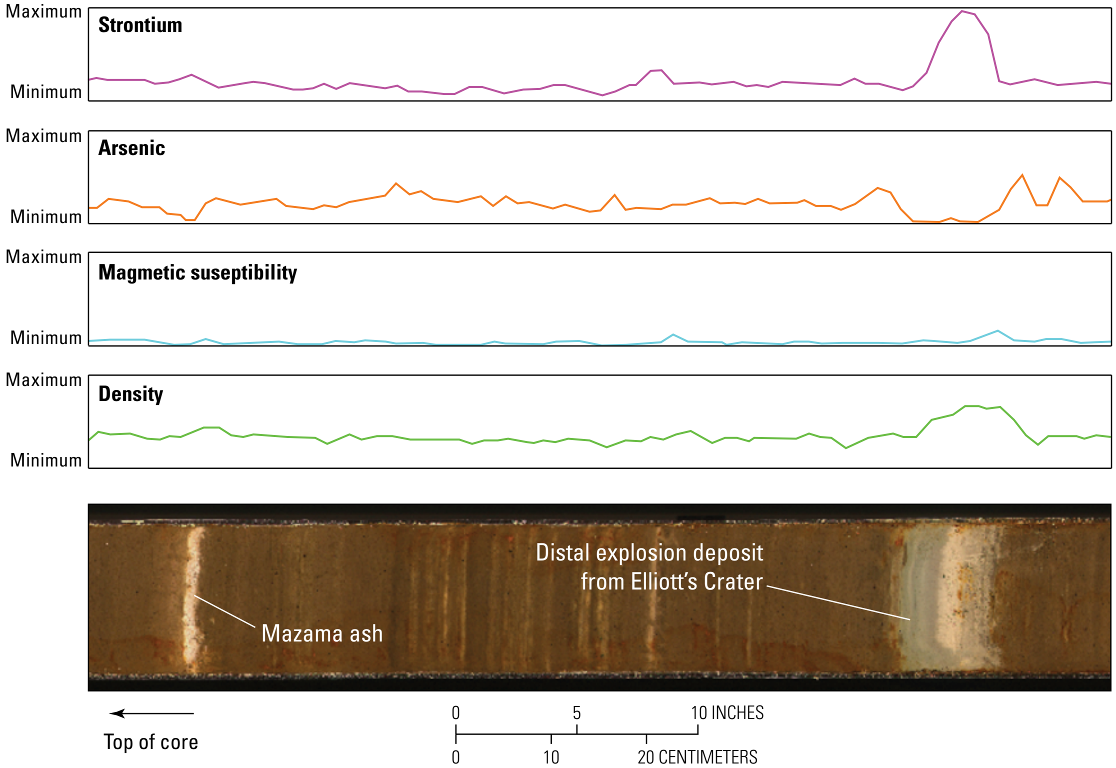


Figure 22. Section from the piston core YL92-1C, collected in south-central Yellowstone Lake (fig. 21). The core is viewed horizontally, with the top of core to the left. The core section shown is from 5.21–5.63 meters (17–18.4 feet) depth. The 0.5 centimeter (0.2 inch) thick white Mazama ash, from the eruption that resulted in the formation of Crater Lake in Oregon, is clearly identifiable and provides a marker bed of known age (7,700 years old). About 29 centimeters (11 inches) below the Mazama ash is a 5 centimeter (2 inch) thick, fining-upward sequence of hydrothermally altered sediment, ranging from fine silt upward to clay, from the explosive events that formed the informally named Elliott's Crater (fig. 21) about 8,000 years ago. The explosion deposit is a distal facies of the Elliott's Crater explosion breccia; the core site for YL92-1C is located about 15.5 kilometers (9.6 miles) southwest of Elliott's Crater. Colored lines above the core indicate relative changes in density, magnetic susceptibility, arsenic content, and strontium content, all of which have marked changes at the position of the Elliott's Crater deposit relative to the other lake sediments in the core.

Thus, the type and duration of the vegetation responses to volcanic and hydrothermal disturbances are governed by the preexisting plant communities and the source, magnitude, and cause of the volcanic or hydrothermal disturbance.

Magnetic Studies of Northern Yellowstone Lake

To better understand the effects of hydrothermal activity on rock magnetization in northern Yellowstone Lake, Bouligand and others (2020) measured the strength of the magnetic field at different heights above the Yellowstone Lake area via surveys by airplane, helicopter, boat, and autonomous underwater vehicle (AUV). Magnetization values varied with rock type, temperature, and hydrothermal alteration of the rock, and findings confirmed a strong correlation between low magnetization and hydrothermal activity (fig. 23). The northeastern part of the lake is characterized by high heat flow and a regional magnetic low punctuated by stronger local magnetic lows, many of which host active hydrothermal vents. In contrast, the northwestern part of the lake hosts higher amplitude magnetic anomalies and no obvious hydrothermal activity or punctuated magnetic lows. The broad northeastern magnetic low reflects widespread hydrothermal activity that has demagnetized the rock. The two regions are separated by a sharp boundary coincident with the currently active approximately 25 kilometer (15.5 mile) long Eagle Bay-Lake Hotel fault zone; the boundary is marked by a steep gradient in heat flow and magnetic values and may reflect a significant subsurface structure that effectively blocks fluid circulation. This structure may be related to the collapsed margin of the Huckleberry Ridge Caldera, which formed 2.08 million years ago (see sidebar on geology of Yellowstone on p. 22–23).

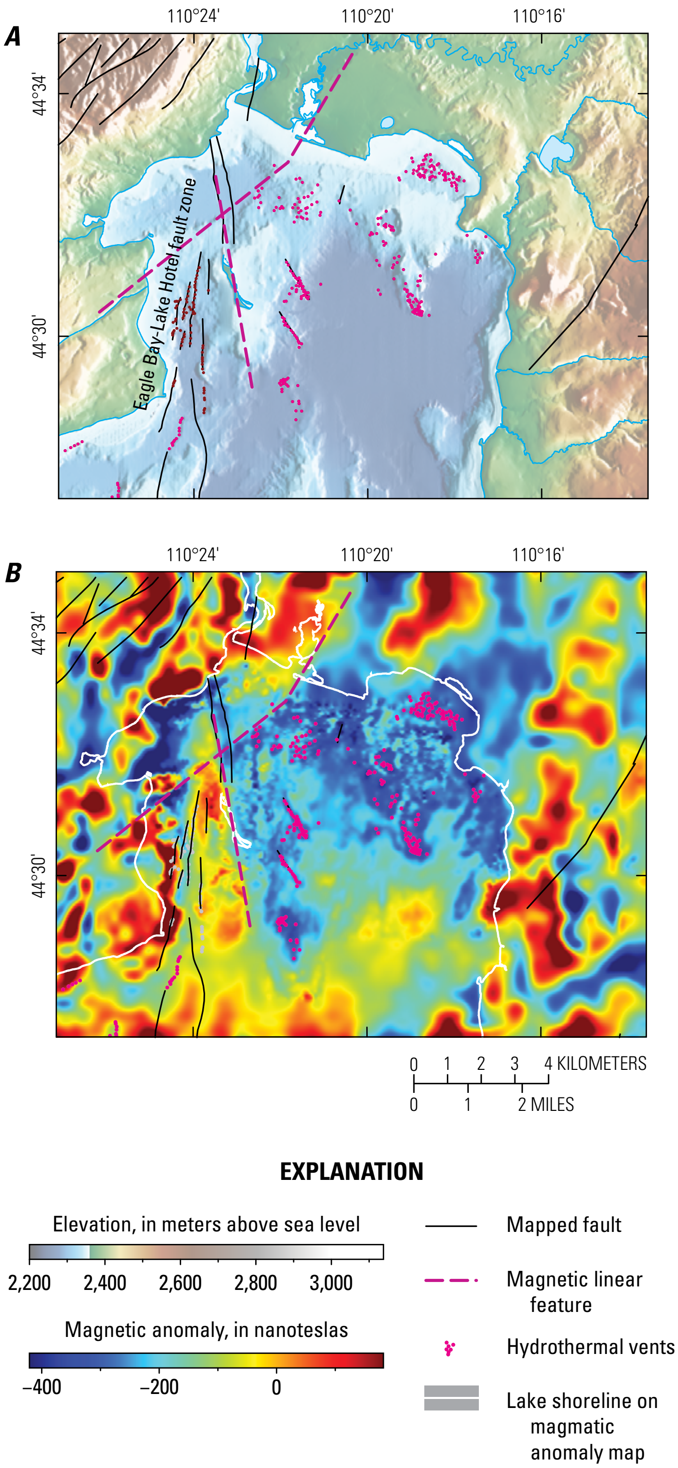


Figure 23. Bathymetry (*A*) and magnetic anomalies (*B*) of the northern part of Yellowstone Lake (area outlined in fig. 21). Magnetic anomalies are reduced to pole (in other words, adjusted to what they would look like if the Earth's magnetic field were vertical, instead of inclined). Note the sharp boundary in magnetic anomalies that coincides with the Eagle Bay-Lake Hotel fault zone, which may be a structure that is sufficiently strong to block fluid circulation. In the northwest part of the lake, strong magnetic lows are associated with hydrothermal vents. Modified from Bouligand and others (2020).

