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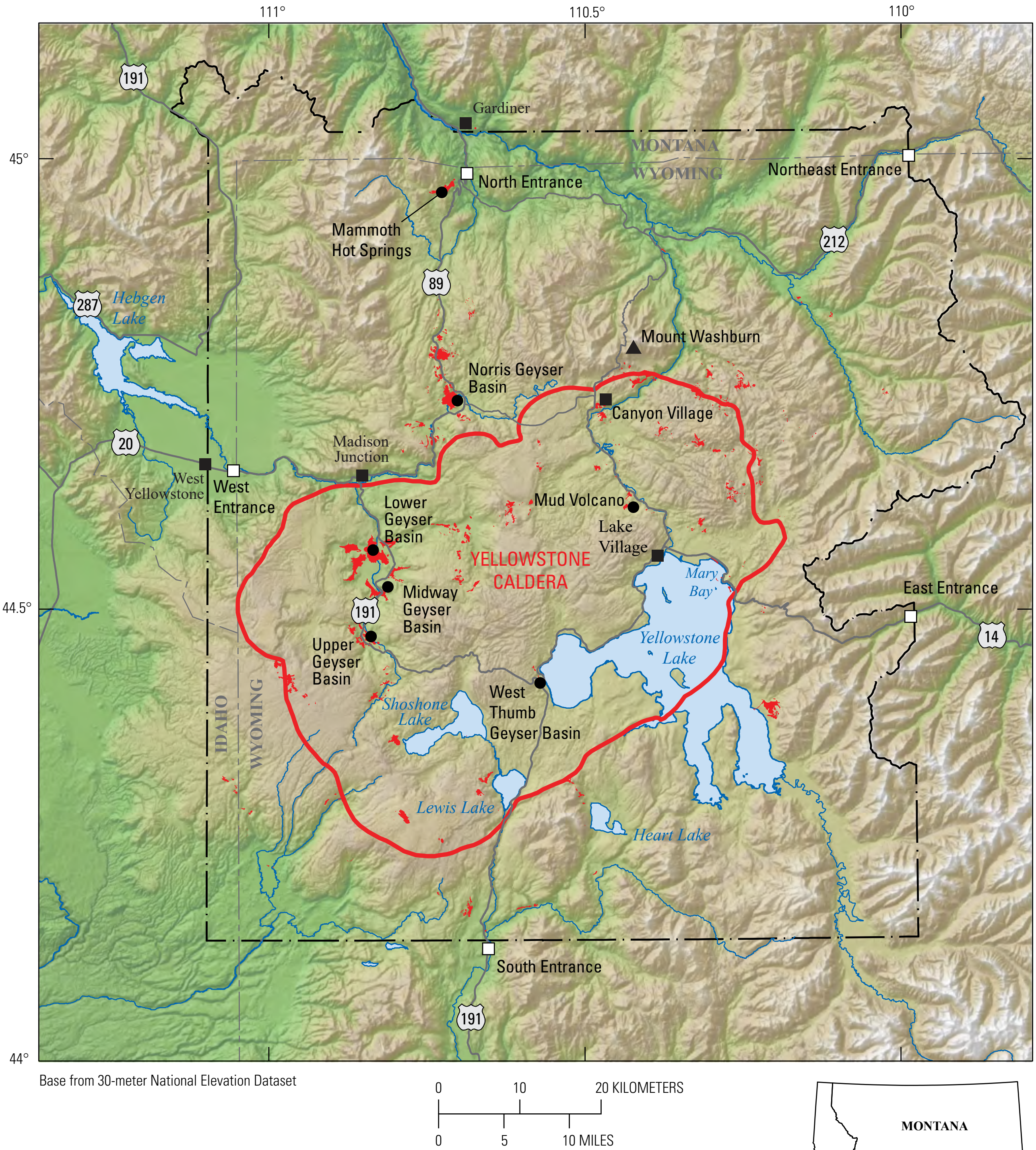
Yellowstone Volcano Observatory

2022 Annual Report

Circular 1508

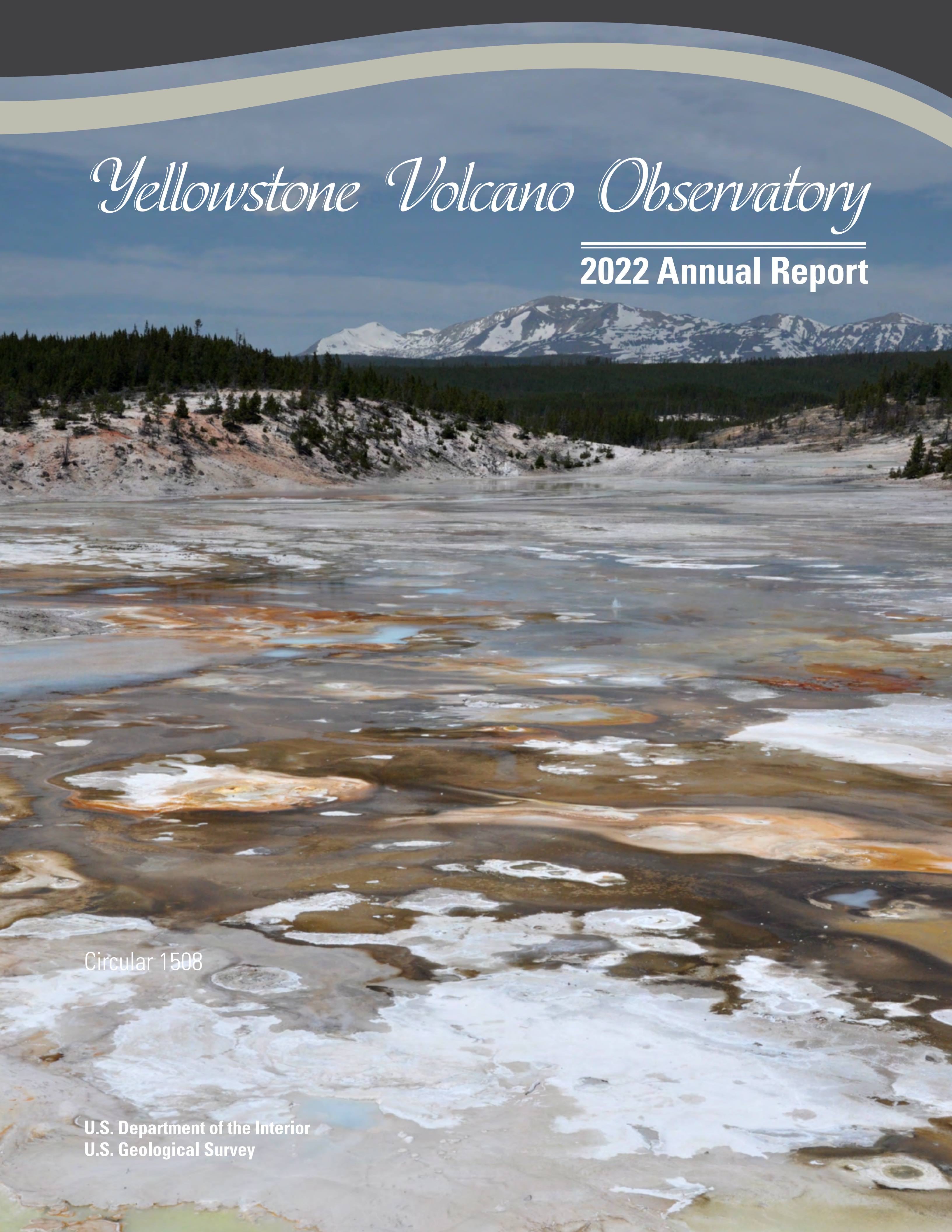
U.S. Department of the Interior
U.S. Geological Survey



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

Cover. Photograph of Silex spring, Yellowstone National Park, under the night sky by Mike Ver Sprill on Shutterstock.

Facing page. Photograph of Porcelain Basin, in Norris Geyser Basin, with Mount Holmes and the Gallatin Range in the distance. By Michael Poland, U.S. Geological Survey, May 31, 2020.



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U.S. Geological Survey, Reston, Virginia: 2023

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Bison grazing in the meadow along the Firehole River, Upper Geyser Basin; Castle Geyser erupting in the distance. Photograph by Michael Poland, U.S. Geological Survey, May 14, 2021.