In a more detailed magnetic survey using a near-bottom AUV, Bouligand and others (2020) focused on the 200 meter (656 feet) wide Deep Hole hydrothermal vent field—the deepest part of Yellowstone Lake. Results show decreased magnetization at the periphery of a vapor-dominated venting area, where mixing with lower temperature hydrothermal waters allows the gas to condense and efficiently alter magnetic minerals in the rock. In contrast, the center of the active Deep Hole hydrothermal vent shows less destruction of magnetic minerals owing to the higher temperatures, which results in less efficient gas condensation and, therefore, less rock alteration.

Hydrothermal Fluids from Deep Hole

Chemical analyses of the vapor-dominated fluids in the Deep Hole vent field indicate that the fluids sampled at temperatures as high as 174 °C (345 °F) are a mixture of vapor-dominated fluid (steam, CO_2, H_2S, and other gases) and lake water entrained from pore fluids in the sediments or by direct mixing with bottom water at the vent (Fowler and others, 2019a,b). Measurements of pH and redox potential at temperature using specially designed electrodes installed at hydrothermal vents on the lake floor (Tan and others, 2020) indicate a pH of 4.2 at 150 °C (300 °F); the high acidity is caused by the high CO_2 content of the fluid.

These discoveries are important because vapor-dominated fluids have little capacity to dissolve and transport other materials, so constructional deposits of silica sinter, like that which make up the cone of Old Faithful Geyser, are not expected in this type of system. However, the vapor-dominated fluids can and do produce distinctive hydrothermal alteration of lake sediments to various types of clays. The clay alteration may reduce permeability and provide a cap beneath which the vapor-dominated upwelling fluids are contained except where they escape in sub-lacustrine vents. Vapor-dominated hydrothermal systems are known at several sites within Yellowstone National Park (for example, Mud Volcano) but were not previously known to exist beneath Yellowstone Lake.

Heat Flow Studies

The thousands of 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 [280 °F]). Studies of thermal features are accomplished by ground-based monitoring (including both occasional observations and continuous temperature monitoring), thermal infrared remote sensing from satellite and aircraft, and proxy measurements of chloride in Yellowstone National Park's rivers (see sidebar on monitoring thermal changes on p. 34–35).

Summary of Heat Flow Studies in 2020

The total radiative heat output from Yellowstone's thermal areas in 2020, estimated from satellite thermal infrared observations, was similar to that measured in previous years. Heat output based on chloride flux in Yellowstone's rivers was slightly lower than measured in years past, although not significantly so. Together, the thermal infrared and chloride flux measurements indicate that the total thermal discharge remained relatively steady.

Thermal Infrared Remote Sensing

Data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument aboard the National Aeronautics and Space Administration's Terra satellite have been acquired intermittently over parts of Yellowstone since the year 2000. In 2020, there were 11 days with ASTER scenes (three nighttime and eight daytime) that covered parts of Yellowstone, of which only one was mostly cloud free—a nighttime scene from May 6 that covered the east side of the park. Landsat-8 thermal infrared data cover the entire park in a single scene and have been regularly acquired since 2013, nominally every 16 days. In a given year, Landsat-8 will acquire at most 44 scenes over Yellowstone (half daytime and half nighttime), although nighttime scenes are not always acquired owing to on-orbit calibration events or data capacity limitations. In 2020, 22 Landsat-8 nighttime scenes were acquired, 10 of which were clear to mostly cloud free. The earliest clear Landsat-8 nighttime thermal infrared image over Yellowstone in 2020 was acquired on March 27 (fig. 24); those data were processed and analyzed for this report.

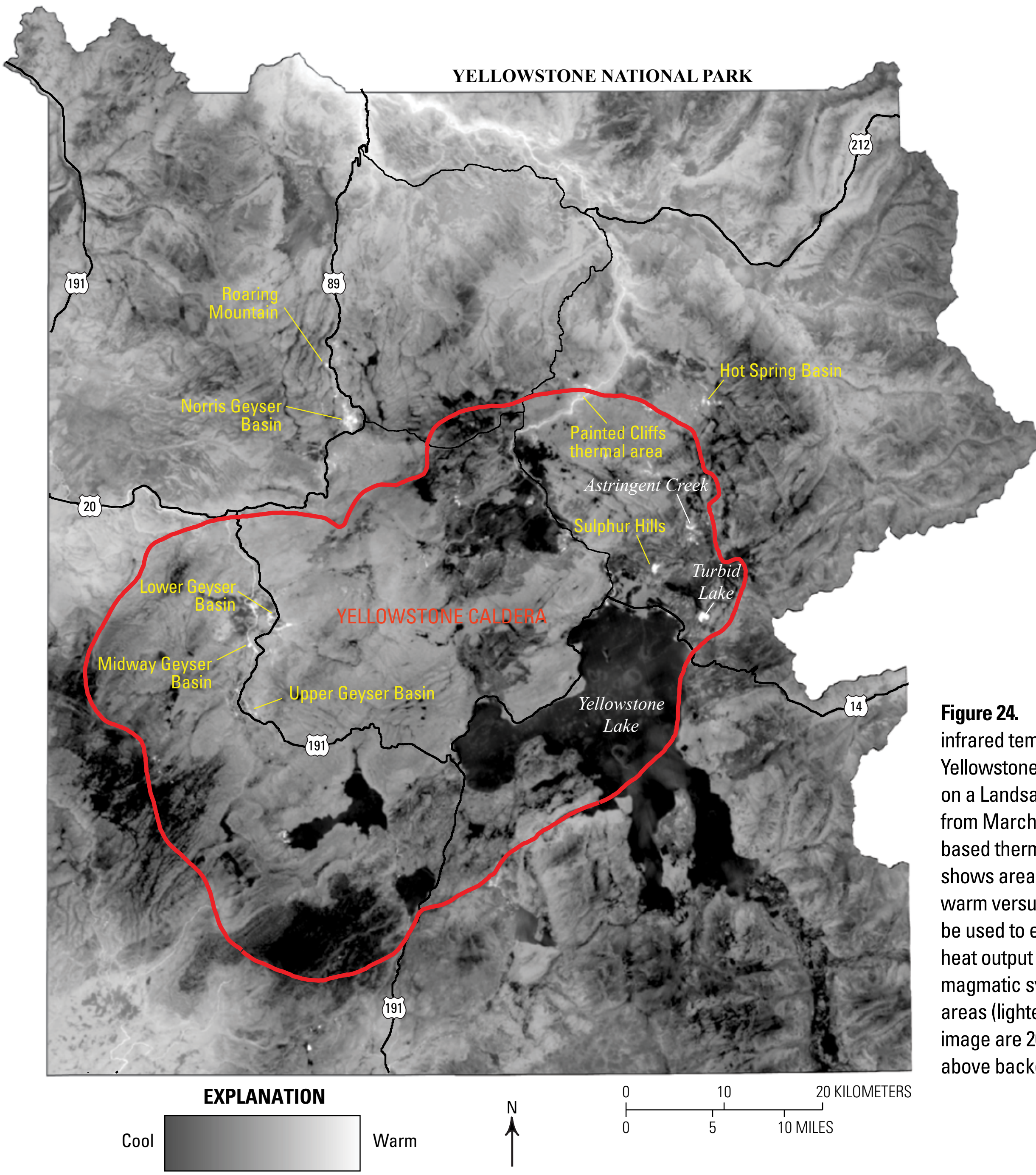


Figure 24. Satellite thermal infrared temperature image of Yellowstone National Park based on a Landsat-8 nighttime data from March 27, 2020. Satellite-based thermal infrared imagery shows areas of ground that are warm versus cool, and it can be used to estimate the radiant heat output from the Yellowstone magmatic system. The warmest areas (lightest in shade) in this image are 20–40 °C (36–72 °F) above background.