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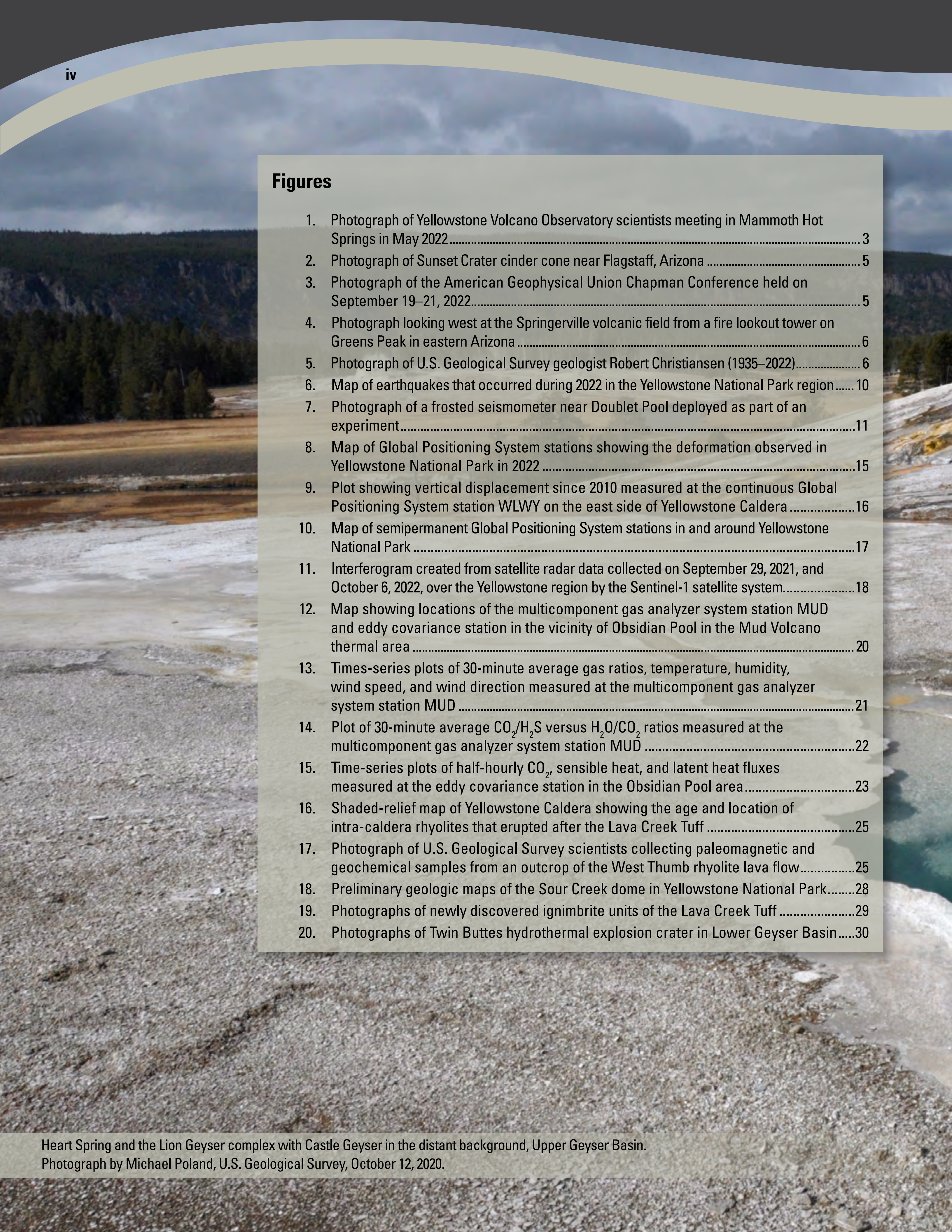

Heart Spring and the Lion Geyser complex with Castle Geyser in the distant background, Upper Geyser Basin. Photograph by Michael Poland, U.S. Geological Survey, October 12, 2020.

Sidebars

Photograph of waterfall in Midway Geyser Basin, Yellowstone National Park., by Oscity on Shutterstock.

Scan here to watch a USGS Public Lecture from November 2021 on common misconceptions about Yellowstone volcanism

Yellowstone Volcano Observatory

2022 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, carries out 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 formed by the U.S. Geological Survey (USGS), Yellowstone National Park, University of Utah, University of Wyoming, Montana State University, EarthScope Consortium,[2] Wyoming State Geological Survey, Montana Bureau of Mines and Geology, and Idaho Geological Survey (see sidebar on YVO on p. 4). The USGS component 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 2022, focusing on the Yellowstone volcanic system. Highlights of YVO research and related activities during 2022 include

- Deployments of seismometers in Norris Geyser Basin and Upper Geyser Basin to investigate interactions between hydrothermal features and influences from external influences, like seismicity and weather,
- Geological studies of post-glacial hydrothermal activity, including explosions in Lower Geyser Basin,
- Refining the ages of Yellowstone volcanic units and updating existing maps of geologic deposits,
- New mapping of ash-flow deposits on the Sour Creek dome, which indicates the eruption that resulted in the formation of Yellowstone Caldera was more complex than previously thought,
- Installation of a new continuous gas monitoring station near Mud Volcano to complement an existing monitoring site in the same location,
- Sampling of gas emissions and thermal waters around Yellowstone National Park to monitor water chemistry over space and time, including from the new thermal area near Tern Lake,
- Research into the age and history of Steamboat Geyser in Norris Geyser Basin, and
- Assessment of thermal output based on satellite imagery and chloride flux in rivers.

The most noteworthy event of the year was not geophysical, but meteorological. Late-season snowfall and cooler than normal spring temperatures allowed for substantial amounts of snow to remain on the ground in Yellowstone National Park into the early summer. During June 10–13, an atmospheric river event caused several inches of rain to fall in the Yellowstone region, resulting in rapid melting of the accumulated snow. The combined runoff from rain and snowmelt caused flooding of a magnitude that is unprecedented in the past century and was especially devastating to the northern part of Yellowstone National Park. The flooding did not affect YVO monitoring stations (one river chemistry monitoring station on the Gardner River was buried by debris; see "Chloride Flux Monitoring" section) but caused substantial damage to park roads and infrastructure. Yellowstone National Park geologists led the effort to acquire light detecting and ranging (lidar) data from areas that were most heavily affected by the flooding. Comparison of these new data to those collected in 2020 will provide an effective tool for calculating landform change volumes in areas affected by the floods.

Steamboat Geyser, in Norris Geyser Basin, continued the pattern of frequent eruptions that began in 2018 with 11 water eruptions in 2022, the lowest number of annual eruptions in the current eruptive sequence (compared to 32 in 2018, 48 each in 2019 and 2020, and 20 in 2021). The episodic activity at Steamboat Geyser is typical for Yellowstone National Park hydrothermal systems, where many geysers experience alternating periods of frequent and infrequent eruptions.

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[1]This report was prepared jointly by members of the Yellowstone Volcano Observatory consortium, including Michael Poland, Laura Clor, Daniel Dzurisin, 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 of the National Park Service, Jamie Farrell of the University of Utah, Ken Sims of the University of Wyoming, and Madison Myers and Ray Salazar of Montana State University. Liz Westby and David Phillips of the U.S. Geological Survey reviewed the report.

[2]On January 1, 2023, UNAVCO, one of the members of the YVO consortium, merged with the Integrated Research Institutions for Seismology (IRIS) to become the EarthScope Consortium, which continues operation of the National Science Foundation's Geodetic Facility for the Advancement of Geoscience.

SIDEBAR

Volcanic Hazards in the Yellowstone Region

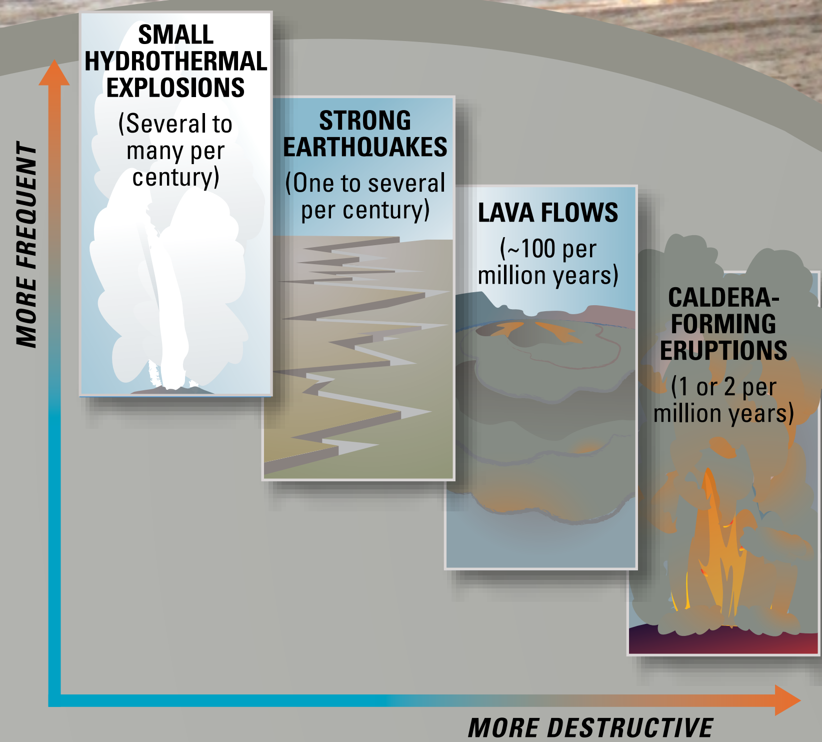
The Yellowstone Plateau in the northern Rocky Mountains of Wyoming, Montana, and Idaho is centered on a youthful, active volcanic system with subterranean magma (molten rock), boiling and pressurized waters, and a variety of active faults. This combination creates a diversity of hazards, but the most catastrophic events—large volcanic explosions—are 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 region 16,000–13,000 years ago. Much smaller explosions, which leave craters only a few meters (yards) across, happen every few years in the Yellowstone region.

Castle Geyser, Upper Geyser Basin, in eruption. Photograph by Michael Poland, U.S. Geological Survey, May 14, 2021.



The most destructive hazards in the Yellowstone region, 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).

Patterns of both seismicity and deformation in 2022 were similar to those in 2021. Total seismicity—2,429 located earthquakes—was slightly less than the 2,773 earthquakes located in 2021 and at the upper end of the historical average range of about 1,500–2,500 earthquakes per year. Deformation patterns during 2022 showed trends that continued from 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, whereas no significant deformation was detected in the Norris Geyser Basin area. Satellite deformation measurements indicated the possibility of slight uplift amounting to about 1 centimeter (less than 1 inch) along the north caldera rim, south of Norris Geyser Basin, in 2021 (similar to deformation that occurred in the late 1990s), but satellite data spanning 2022 show no uplift in that area.

Throughout 2022, the aviation color code for Yellowstone Caldera remained at "green" and the volcano alert level remained at "normal."

YVO Activities

YVO had a busy year in 2022, thanks to the easing of the Coronavirus Disease 2019 (COVID-19) pandemic. YVO scientists participated in in-person and virtual scientific meetings as well as simulations of volcanic activity meant to help with planning for future eruption responses. Unfortunately, the year also marked the passing of an icon in geologic studies of the Yellowstone region and the first Scientist-in-Charge of the Yellowstone Volcano Observatory, Robert Christiansen.