Monitoring Thermal Changes at Yellowstone Caldera

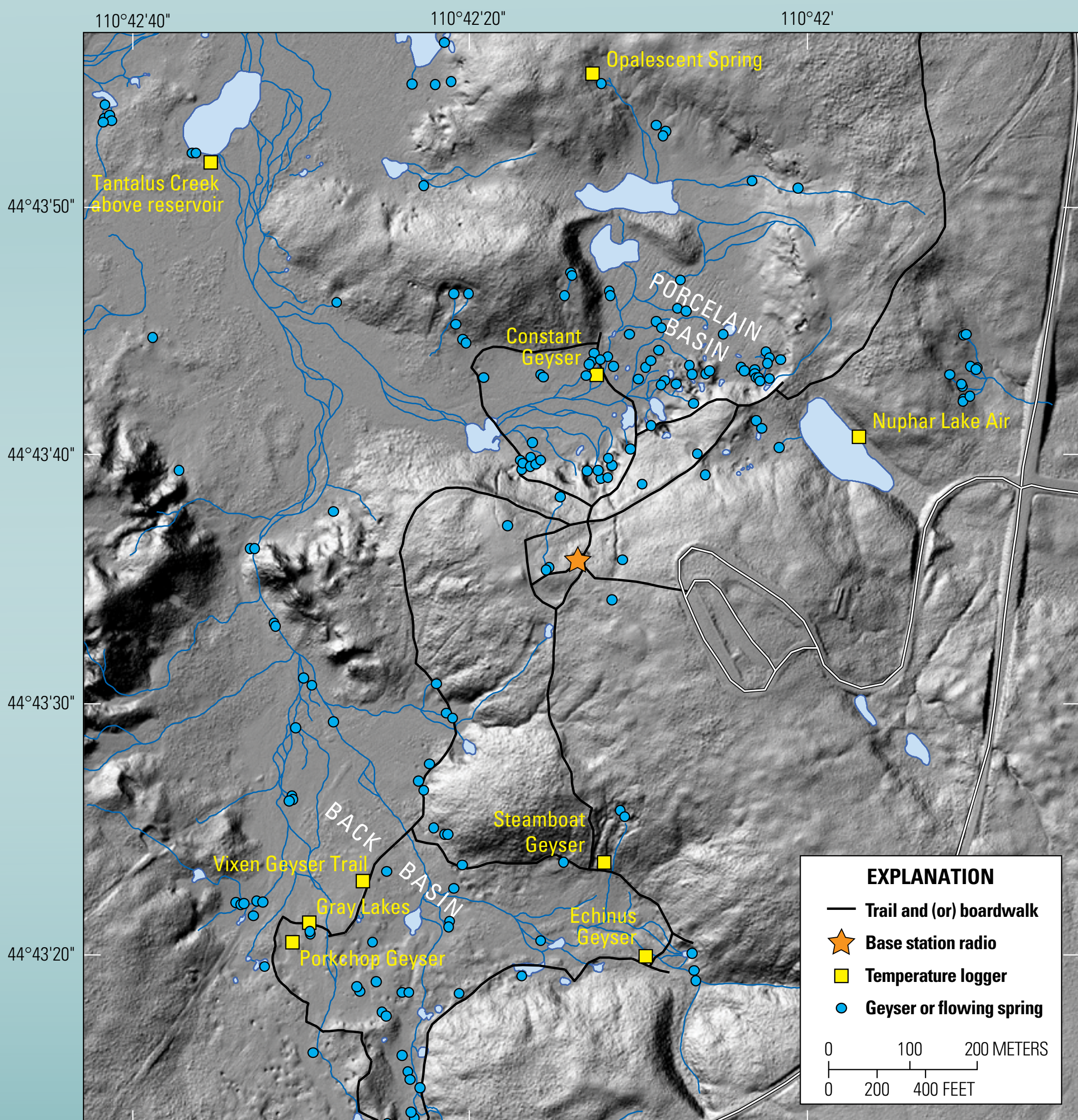
A lot of heat is released in the Yellowstone area from thermal features like hot springs, geysers, mud pots, and fumaroles. Tracking the temperatures and sizes of thermal areas is critical for monitoring Yellowstone Caldera's hydrothermal activity and also for understanding and preserving these spectacular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

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

However, 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 example, tracking the chemistry of the Yellowstone'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 a reliable way to monitor overall hydrothermal activity. This is now done 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 can measure surface temperature and detect changes over time. One of the advantages of satellite-based thermal infrared remote sensing is that nearly all of the thermal areas in the park can be viewed at once. 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.

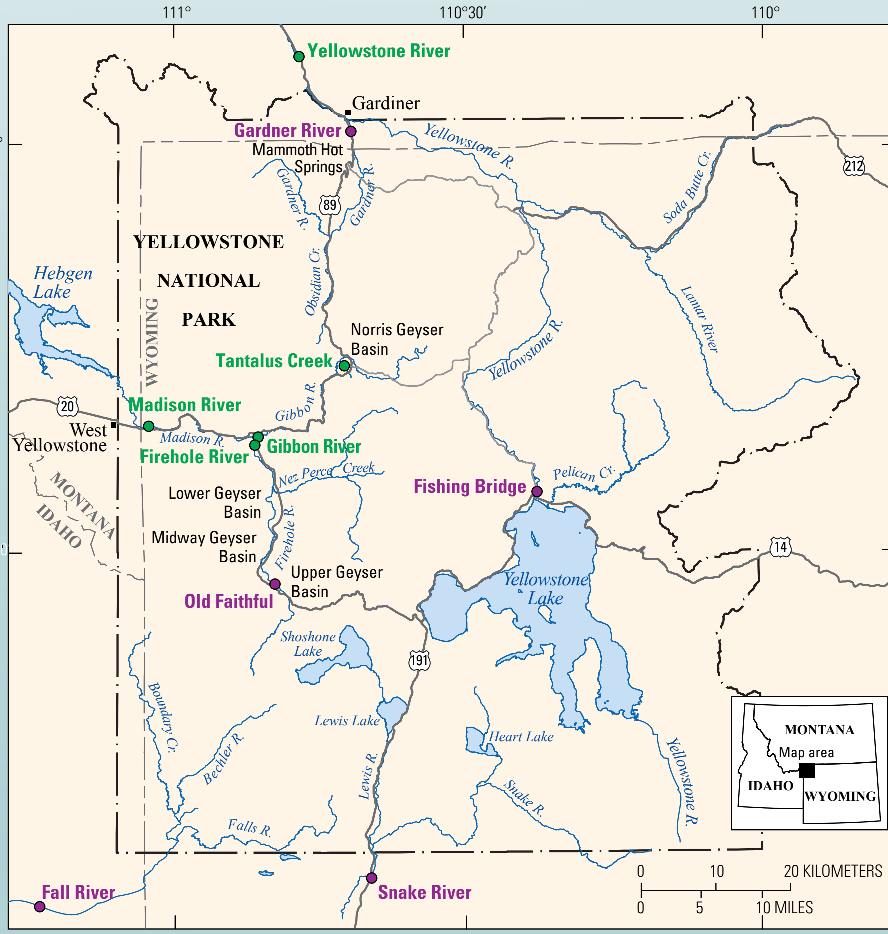
One of the challenges of thermal infrared remote sensing is that temperature contrasts can be low, and thus difficult to discern. Hot springs and fumarole fields are relatively subtle thermal features compared to extremely hot features like active lava flows or fires. This is because they exhibit sub-boiling to boiling temperatures at the surface in areas that are generally small with respect to the pixel size of thermal infrared satellite data. During the day, most surface heating comes from the sun, and rocky, sun-facing slopes can mask or exceed the thermal infrared emittance from thermal areas. Using nighttime thermal infrared data minimizes the effects of solar radiance and maximizes thermal contrast between thermal and background areas. At night, water bodies are generally warmer and



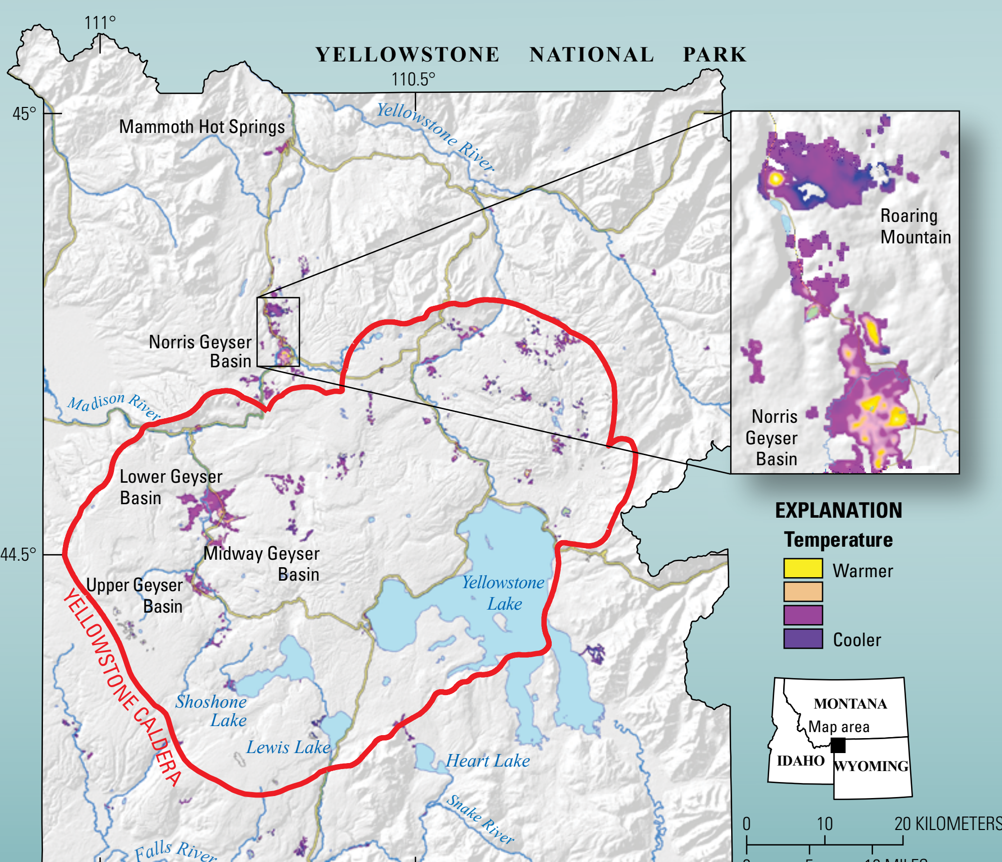
Base from 2009 EarthScope lidar dataset

Map of temperature measurement sites in Norris Geyser Basin.

more radiant than the surrounding land surface and can mask thermal areas adjacent to lakes. In Yellowstone, lakes that do not receive thermal input from nearby hot springs or underwater vents are frozen from late winter through early spring. Therefore, nighttime thermal infrared data from January through May are preferred. During these times, cloud-free thermal infrared data can differentiate most thermal areas from ambient background areas because of greater thermal contrast, and these data can be used to evaluate surface thermal metrics, such as geothermal radiant heat flux and geothermal radiative power output. Another advantage of wintertime data is their utility for characterizing thermal input to lakes. These data have revealed the presence of warm vents and springs not previously cataloged into the thermal vent inventory database.



Map showing specific-conductance-monitoring sites for determining chloride flux in rivers that drain thermal areas in Yellowstone National Park. Green stations are telemetered and data from purple stations are downloaded manually.



Base from 30-meter National Elevation Dataset

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 (36–54 °F) above background; the cooler areas (purple) are 2–3 °C (4–5 °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 the Yellowstone region.

The results of analyses of the March 27, 2020, Landsat-8 thermal infrared data were similar to analyses from previous years. The thermal areas with the highest pixel temperatures above background were Sulphur Hills, Midway Geyser Basin, Lower Geyser Basin, and Turbid Lake. The thermal areas with the highest geothermal radiant emittance (in watts per square meter) were Turbid Lake and Sulphur Hills. The thermal areas with the highest total geothermal radiative power output (in megawatts), which tend to be the largest areas, include Norris Geyser, Lower Geyser, and Hot Spring Basins, Astringent Creek, Roaring Mountain, and the area locally known as "Painted Cliffs." Summation of the geothermal radiative power output for all of Yellowstone's thermal areas measured from the March 27, 2020, Landsat-8 thermal infrared data is about 1.9 gigawatts, which is typical for that time of year. This value is greater than that determined from images acquired in 2017–2019 (1.1–1.3 gigawatts [see 2017, 2018, and 2019 YVO annual reports]) because the 2020 image was acquired earlier in the year, when the contrast between thermal areas and background is greater.

An important aspect of monitoring Yellowstone thermal output using thermal infrared data is to identify previously unknown thermal areas and changes in thermal output over time. For example, the discovery of a new thermal area near Tern Lake in 2018 was made possible by examination of satellite thermal infrared data (see 2018 YVO annual report). Analysis of satellite thermal infrared imagery has identified a number of anomalously warm areas in Yellowstone National Park that do not correspond to mapped thermal areas. Likewise, there are numerous mapped thermal areas that do not emit detectable thermal infrared radiance and that may no longer be active. Field observations are required to validate satellite-based observations. Field visits to some of these sites were planned in 2020 but had to be postponed because of the COVID-19 pandemic. USGS and Yellowstone National Park scientists are hoping to visit these sites during the 2021 field season.

Chloride Flux Monitoring

Measuring the thermal output of Yellowstone's large magmatic system is not straightforward, as there are thousands of thermal features spread across 3,470 square miles. One way to capture and integrate the contributions from this broad area is to monitor river chemistry. Since thermal-water discharge eventually enters a nearby river, rivers act as a collection and delivery system for thermal fluids. Nearly all the chloride in rivers that drain Yellowstone comes from emerging hot spring water heated underground by underlying magma. Monitoring river chemistry is therefore an important way to track the behavior and overall changes in Yellowstone's hydrothermal system. By monitoring the chloride flux, the hydrothermal discharge and heat flux from Yellowstone can be estimated, and both short- and long-term variations can be used to identify changes in the deep hydrothermal system, earthquake activity, geyser eruptions, and other natural events (like floods and the impacts of wildfire).

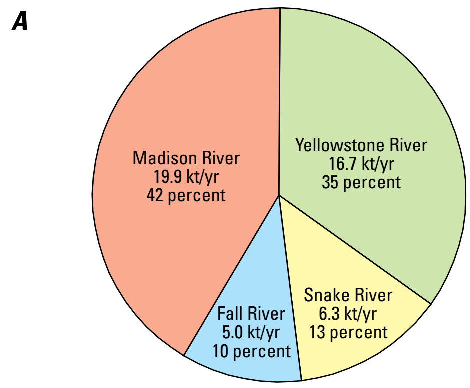
The USGS and Yellowstone National Park have collaborated on chloride-flux monitoring in Yellowstone National Park since the 1970s and have been continually improving the monitoring network and systems used to quantify solute concentrations and fluxes. Beginning in 2010, the USGS installed stations along major rivers to automatically measure specific conductance (an indication of how well water conducts an electrical current), which is a proxy for the concentration of chloride and other solutes. The use of specific conductance also allows for continuous measurements every 15 minutes.

Monitoring the chloride (and other geothermal solutes) flux in the major rivers of Yellowstone continued in 2020. Specific conductance measurements were made at monitoring sites along Tantalus Creek and the Madison, Firehole, Gibbon, Snake, Gardner, Yellowstone, and Fall Rivers (see sidebar on monitoring thermal changes on p. 34–35). The current network provides information at several scales (park-wide, watersheds, and individual geyser basins). The Madison, Yellowstone, Snake, and Fall River monitoring sites capture the hydrothermal discharge within their watersheds, and the sum of these four rivers captures the entire hydrothermal discharge from Yellowstone National Park. Additional monitoring sites along their tributaries provide higher resolution and can be used to identify changes at geyser-basin or hot-spring scales. In 2020, a new monitoring station was established along the Yellowstone River at Fishing Bridge (near the outlet of Yellowstone Lake; fig. 25). The new monitoring site will capture the hydrothermal discharge from large hydrothermal areas and basins within and around Yellowstone Lake.