YVO Research and Coordination Meetings

After 2 years of delays owing to the COVID-19 pandemic, YVO finally held an in-person coordination meeting in Mammoth Hot Springs during May 11–13, 2022. These meetings typically take place every 2 years, but because the pandemic forced the cancelation of the 2020 meeting, the most recent previous coordination meeting was in 2018 (see the 2018 YVO annual report [YVO, 2021a], available at https://doi.org/10.3133/cir1474). More than 40 attendees, representing nearly all the YVO member agencies, participated in the meeting. The first day of the gathering—which coincided with a magnitude-4.2 earthquake, the largest in Yellowstone National Park since 2017 (see "Seismology" section)—provided an opportunity to discuss science and monitoring results from the preceding 4 years, including the outcomes of seismic deployments, geologic mapping and age dating, investigations of hydrothermal processes, research into hydrothermal explosions, and studies of thermal output from the Yellowstone region. On the second day, YVO conducted a tabletop exercise that simulated a volcanic crisis in Yellowstone National Park (fig. 1). The purpose of the exercise was to practice and update YVO's response plan for geological events (YVO, 2014). The third and final day of the meeting provided an opportunity to debrief the tabletop exercise and discuss how YVO's procedures could be improved, with the goal of outlining a revised response plan. Also, while so many YVO scientists were gathered in the same place, a public event was held in Gardiner, Montana, with more than 50 members of the community attending to hear updates about recent Yellowstone research and monitoring results, as well as to interact individually with scientists from different YVO institutions and fields of expertise (see "Communications and Outreach" section).

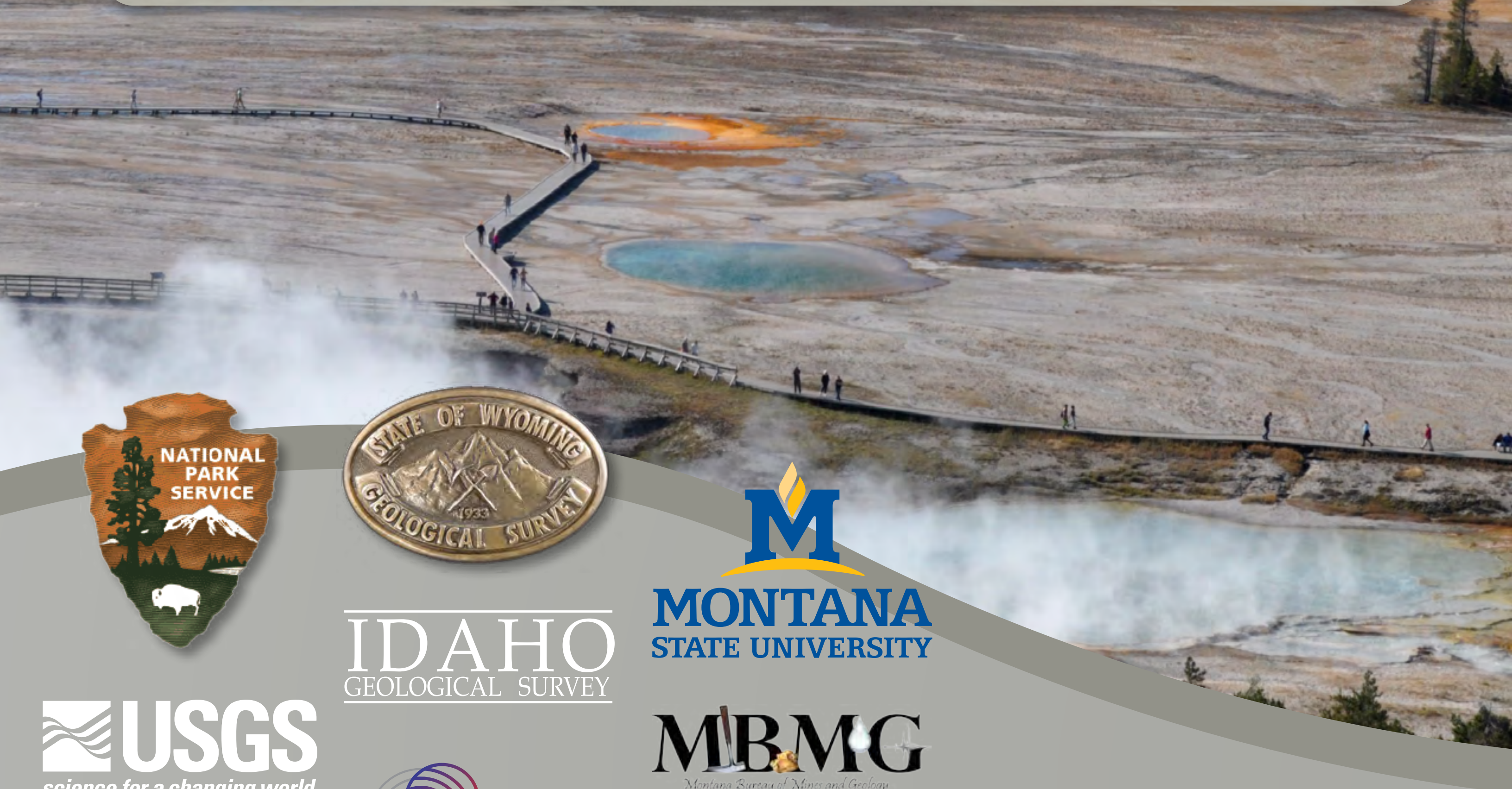
Figure 1. Photograph of Yellowstone Volcano Observatory scientists meeting in Mammoth Hot Springs in May 2022 to discuss the protocols for responding to a geologic event in Yellowstone National Park. Photograph by Scott Johnson, EarthScope Consortium, May 12, 2022.

SIDEBAR

What is the Yellowstone Volcano Observatory?

The Yellowstone Volcano Observatory (YVO) was formed on May 14, 2001, to strengthen the long-term monitoring of volcanic and seismic unrest in the Yellowstone National Park region. YVO is a virtual observatory that does not have an on-site building to house employees. Instead, it is a consortium of nine organizations spread throughout the western United States that collaborate to monitor and study the volcanic and hydrothermal systems of the Yellowstone region, 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 EarthScope Consortium. Scientists from these two organizations analyze and provide data to the public as well as carry out research on active tectonic and volcanic processes in the region. Yellowstone National Park is the land manager and 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 the Yellowstone region'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.



NATIONAL PARK SERVICE

STATE OF WYOMING GEOLOGICAL SURVEY 1933

MONTANA STATE UNIVERSITY

IDAHO GEOLOGICAL SURVEY

USGS science for a changing world

MBMG Montana Bureau of Mines and Geology

EarthScope Consortium

THE UNIVERSITY OF UTAH

UNIVERSITY of WYOMING

Member agencies of the Yellowstone Volcano Observatory.

Turquoise Pool and Opal pool, with Excelsior Geyser in the foreground, Midway Geyser Basin. Photograph by Michael Poland, U.S. Geological Survey, October 7, 2022.

Scan here to watch a video describing YVO

In addition to the coordination meeting, YVO scientists also participated in activities related to the volcanoes of the southwest United States, which fall under YVO's area of responsibility. These volcanoes—a style referred to as "distributed volcanism"—are typified by cinder cones, lava flows, and other volcanic landforms that occur in distinct fields and are found throughout the western United States (fig. 2). During the month of February, USGS scientists affiliated with YVO participated in organizing a virtual tabletop exercise centered on a hypothetical eruption in the San Francisco Volcanic Field located near Flagstaff, Arizona. The scenario involved dozens of volcanologists from the USGS and academic institutions meeting online multiple times each week, and included mock datasets, information statements, and alert level changes posted throughout the month to simulate the onset and development of a real volcanic crisis. The purpose of the exercise was to test plans for enhancing interactions between USGS, which is mandated by the Federal Government to monitor and respond to hazardous volcanic activity in the United States, and non-USGS volcanologists who bring unique perspectives to better understand volcanic activity that may aid USGS scientists and land managers in hazards assessment and mitigation. The emphasis of the tabletop exercise was on communication and coordination between all parties involved in observing, researching, and forecasting volcanic behavior. The San Francisco Volcanic Field was chosen as the subject of the scenario because it is one of the youngest of the many distributed volcanic fields throughout the western United States and is relatively well studied. There is a large population center on its border (the City of Flagstaff), and there will likely be eruptions from the area again. The 1084–87 C.E. eruption of Sunset Crater (fig. 2) was the most recent volcanic event from the San Francisco Volcanic Field, and the eruption affected indigenous people of the region.

Distributed volcanism was also the focus of the American Geophysical Union Chapman Conference on Distributed Volcanism and Distributed Volcanic Hazards, held in Flagstaff during September 19–21, 2022, and co-organized by USGS and academic scientists (fig. 3). The goal of the meeting was to bring together scientists to discuss, develop, and test conceptual models of distributed volcanism—a subject of growing importance given the continuing worldwide growth of cities, communities, and critical infrastructure near and within these sparsely monitored volcanic fields. The 3 days of the meeting provided an opportunity to share research results and strategies, articulate the most important problems that prevent a better understanding of distributed volcanism, and formulate a vision for addressing the hazards posed by distributed volcanic fields. The meeting was followed by a 2-day trip to the Springerville volcanic field (fig. 4), a comprehensively mapped volcanic field in eastern Arizona, to observe directly some of the characteristics of distributed volcanism.

Figure 2. Photograph of Sunset Crater cinder cone near Flagstaff, Arizona. Eruptions between 1084 and 1087 C.E. produced three lava flows that covered 8 square kilometers (3 square miles) and a field of scoria and spatter that covers 2,300 square kilometers (890 square miles). Archeological evidence shows that there were communities of people living in the area who were affected by the eruption. Photograph by Michael Ort, Northern Arizona University, 2015.