The use of specific conductance as a proxy for chloride requires knowledge of the relation between specific conductance, chloride, and other geothermal solutes (SO_4, F, HCO_3, SiO_2, K, Li, B, and As), and the relation needs to be confirmed annually. Water samples were collected during two 2020 field trips to assess the solute-specific conductance correlations.

Figure 25. Photograph of the U.S. Geological Survey (USGS) streamgage site just north of Fishing Bridge on the Yellowstone River. View is looking north (downriver). In 2020, a specific conductance monitoring station was installed at this site. USGS photograph by Blaine McCleskey on June 7, 2010.

In 2020, the total chloride flux leaving Yellowstone National Park was 47.9±4 kilotons, which was determined by summing the flux from the Madison, Yellowstone, Snake, and Fall Rivers. This is lower than historical measurements of 52.6±4.1 kilotons (1983–2003 and 2013–2019), but within the uncertainty of the measurements and calculations. The percentages of the total flux from the Madison (42 percent), Yellowstone (35 percent), Snake (13 percent), and Fall (10 percent) Rivers for 2020 are shown in figure 26*A*. The 2020 chloride flux from the Firehole River, Madison River, and Fall River were lower than most historical fluxes measured at these sites (fig. 26*B*). Continued chloride flux monitoring will determine if the observed decrease in hydrothermal discharge from the thermal areas along the Firehole and Fall Rivers persists in subsequent years.



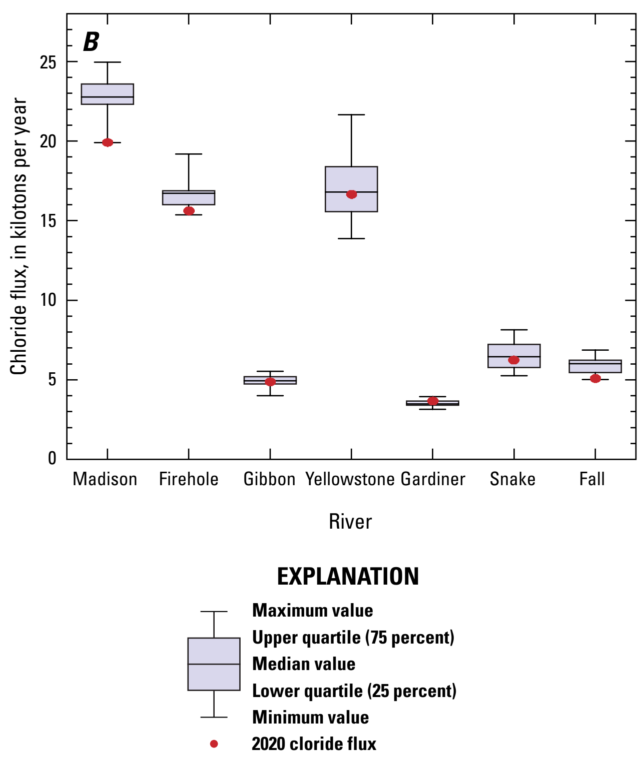


Figure 26. *A*, Pie diagram showing the 2020 chloride flux, in kilotons per year (kt/yr), and the percentage of the total flux (47.9 kt/yr) for the four major rivers (Madison, Yellowstone, Snake, and Fall Rivers) that drain the Yellowstone region. Fluxes were measured at gaging locations where the rivers leave the park (see sidebar on p. 34–35). *B*, Boxplot showing the distribution of chloride flux measurements collected from 1983 to 2020. The 2020 chloride flux for each monitoring site is shown.

Geysers and Hot Springs

Yellowstone hosts thousands of thermal features, including geysers, hot springs, fumaroles, and mud pots. These features are incredibly dynamic, displaying a range of behaviors that vary over time. Some geysers, especially those like Old Faithful that exist in comparative isolation, follow patterns that allow their activity to be forecast. However, the vast majority of Yellowstone's geysers, springs, and other thermal features have unpredictable behavior.

Summary of Geyser Activity and Research in 2020

As was true in 2018 and 2019, the most noteworthy geyser activity in Yellowstone National Park during 2020 continued to be water eruptions from Steamboat Geyser, the tallest active geyser in the world. But Steamboat Geyser was not the only geyser putting on a show during the year. Giantess Geyser also dazzled visitors and Echinus Geyser experienced some eruptions, albeit when no one was able to enjoy the sight. Not all springs and geysers showed increases in activity. In the remote southwest part of Yellowstone National Park, a well-known hot spring (fig. 12) went dry for the first time on record during the early part of 2020. Efforts by Yellowstone National Park geologists to document thermal features continued in the Upper Geyser Basin. In addition, new research addressed the challenges in dating geyser cones, and revealed that Old Faithful went dormant for approximately 150 years during droughts in the 13th and 14th centuries.

Steamboat Geyser

Steamboat Geyser is a prominent feature of Norris Geyser Basin. The geyser typically experiences frequent minor eruptions that include water splashing as high as a few meters (yards) above the vent and infrequent major eruptions with water columns more than 100 meters (about 300 feet) in height that are separated in some cases by several years. The geyser has a history, however, of entering phases of more frequent major eruptions, as in the 1960s and 1980s, when dozens of eruptions occurred per year, some separated by only days to weeks.

In 2018, Steamboat Geyser entered a new phase of increased activity, with 32 major water eruptions—a new record for a single calendar year (see YVO 2018 annual report). That trend continued in 2019 with 48 major eruptions, shattering the record set during the previous year. Activity in 2020 equaled that mark with another 48 major eruptions. Each eruption of Steamboat Geyser followed the same general pattern: gradually increasing minor activity over hours to days and culminating in a major water eruption lasting tens of minutes. A steam phase, lasting for about a day, follows the water eruption, and the minor activity ceases for several days until the buildup to the next eruption begins and the cycle repeats. Also, as is common with Steamboat Geyser eruptions, Cistern Spring, located about 100 meters (300 feet) downslope, drains within a day after each eruption and then gradually refills over the following days.

The times between eruptions in 2020 followed the same patterns that were established in 2019—there was wide variation, from a little more than 3 days to more than 17 days. The 2018–2020 sequence of Steamboat Geyser eruptions shows a seasonal influence on the interval between eruptions, with longer times in the winter and spring compared to shorter times during the summer and fall (fig. 27). This pattern may reflect a greater amount of water available in the subsurface during the summer and fall, owing to groundwater recharge from snowmelt, and less water available in the winter and spring months.

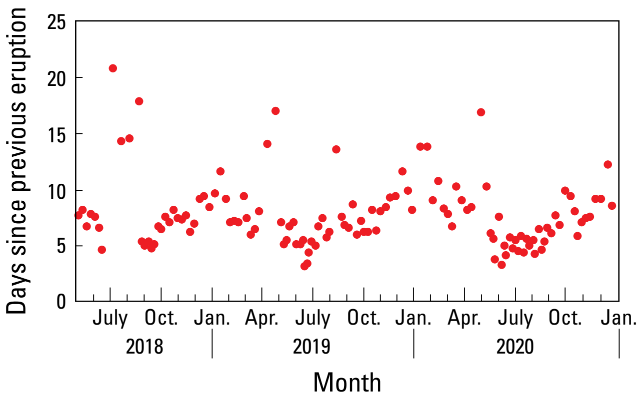


Figure 27. Plot showing the time between eruptions of Steamboat Geyser from May 2018 to December 2020. The time is longer in the winter and shorter in the summer, perhaps reflecting greater groundwater abundance owing to seasonal snowmelt in the warmer months.

YVO used three indicators to detect eruptions of Steamboat Geyser: (1) increased seismic noise recorded at a seismometer located in the Norris Museum, about 300 meters (1,000 feet) from the geyser, (2) a spike in temperature recorded on the sensor in the geyser's outflow channel, and (3) a spike in discharge recorded at the Tantalus Creek streamgage, through which all water from Norris Geyser Basin hydrothermal features passes. All these data are freely available on the YVO website, accessible at https://volcanoes.usgs.gov/volcanoes/yellowstone/monitoring_map.html.

Giantess Geyser

Just after 9 a.m. Mountain Daylight Time on August 26, Giantess Geyser, located on Geyser Hill not far from Old Faithful in the Upper Geyser Basin, erupted for the first time in 6 years (fig. 28). Giantess Geyser was named by the 1870 Washburn-Langford-Doane expedition to Yellowstone, which noted the beauty of the eruptions. For decades, the geyser experienced violent but infrequent eruptions two to six times each year. After 2011, however, the geyser was dormant for more than 2 years—the longest known period of dormancy to that point—before erupting in January 2014. The geyser then went to sleep once again until 2020.