Figure 3, Photograph of the American Geophysical Union Chapman Conference on Distributed Volcanism and Distributed Volcanic Hazards, held in Flagstaff, Arizona, during September 19–21, 2022. Attendees from around the world discussed the volcanic processes and hazards associated with distributed volcanic fields, like the San Francisco Volcanic Field just outside the City of Flagstaff, and how knowledge and monitoring gaps might be addressed. Photograph by Michael Poland, U.S. Geological Survey, September 21, 2022.

Figure 4. Photograph looking west at the Springerville volcanic field from a fire lookout tower on Greens Peak in eastern Arizona. Each of the hills in the distance is a cinder cone that marks the site of a past eruption. The most recent eruption in the volcanic field occurred about 300,000 years ago. Photograph by Michael Poland, U.S. Geological Survey, September 22, 2022.

Robert Christiansen (1935–2022)

USGS geologist and founding Scientist-in-Charge of the Yellowstone Volcano Observatory Robert (Bob) Christiansen (fig. 5) passed away on September 15, 2022, in Palo Alto, California. Bob, or Chris, as his colleagues and friends often called him, leaves a legacy of scientific achievement, articulate writing, and a warm and humble personality that endeared him to all. He received his Ph.D. from Stanford University and then began working at the USGS in 1961. He initially worked for 10 years in the Denver, Colorado, office before moving to the Menlo Park, California, office where he worked until his retirement in 2003. He remained an active Scientist Emeritus until his death.

Bob was part of a USGS group that was tasked in 1965 with creating a comprehensive geologic map of the young volcanic rocks in Yellowstone National Park and the surrounding area. The study was funded mainly by the National Aeronautics and Space Administration to create a test area to compare with images captured by satellites from space. Bob and his colleagues tried to understand when and how the volcano erupted, the amount of magma that was vented, and where the resulting ash and lava flows were distributed. From 1966 to 1971, Bob and USGS colleagues spent summer months in the Yellowstone region carrying out field work and mapping. In other times of the year, they analyzed aerial photographs, scrutinized the rocks they sampled, measured the chemical composition of the rocks, and determined their ages. The work lasted long beyond the initial field seasons as Bob and his collaborators worked to understand the complex geologic history of the region.

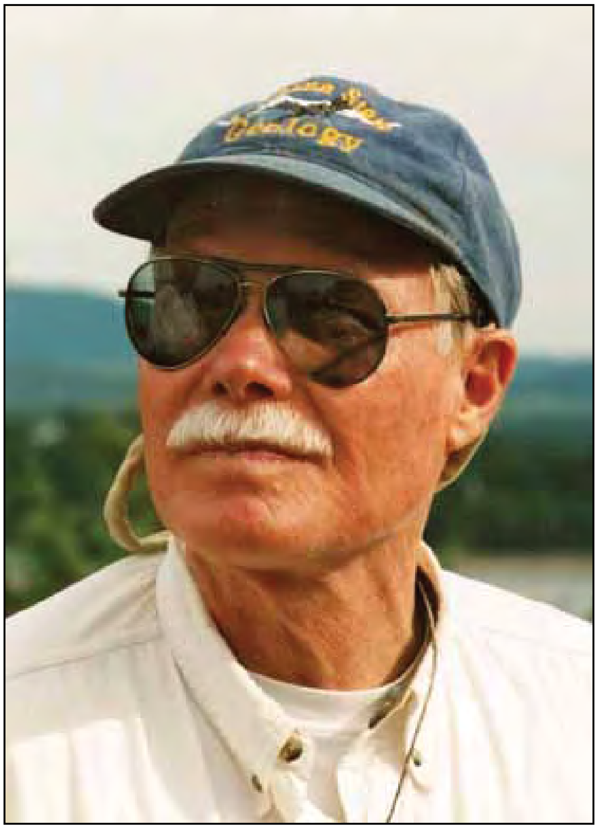


Figure 5. Photograph of U.S. Geological Survey geologist Robert Christiansen (1935–2022). Photograph by Mary Jane Coombs, California Environmental Protection Agency, May 2001.

The results of these monumental efforts were published in a 2001 USGS Professional Paper that is a comprehensive description of the volcanic history of the Yellowstone region and a geologic map of the Yellowstone Plateau (Christiansen, 2001). Bob also led the publication of a 2007 USGS report titled "Preliminary Assessment of Volcanic and Hydrothermal Hazards in Yellowstone National Park and Vicinity" (Christiansen and others, 2007), as well as many other scientific studies that describe other aspects of Yellowstone volcanism, including the chemical and isotopic composition of volcanic rocks and the characteristics of the magma reservoir beneath Yellowstone Caldera.

Although very well known for his work in Yellowstone National Park, Bob also contributed fundamental advances to our understanding of volcanoes throughout the United States, including the volcanism and plate-tectonic evolution of the western United States in the Cenozoic geologic era, explosive eruptions at Kīlauea, Hawai‘i, voluminous and long-lived activity at Mount Shasta in northern California (including a massive collapse about 300,000 years ago), and the 1915 eruption of Lassen Peak in California. In addition, Bob provided leadership of USGS volcanology programs throughout his career. He was the Chief Scientist for monitoring and scientific analysis of the 1980 eruption at Mount St. Helens in Washington, the coordinator of the USGS Geothermal Research Program between 1976 and 1979, and he served as Chief of the USGS Branch of Igneous and Geothermal Processes between 1987 and 1991.

Bob Christiansen will be remembered by his many colleagues and friends as insightful and meticulous in his numerous scientific investigations. His comprehensive research of the Yellowstone volcanic system is the foundation for our current understanding of the volcanic, earthquake, and hydrothermal systems of the Yellowstone region. The lessons Bob learned are now passed on in every evening talk by a Yellowstone National Park Ranger and written in every pamphlet and book on geology handed out in the park visitor centers.

Seismology

Earthquakes have been monitored in the Yellowstone region since the 1970s (see sidebar on seismicity on p. 8–9). 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. 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.

Scan here to view all Yellowstone monitoring sites

Overall Seismicity in 2022

During 2022, the University of Utah Seismograph Stations located 2,429 earthquakes in the Yellowstone region (fig. 6), which is at the upper end of the long-term typical range of earthquakes per year of 1,500–2,500. The total includes 1 magnitude 4 earthquake, 6 magnitude 3 earthquakes, 128 magnitude 2 earthquakes, and 2,294 earthquakes with magnitudes less than 2. Three earthquakes during the year were felt, meaning that people reported some shaking. The largest event of the year was a magnitude 4.2 earthquake, which occurred on the east side of Yellowstone National Park on May 11 at 7:32 a.m. local time.

Of the total number of recorded earthquakes, about 66 percent 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 of time. Swarm activity is common in the Yellowstone region and typically includes about half of all earthquakes that take place in the region. The largest swarm in 2022 included 1,177 events in the area of Grizzly Lake, between Norris Geyser Basin and Mammoth Hot Springs in the northern part of Yellowstone National Park. The swarm began in January and continued throughout the year, waxing and waning several times but with much of the seismicity (more than 500 events) occurring in September. The largest event of the swarm was a magnitude 3.9 earthquake that occurred on September 18.

During the year, in addition to annual maintenance of the Yellowstone Seismic Network, the University of Utah made upgrades to one of the two main data transmission nodes on Mount Washburn. Changes included improvements to the backup power system, which will enable more reliable transmission of seismic data throughout the year.

Seismic Studies of Geyser Systems

In both the spring (April) and fall (November) of 2022, the University of Utah and the University of California, Berkeley, in collaboration with Yellowstone National Park, deployed seismometers in Upper Geyser Basin and Norris Geyser Basin as part of a research project funded by the National Science Foundation. The data were collected under Yellowstone National Park research permit YELL–2022–SCI–8058. The seismic array in the Upper Geyser Basin was focused on four main targets: Old Faithful Geyser, Doublet Pool (fig. 7), Oblong Geyser, and Artemisia Geyser. The deployment in Norris Geyser Basin had two main targets: Steamboat Geyser and Cistern Spring. During both the spring and fall deployments, the instruments recorded continuous seismic data for approximately 1 week and then were removed.

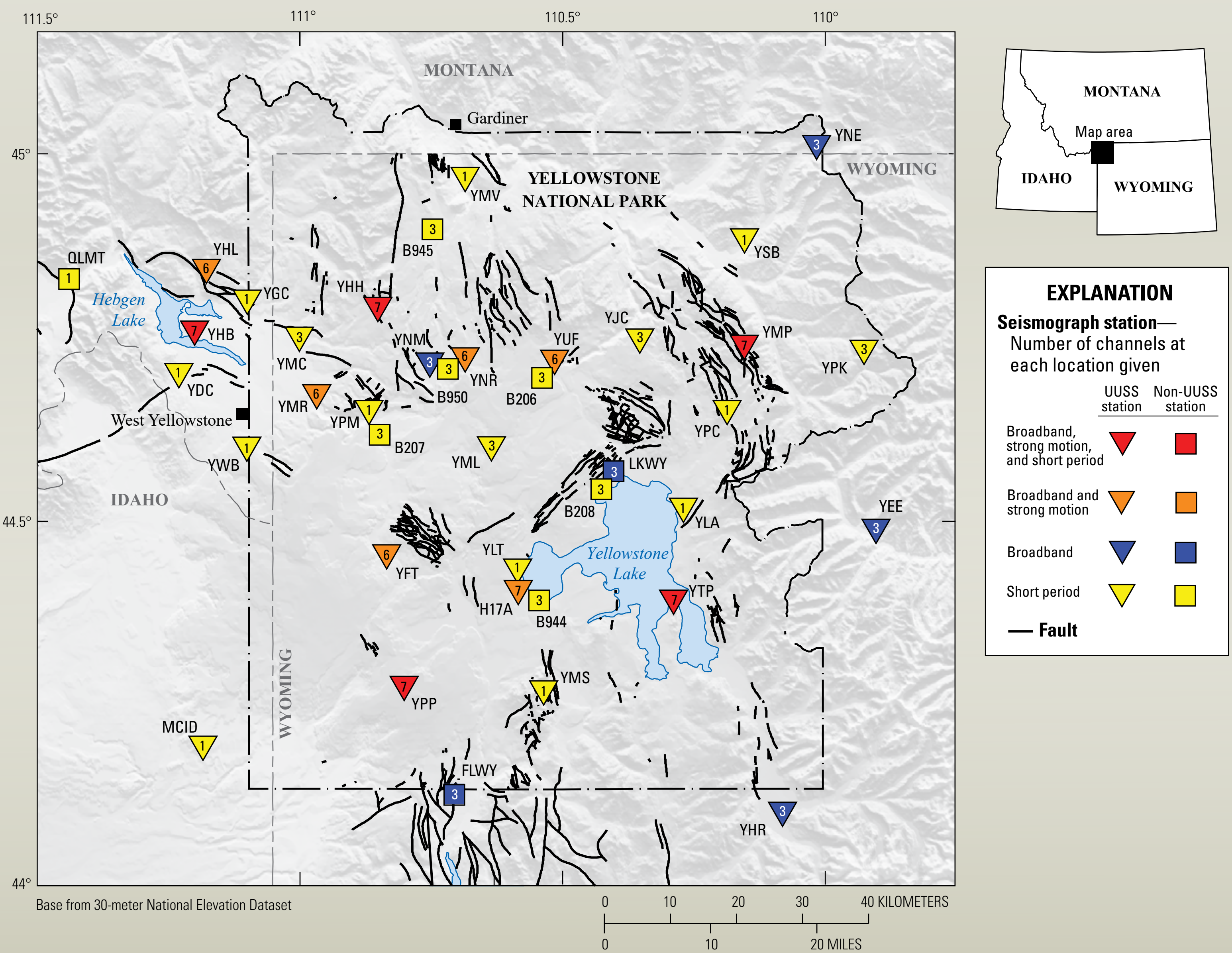
In the Upper Geyser Basin, additional work included deployment of a hydrophone and temperature sensors in the pools, collection of weather data, and measurement of the gas content from Doublet Pool. The purpose of the deployments was to continue the ongoing study of eruptive and non-eruptive

Seismicity in Yellowstone Plateau

Seismicity in the Yellowstone Plateau is monitored by the University of Utah Seismograph Stations. The earthquake monitoring network, known as the Yellowstone Seismic Network, consists of about 46 seismometers installed in the seismically 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 Plateau 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 region 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 when the solar panels or antennas are covered in snow

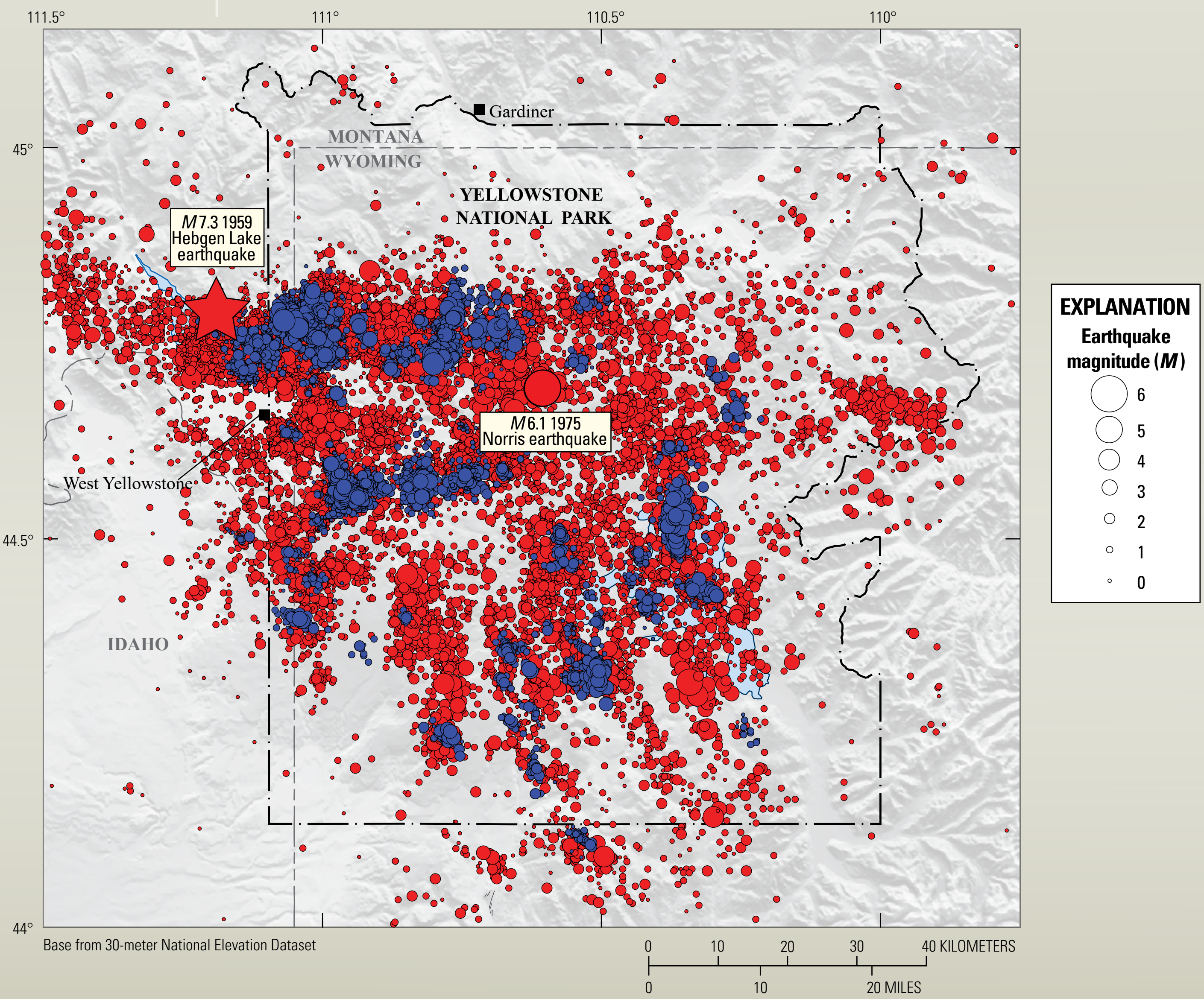


Map of seismometer stations operated by the University of Utah Seismograph Stations (UUSS) and other agencies. Map extent shows the Yellowstone Plateau earthquake catalog region.

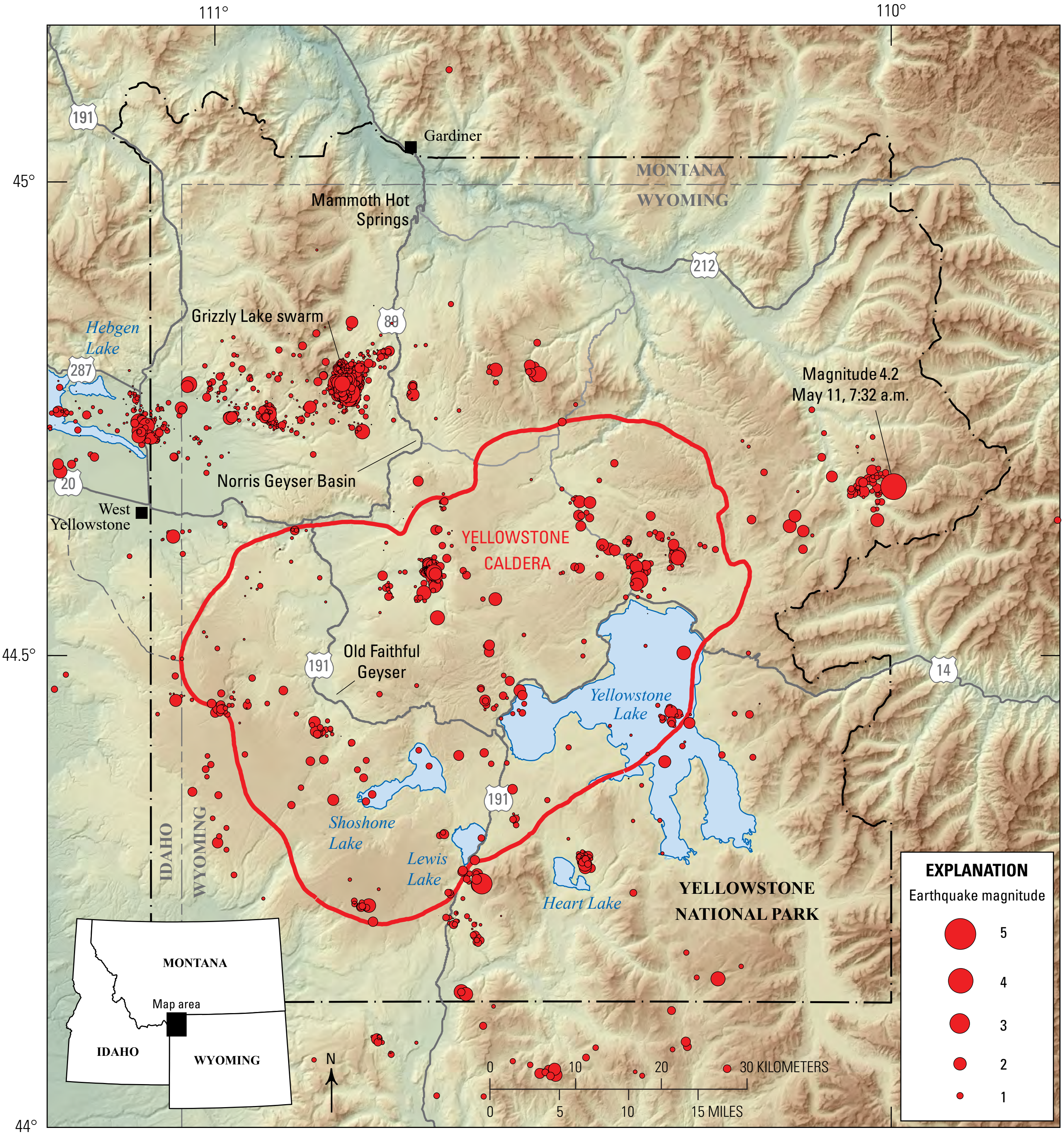
and ice. Sometimes seismometers that go offline during the winter cannot be accessed until the following spring.