The August 26 eruption began with violent water and steam jetting, with the water pulsating 5–10 meters (16–32 feet) high and the steam reaching 50–60 meters (160–200 feet) high. Over the next several hours, the eruption transitioned repeatedly between violent water and steam activity to gentler steam- or water-only eruptions. The eruption persisted for 2 days. A second eruption of 2020 started on the afternoon of September 10 and lasted for over a day. It remains to be seen whether this activity marks a return to more frequent activity of Giantess Geyser.

Figure 28. Photograph of Giantess Geyser in eruption at approximately 10:00 a.m. Mountain Daylight Time on August 26, 2020. Old Faithful is erupting in the center background. National Park Service photograph by Stan Mordensky.

Echinus Geyser

Echinus Geyser, named for its spiny appearance that resembles a sea urchin (class Echinoidea), is located in the Norris Geyser Basin. Prior to 1998, the geyser erupted every 35–75 minutes on average, but late that year eruptions became infrequent and unpredictable. The geyser occasionally experienced spates of activity, as in late 2017, when it erupted repeatedly about every 2 hours for more than a month (see 2017 YVO annual report).

Before 2020, the last known eruption of Echinus Geyser was in January 2019. In December 2020, the Norris temperature monitoring network (see sidebar on monitoring thermal changes on p. 34–35) recorded four eruptions as sudden increases and then drops in water temperature before returning to background levels (fig. 29). The temperature changes were confirmed to be geyser eruptions by Yellowstone National Park trail cameras that recorded the events. These eruptions would not have been known without the Norris temperature monitoring network and trail cameras, given that the region is poorly accessible in winter months owing to heavy snow.

Thermal Feature in Southwest Yellowstone Goes Dry

In May 2020, a routine National Park Service fire surveillance flight noted that a hot-spring pool along the Ferris Fork of the Bechler River in the southwest part of Yellowstone National Park had dried up. The feature is along a trail and well known to hikers because of the large amount of water it discharges into the river. In 2018, the site was visited by USGS and Yellowstone National Park scientists (fig. 12). Satellite imagery indicates that the feature was still active as of July 2019 but had dried up by July 2020 (fig. 30). It is unclear when or why the feature dried up. There is no record of any previous episode of drying, although the spring's remote location means that observations are limited. YVO scientists will keep track of this feature in the months and years to come using satellite, airborne, and in-person observations to document any further changes in activity.

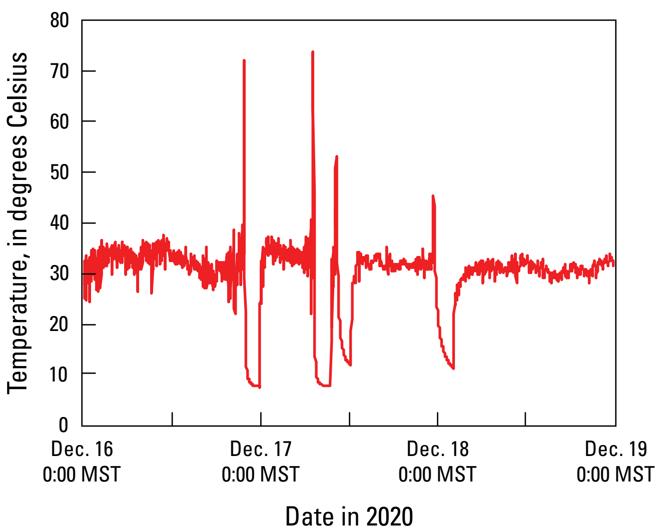


Figure 29. Temperature record for Echinus Geyser in mid-December 2020 showing evidence of four eruptions. MST, Mountain Standard Time.

Hydrothermal Feature Survey

Over the 2020 field season, the Yellowstone National Park Geology Program continued its multi-year effort to visit and document every hydrothermal feature in the park, building on a previous survey completed during 1998–2007. In 2018–2019, the hydrothermal feature inventory project documented more than

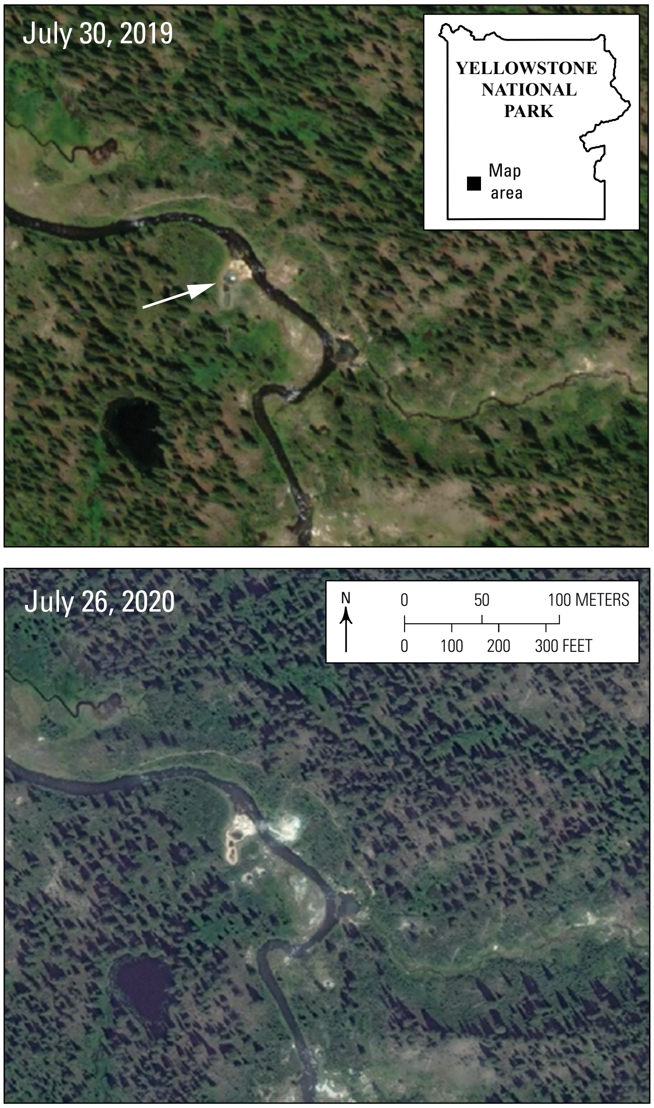


Figure 30. WorldView-2 satellite imagery from July 30, 2019 (left), and July 26, 2020 (right), showing a thermal feature on the Ferris Fork of the Bechler River (fig. 12) in southwest Yellowstone National Park. The feature (indicated by white arrow) is clearly bubbling in the center of the pool and discharging water into the river in the 2019 image but is mostly dry in the 2020 image. WorldView-2 imagery reproduced in accordance with a NextView end user license agreement with Maxar (formerly DigitalGlobe).

1,100 features in the Norris Geyser Basin south of the Gibbon River, as compared to 493 in the previous inventory. This does not reflect an increase in the number of thermal features, but rather a change in inventory protocol—specifically, the types of features that were included in the inventory. Smaller features not included or grouped with other features during the first survey have been classified as separate features in the second survey. Inventory efforts shifted to the Upper Geyser Basin in 2019, where 1,336 features were documented in part of the region compared to 668 features in the same area during the previous inventory project.

During the 2020 field season, the Geology Program continued to focus on the Upper Geyser Basin documenting an additional 698 hydrothermal features and bringing the total inventory in the Upper Geyser Basin to more than 2,000. Work in the Upper Geyser Basin, delayed in 2020 owing to the COVID-19 pandemic, is expected to be completed in 2021.

The new inventory will support the Yellowstone National Park's mission to preserve and protect natural resources for the enjoyment and education of present and future generations. It will also provide a more detailed baseline against which future changes can be compared.

In addition to the park-wide inventory, Yellowstone National Park scientists are conducting monthly assessments of 22 individual thermal features, including, for example, Dragons Mouth Spring in the Mud Volcano area, Morning Glory Pool in the Upper Geyser Basin, Cistern Spring in Norris Geyser Basin, and Excelsior Geyser in Midway Geyser Basin. This indexing program involves collecting monthly measurements of pH, conductivity, and temperature, as well as acquiring thermal imagery. Comparison of how these parameters change over time could be useful in identifying variations in hydrothermal activity in various parts of Yellowstone National Park. Yellowstone National Park scientists, in collaboration with the Geyser Observation and Study Association, also maintain a network of nearly 100 temperature logging instruments installed at features throughout the park. Special deployments of temperature logging instruments in 2020 included thermal features of the Heart Lake and Shoshone Geyser Basins.