Since 1973, there have been more than 58,000 earthquakes located in the Yellowstone region. More than 99 percent of those earthquakes are magnitude 2 or below and are not felt by anyone. 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 2 earthquakes in the magnitude 5 range, 30 earthquakes in the magnitude 4 range, and 410 earthquakes in the magnitude 3 range. The largest earthquake ever recorded in the Yellowstone region 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 consist of short bursts of small-magnitude earthquakes, containing 10–20 events 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 region 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.



Base from 30-meter National Elevation Dataset

Figure 6. Map of earthquakes (red circles) that occurred during 2022 in the Yellowstone National Park region. Circle size is scaled to the magnitude of the earthquake, where larger circles represent stronger earthquakes.

Figure 7. Photograph of a frosted seismometer near Doublet Pool (in the background) deployed as part of an experiment to better understand geyser plumbing systems and interactions between geysers and external forces, like weather and regional seismicity. The seismometer is about the size of a coffee can. Photograph by Mara Reed, University of California, Berkeley, April 2022.

hydrothermal features in Yellowstone National Park—specifically, scientists hope to achieve a better understanding of the difference between erupting and non-erupting features, the interactions between hydrothermal features, and the potential influence of external factors such as weather conditions and seismic activity.

Geodesy

Geodesy is the scientific discipline focused on changes in the shape of Earth's surface, called deformation. In and around Yellowstone Caldera, deformation is caused by a combination of magmatic, tectonic, and hydrothermal processes. Ground motion is measured using networks of GPS[3] 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. 12–14). Changes in Earth's gravity field, which can indicate subsurface mass changes caused by movement of magma or groundwater, for example, are also a subfield of geodesy. Geodetic measurements are used to develop models of the sources of deformation and gravity changes as far as several kilometers (miles) below the surface, which can provide insights into the physical processes responsible for changes measured at the surface.

Overall Deformation in 2022

Ground deformation throughout 2022 resembled that of 2021. Subsidence of Yellowstone Caldera occurred at a rate of 2–3 centimeters (about 1 inch) per year (fig. 8), continuing the trend that, except for a brief period of uplift in 2014–2015, has persisted since 2010. The subsidence is interrupted each summer by a few-month pause, or even a small amount (about 1 centimeter, or 0.4 inch) of uplift (fig. 9), caused by groundwater recharge from snowmelt. In 2021, satellite deformation data suggested uplift of about 1 centimeter (0.4 inch) along the north rim of the caldera to the south of Norris Geyser Basin (see 2021 YVO annual report [YVO, 2022a])—an area that also experienced uplift during 1996–2004. Data from 2022, however, show slight subsidence in this area, indicating that the episode of uplift in this region was brief and small. At Norris Geyser Basin, a period of uplift began in late 2015 or early 2016, stalled in late 2018, and was followed by a minor amount of subsidence that ceased in 2020. There were no significant changes in 2022 (fig. 8).

In 2022, there were five borehole tiltmeters and four borehole strainmeters operating 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 measurements are less useful for determining long-term (months to years) deformation patterns. The tiltmeter and strainmeter networks detected no meaningful changes during 2022.

[3] 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.

SIDEBAR

Monitoring Geodetic Change in the Yellowstone Region

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.

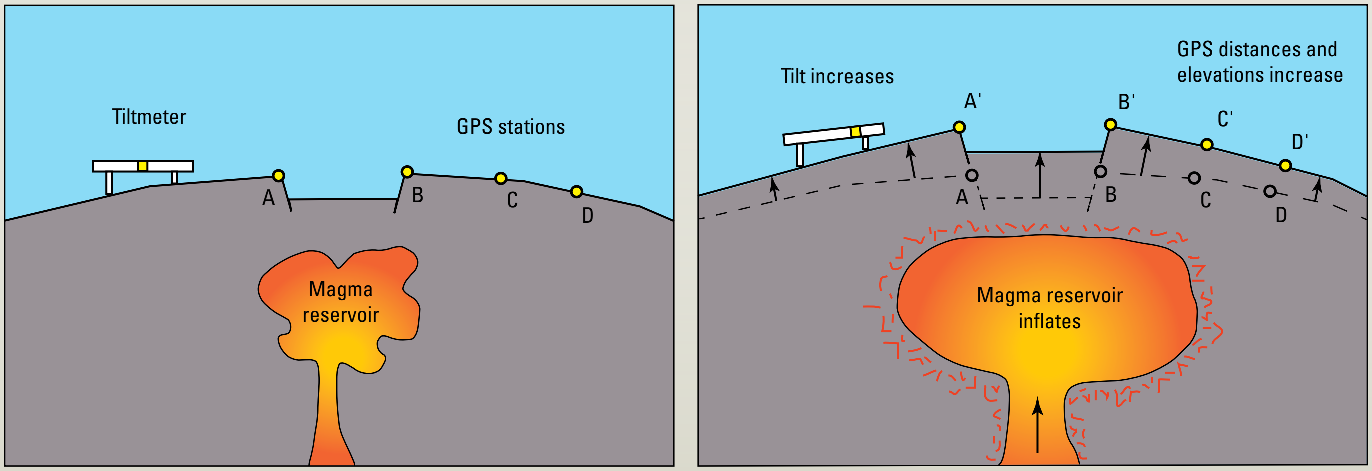
By measuring the pattern and style of surface deformation, it is possible to determine the location of subsurface fluid storage areas. For example, as magma or water accumulates in a reservoir below ground, the surface above will swell. The pattern of this surface inflation can be used to identify the 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 volcanic 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. The EarthScope Consortium operates the Geodetic Facility for the Advancement of Geoscience, which includes the Network of the Americas, a hemispherical-scale geodetic network composed of geodetic-grade Global Positioning System (GPS) instrumentation as well as high-precision borehole tensor strainmeters and tiltmeters, all of which are present in Yellowstone National Park. 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 why GPS, the backbone of the Yellowstone Volcano Observatory deformation monitoring network, is so important.

There are 15 continuously recording GPS stations within Yellowstone National Park and many more in the surrounding region. Measurements 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 in the Yellowstone region 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 EarthScope Consortium's archives, where they are made publicly available at https://earthscope.org.

Semipermanent GPS sites are temporary stations that are deployed in late spring and collected in early fall. Measurements from these portable sensors substantially add to the number of instruments measuring deformation in the Yellowstone region and help track year-to-year changes. 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 compared to continuous GPS are that semipermanent GPS measurements are intermittent whereas continuous GPS measurements are collected year-round, and semipermanent GPS data are not telemetered, so they are available only after the stations have been retrieved. Used together, however, the two approaches complement one another by providing precise ground deformation measurements from more than 30 sites in the Yellowstone region.

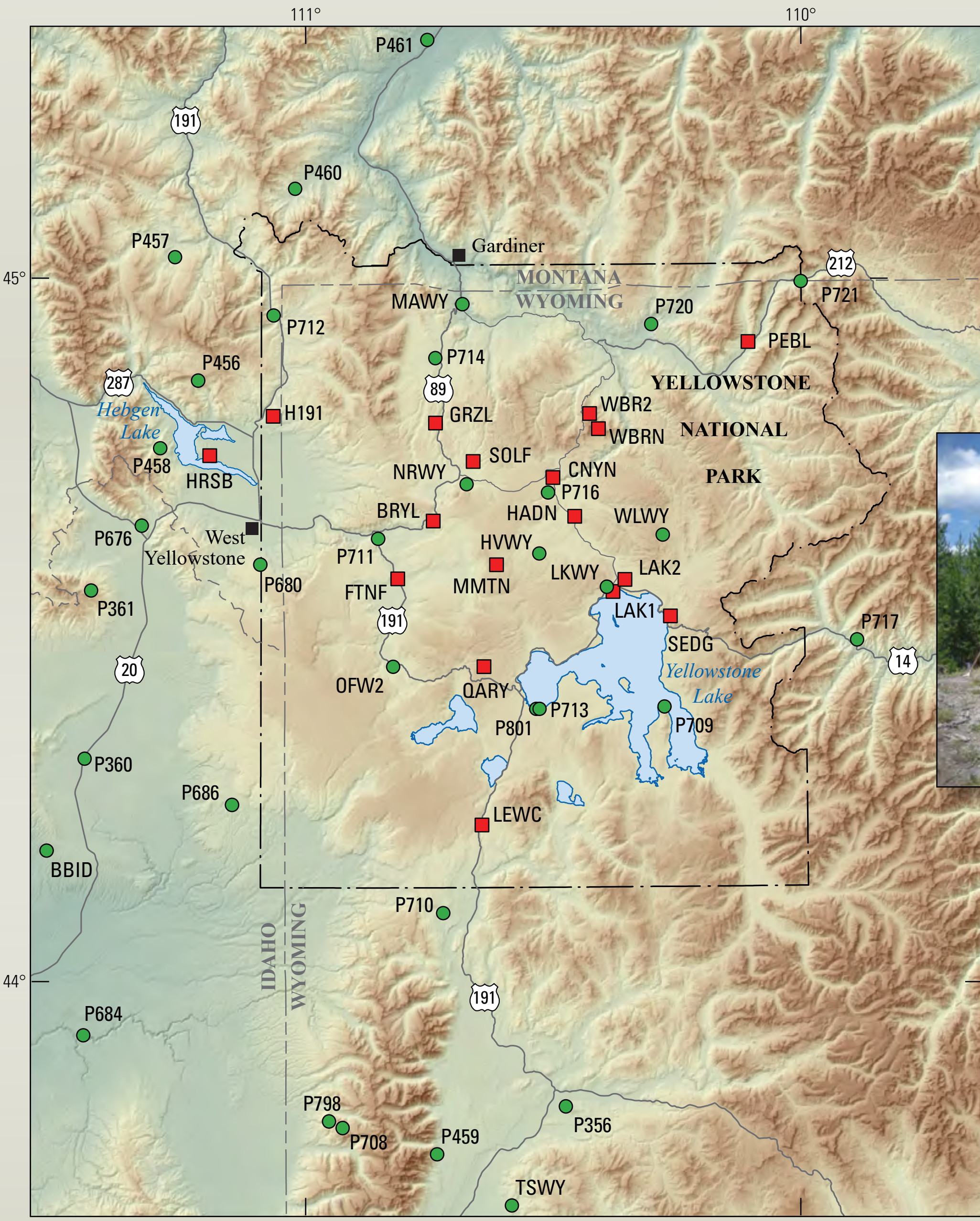
YVO scientists also use satellite measurements, called interferometric synthetic aperture radar (InSAR), to take a broad snapshot of deformation. Two radar images of the same area that were collected at different times from similar vantage points in space are compared against each other. Any movement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