Geyser Activity Since the Last Ice Age

Prior to about 15,000 years ago, Yellowstone was covered by a thick ice cap that likely scoured away any older geyser deposits. It has therefore been assumed that the physical forms of Yellowstone's geysers grew since the glaciers retreated. Until recently, this had not been confirmed because it is difficult to date geyser deposits.

In April 2018, November 2018, and April 2019, USGS scientists collected sinter samples from Castle and Giant Geysers (fig. 31) in the Upper Geyser Basin. The sinter was then dissolved in the laboratory, and organic material residue was extracted for radiocarbon dating—a technique that uses the decay of the radioactive isotope of carbon (^{14}C) to determine ages. Results were surprising. The ^{14}C ages calculated for the samples did not coincide with their stratigraphic position in the geyser structure. Some of the oldest apparent ^{14}C ages were found at the top of the cone, where sinter formed most recently, and young ^{14}C ages were found in layers at the base of the geyser, where deposits are likely to be oldest. This unexpected result suggests that the organic material that is trapped in the sinter was derived either from material blown in by the wind, such as pollen or needles from nearby trees, or from microbial mats (thermophile bacteria) that grew on the sinter. These microbes incorporate carbon not only from the atmosphere but also from water erupted from the geysers—water that has many sources with variable amounts of ^{14}C. As a result, the ^{14}C-derived ages do not accurately reflect how long ago the microbes died.

Other methods proved equally challenging. One example is the uranium-thorium disequilibrium method, which is based on the isotopic compositions of radioactive uranium and thorium incorporated in the opal that makes up the sinter. Unfortunately,

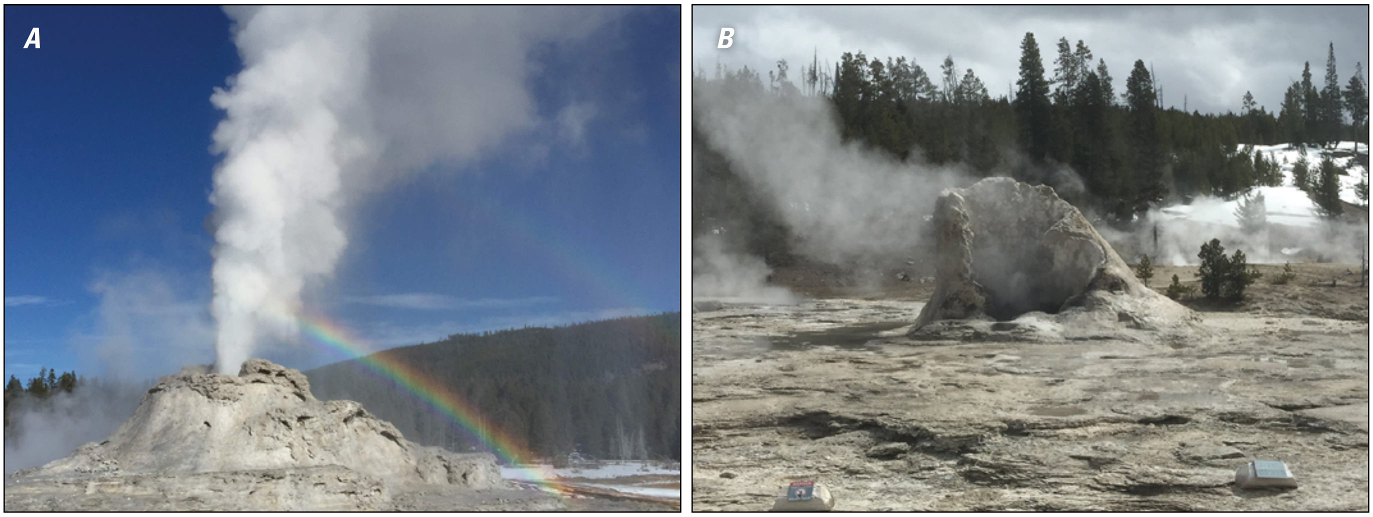


Figure 31. Photographs of Castle (*A*) and Giant (*B*) Geysers, from which sinter samples were collected in an attempt to date the geyser cones. U.S. Geological Survey photographs by Shaul Hurwitz on November 5, 2019 (Castle Geyser), and April 15, 2018 (Giant Geyser).

the sinter collected from the geysers contained very low uranium concentrations and elevated thorium concentrations that yielded post-glacial ages between 2,200 and 7,400 years old but with large uncertainties that limit the utility of the resulting dates. Cosmogenic exposure dating was also attempted, but the concentrations of the radioactive isotope beryllium-10 (^{10}Be) measured in the sinter indicated that contamination from past rainwater strongly influenced concentrations in the opal, rendering the resulting dates unreliable.

Dating of specific geyser cones has proven to be an exceptional challenge, and to this point it can only be concluded that Yellowstone's large geysers indeed formed after glaciers receded from the caldera about 15,000 years ago, and that it takes thousands of years to construct the large geyser cones. Future work will focus on attempting new dating methods to refine the understanding of geyser cone development over time.

A Dormant Period for Old Faithful

Old Faithful Geyser has been reliably active since it was first described by scientists and explorers in the 1800s. But there is evidence that the geyser was not always so faithful. Embedded in the geyser mound are mineralized trees—lodgepole pines of the sort that currently dominate nearly 80 percent of the total forested area in Yellowstone National Park. Because lodgepole pine trees do not grow on active geyser mounds, their presence suggests that there was a time when Old Faithful Geyser did not erupt—providing enough time for the trees to grow and thrive. Samples collected from these mineralized wood specimens were dated using the radiocarbon method. All analyses produced similar ages that represent a total of about 130 years, indicating that the lodgepole pine trees grew on the geyser mound in the 13th and 14th centuries (1233–1362 C.E.).

In the Yellowstone region, climate reconstructions based on tree ring records have shown that a severe and sustained drought occurred in the mid-13th century, coinciding with the onset of tree growth on the Old Faithful Geyser mound. This relation suggests that the pause in Old Faithful eruptions during the 13th and 14th centuries was related to diminished precipitation and groundwater supply to the geyser for several decades. The severe 13th century drought had significant effects well beyond Old Faithful Geyser. In fact, severe and persistent droughts affected large parts of the United States and had a tremendous effect on indigenous peoples (for example, see Benson and others, 2007).

It was initially a mystery as to why such old trees were preserved on the geyser mound, since lodgepole pines usually decompose completely within 300 years in Yellowstone's nonthermal areas. YVO scientists surmise that wood from the lodgepole pines was preserved for over 650 years on the geyser mound because it was near-continuously wetted by the alkaline, silica-rich thermal waters erupted from geysers. These waters deposit the mineral opal on tree stems and wood tissues, which prevents the disintegration of cellulose by fungi, bacteria, and insects—it causes silicification, or mineralization, of the wood! This silicification process can be rapid and take only days or weeks.

Because climate models forecast increasingly severe regional droughts by the mid-21st century, results from this study suggest that geyser eruptions could become less frequent in the future. Indeed, periods of decreased precipitation have been shown in modern times to result in less frequent eruptions of Old Faithful Geyser, and the new research indicates that severe, long-duration droughts could terminate eruptions altogether for decades. For now, however, Old Faithful remains just that—faithful—with eruptions occurring about every 90 minutes.

Communications and Outreach

Because of the COVID-19 pandemic, in-person outreach activities were severely limited. On January 15, YVO Scientist-in-Charge Mike Poland presented a talk entitled "The Yellowstone Volcano: News from the Front" at the Museum of the Rockies in Bozeman, Montana, and he presented a seminar to the Montana State University Department of Earth Sciences the following day.