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

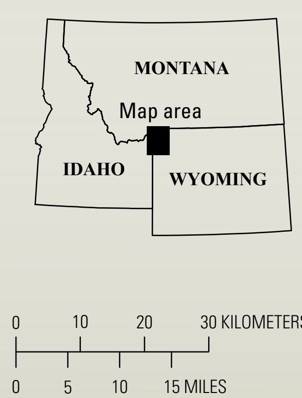
clouds and are equally effective in darkness; using InSAR, it is possible to track ground deformation even in poor weather and at night. Although it is less precise than GPS, InSAR has the advantages of showing the entire pattern of surface deformation as a spatially continuous image, and the technique does not require access to, or installations in, the study area. Disadvantages are that current InSAR satellites collect images several days apart (whereas GPS measurements are continuous), InSAR only shows deformation in one direction (line-of-sight of the satellite) compared to the three-dimensional deformation measured by GPS, and InSAR measurements are not usable during winter months 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 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.



Base from 30-meter National Elevation Dataset

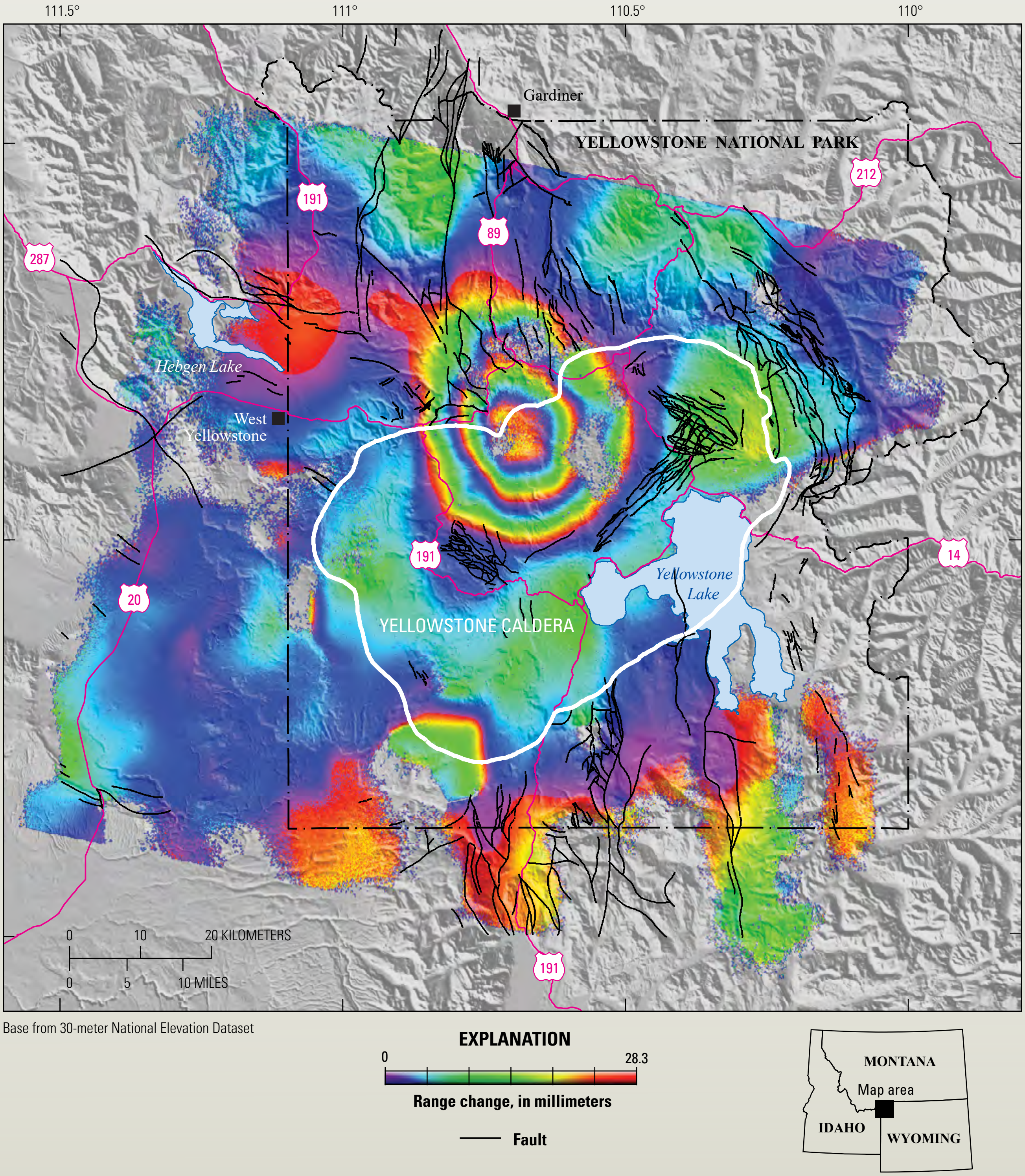
Scan here to watch a video describing deformation in Yellowstone National Park



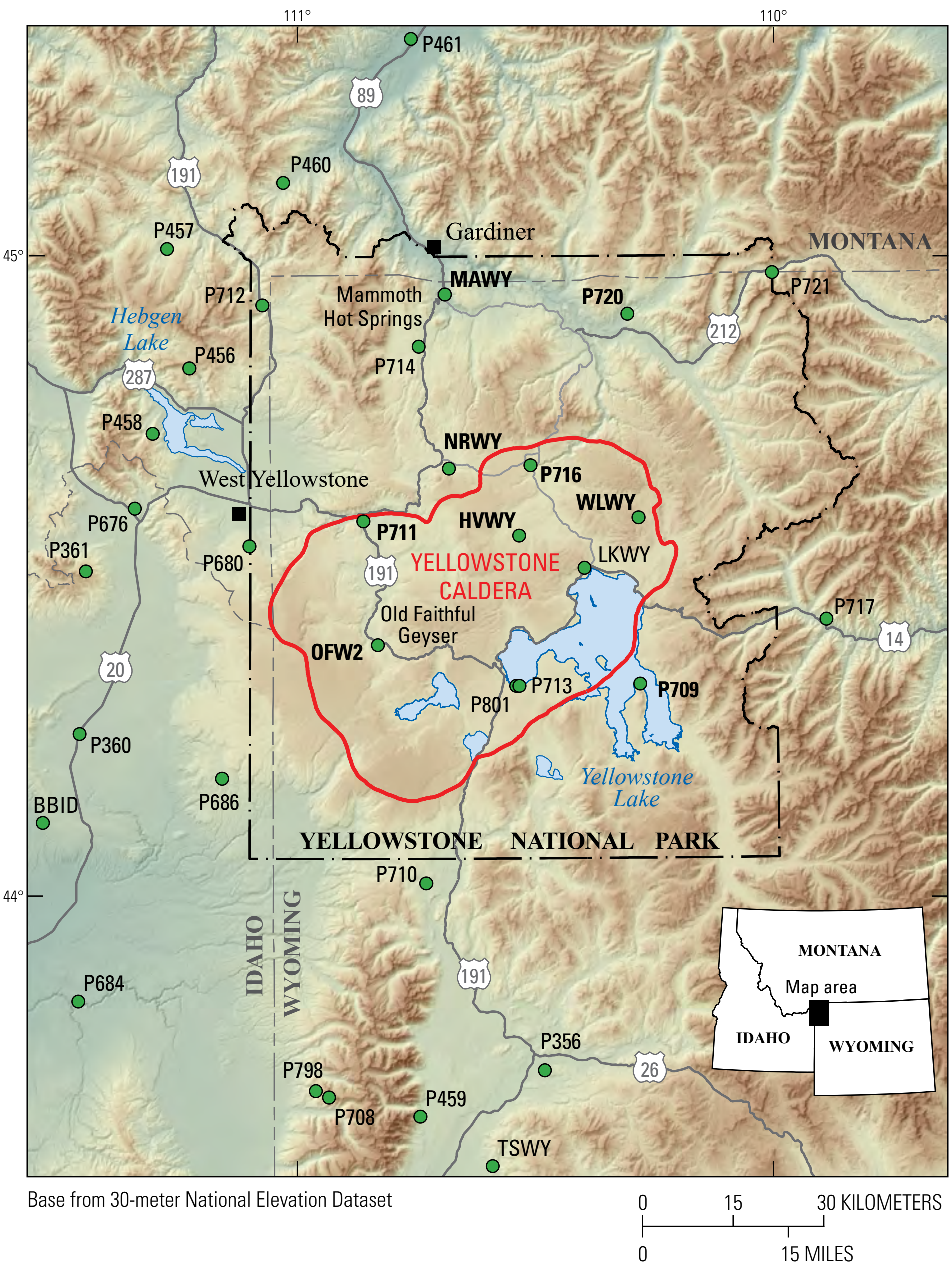
Map showing locations of continuous (green dots) and semipermanent (red squares) Global Positioning System (GPS) sites in the Yellowstone region. Photograph shows continuous GPS station P711 in Yellowstone National Park.