Most outreach efforts in 2020 were necessarily remote or virtual. YVO continued to produce products that have now become traditional, including monthly video updates of activity (posted on "USGSVolcanoes" Facebook and Twitter pages, the USGS YouTube channel, and the multimedia section of the YVO website) and weekly Yellowstone Caldera Chronicles articles, which are posted to social media pages and published by a number of regional news outlets. YVO also published two long-format videos, one about Yellowstone deformation and how it is measured and another about how YVO monitors activity in Yellowstone, with some examples of recent discoveries. Both videos are available via the USGS YouTube page as well as the multimedia section of the YVO website. In addition, several YVO scientists contributed expertise to planned upgrades to visitor center displays in Yellowstone National Park.

The most noteworthy social media engagement of the year was in the aftermath of the March 31 magnitude 6.5 central Idaho earthquake. As with the magnitude 7.1 Ridgecrest, California, earthquake the year before, the Idaho earthquake, and to a lesser extent the Magna, Utah, magnitude 5.7 earthquake on March 18, generated concern that Yellowstone might be jarred into eruption. YVO scientists responded by answering questions and proactively addressing misinformation, as well as by writing a Yellowstone Caldera Chronicles article on the topic of Basin and Range earthquakes of the sort typified by the Utah and Idaho events. These types of earthquakes are common in the western United States, and future such events will no doubt generate similar levels of interest and misinformation, but YVO articles are now in place to answer frequently asked questions in these situations.

Online Geology of Yellowstone Map

There is an impressive array of geologic data available for the Yellowstone area—earthquake locations, rock units, topography, geochemical sample sites, hydrology, and more. For the most part, this information has been hosted on different websites maintained by different institutions. That all changed in 2020 when the Wyoming State Geological Survey (WSGS) launched the Geology of Yellowstone Map—effectively a one-stop shop for digitally exploring Yellowstone's unique geological landscape (fig. 32). The map can be accessed via the WSGS homepage (https://www.wsgs.wyo.gov) under the "interactive maps" panel.

Traditionally, anyone wishing to access geology-related geospatial data for Yellowstone had to search online, download, and view these datasets individually. This can be time consuming when dealing with multiple datasets from different sources and requires access to specialized geographic information system software. The new online map, however, allows users to easily view all these datasets via a simple web interface. The only thing that is needed is an internet connection.

To develop the map, the WSGS compiled openly available geospatial data from YVO partners and other external sources into an ArcGIS geodatabase. Data were minimally modified to achieve consistency in the database (for example, clipped to spatial extent, projected into a common coordinate system, given consistent attribute field names) but were otherwise unchanged from the original sources. Each dataset was placed into a group, formatted, symbolized, and published to ArcGIS Online. The result is a publicly accessible web map that contains more than 100 distinct layers.

Data displayed in the Geology of Yellowstone Map include bedrock and surficial geology, monitoring stations, thermal features, water resources, topography, geologic hazards, and basic orientation information. Inside the map, users can toggle layers on and off, interactively pan and zoom to areas of interest, search for specific locations, and open attribute tables to view the data in tabular form. Clicking on a feature leads to a pop-up window with additional attribute data and web links. Menus on the map provide an explanation of each layer and a reference to the original data source—helpful for users who want to download the data for themselves or learn more about geologic research in Yellowstone.

After its initial release in May, the Geology of Yellowstone Map was updated in December 2020 with new datasets that showcase additional monitoring stations and recently revised thermal feature locations. Going forward, the WSGS plans to continue updating the map as new studies are published and more data are released.

Summary

As was the case for 2018 and 2019, perhaps the most spectacular activity in Yellowstone during 2020 was the continued sequence of major water eruptions at Steamboat Geyser, which equaled the record set in 2019 for the greatest number of eruptions (48) in a calendar year. This episodic activity is typical of many geysers in Yellowstone, as demonstrated once again in 2020, when Giantess Geyser had its first eruptions in 6 years and Echinus Geyser experienced four eruptions in December 2020 after nearly 2 years of quiescence. On the other hand, Giant Geyser, which experienced a series of eruptions during mid 2017 through early 2019, did not erupt at all in 2020, having apparently gone back to sleep, and a well-known feature along the Ferris Fork of the Bechler River in the southwest part of Yellowstone National Park went dry. Yellowstone geysers are nothing if not dynamic. Other monitoring techniques also indicated background levels of activity. The number of located earthquakes, 1,722, was greater than that recorded in 2019 (1,217 located events) but was still well within the average range of annual located events and less than the numbers located in 2018 (2,007) and 2017 (3,427). GPS data indicated no significant deformation at Norris Geyser Basin

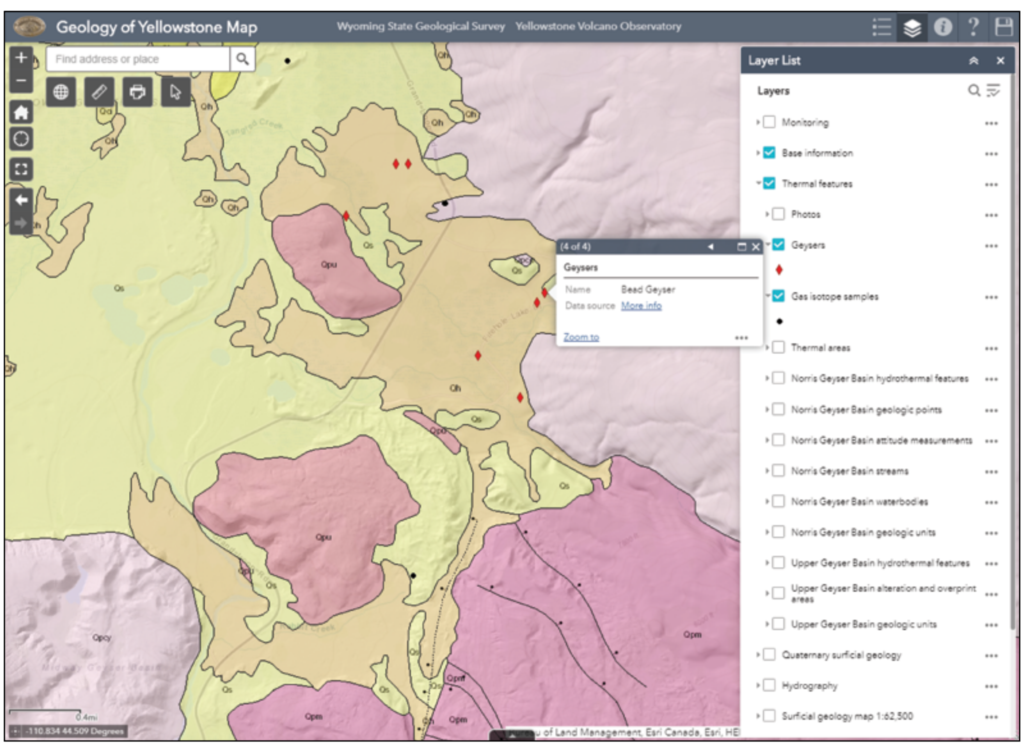


Figure 32. Screen capture of the Geology of Yellowstone Map by the Wyoming State Geological Survey. This display, which is zoomed in on the Lower Geyser Basin, shows a geologic map overlaid on a shaded-relief layer that was created from a digital elevation model. Red diamonds and black circles denote geysers and gas sample locations, respectively.

throughout the year, and Yellowstone Caldera continued to subside at rates of a few centimeters per year, as it has since 2015. Gas and thermal emissions measured north of the Norris Geyser Basin have been steady over the past several years, and heat flux estimates from both satellite imagery and river chemistry indicate no major changes with respect to previous years.

The COVID-19 pandemic severely restricted field work in 2020, although critical equipment maintenance and deployments and several scientific studies were still conducted. The deployment of hundreds of temporary seismic stations in August–September 2020 will provide a high-resolution image of the upper portion of the mostly solid magma reservoir beneath Yellowstone Caldera. Mapping efforts also continued, focusing on better understanding the age and history of hydrothermal explosion craters in the Lower Geyser Basin and on correcting boundary mismatches on geologic maps of different scales and vintages to produce a standardized geological map of the entire park. Much scientific work, however, was done in the office or laboratory, analyzing previously collected data. This included a diverse array of studies of the floor of Yellowstone Lake and explorations of hydrothermal activity in various areas of Yellowstone National Park—including at Old Faithful, where a period of inactivity about 800–650 years ago was documented. New research results will be highlighted in future editions of YVO's weekly series of online articles, Yellowstone Caldera Chronicles, which can be accessed at https://www.usgs.gov/volcanoes/yellowstone/caldera-chronicles, as well as in annual reports, monthly updates and videos, and public presentations.

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