SIDEBAR

Monitoring Geodetic Change in the Yellowstone Region



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).



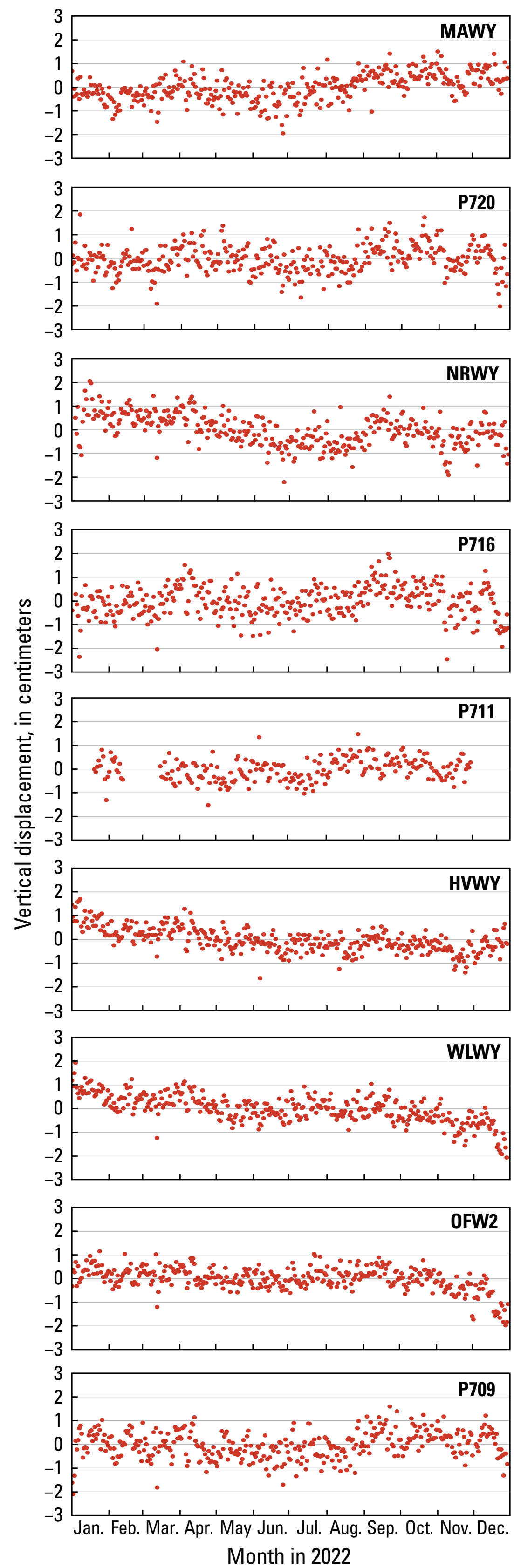


Figure 8. Map of Global Positioning System (GPS) stations showing the deformation observed in Yellowstone National Park in 2022. Vertical displacement (up or down movement of the ground) throughout the year is plotted for nine selected GPS stations (green dots) located around the national park. The vertical axis of all plots is in centimeters (1 centimeter is equal to about 0.4 inch). Downward trends indicate subsidence and upward trends indicate uplift. General trends during 2022 are subsidence within Yellowstone Caldera (exemplified by stations WLWY and OFW2) and less than a few millimeters of net vertical motion elsewhere, including at Norris Geyser Basin (station NRWY). Apparent subsidence at all sites in early November is due to intense winter precipitation at that time that temporarily covered GPS antennas in snow and ice. Gaps during time series indicate periods when GPS stations were not operational.

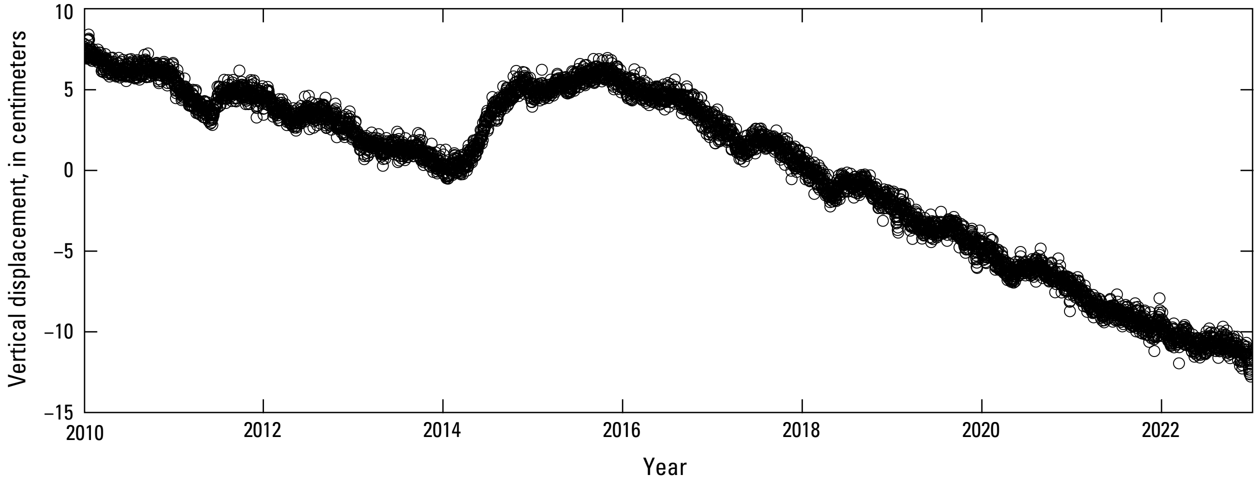


Figure 9. Plot showing vertical displacement (up or down movement of the ground) since 2010 measured at the continuous Global Positioning System station WLWY on the east side of Yellowstone Caldera (see fig. 8 for station location). Each black circle represents a single day of data. The station measured subsidence during 2010–2022 except for a brief period of uplift in 2014–2015, with an overall subsidence rate of 2–3 centimeters (about 1 inch) per year. Each summer, the subsidence trend is interrupted by a pause in deformation or a transition to slight uplift owing to groundwater recharge from snowmelt.

Continuous GPS Results

Throughout 2022, 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. 8, especially stations WLWY and OFW2). During summer months, the subsidence stalls, and can even reverse slightly, with as much as about 1 centimeter (0.4 inch) of uplift interrupting the ongoing subsidence. This seasonal variation is observed during most summers and is probably related to runoff from snowmelt that recharges the groundwater system, causing the ground to swell like a wet sponge, and is not due to the magmatic or hydrothermal systems. During 2022, the seasonal pause in subsidence was manifested as slight uplift at most GPS stations in Yellowstone National Park, and it began in late June and lasted until late October. The strong onset of the signal may have been a product of the intense rainfall that occurred in the Yellowstone region in mid-June and that led to the unprecedented flooding in the northern part of Yellowstone National Park.

At Norris Geyser Basin, there was little net deformation in 2022. 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, which stopped in 2020. As with the GPS stations in the caldera, seasonal uplift at Norris Geyser Basin began suddenly in late June, accumulating about 2 centimeters (less than 1 inch) by late July and an additional centimeter (0.4 inch) by September. After a month of no change, slight subsidence began in late October, interrupted by a strong winter snowstorm that manifested as temporary and reversable subsidence of about 3 centimeters (1.2 inches). Once the storm abated, data returned to the previous level over the course of a week.

The 2021 YVO Annual Report (YVO, 2022a) described InSAR data spanning 2020–2021 that documented possible uplift of about 1 centimeter (0.4 inch) along the north rim of the caldera to the south of Norris Geyser Basin—a source of historical uplift and subsidence in the late 1990s and early 2000s (Wicks and others, 2020). It was not clear in 2021 if GPS station P711, southwest of Norris Geyser Basin, was affected by this uplift. Data collected in 2022 indicate that station P711 recorded the same seasonal signal observed elsewhere in Yellowstone National Park but no obvious regional uplift, and InSAR data indicate that the north caldera uplift did not continue into 2022 (see “InSAR” section, below).

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

Semipermanent GPS Results

In 2022, the semipermanent GPS network in the Yellowstone region comprised 15 stations in the park and one in the adjacent Hebgen Lake Ranger District of Gallatin National Forest (fig. 10). Fourteen of the 16 stations were deployed during May 10–16; a backcountry station near Mary Mountain and another on Mount Washburn were deployed during July 12–13. Five of the stations that were deployed in May were revisited in mid-July; all were in good condition and recording data. The Mary Mountain station was retrieved in September, whereas 14 of the remaining 15 stations were retrieved during the first week of October. Station PEBL was inaccessible at that time because of roadwork to repair damage from the June flooding. That station was retrieved in early November. These semipermanent deployments are designed to complement the permanent GPS network and to take advantage of generally benign summertime conditions to collect data while avoiding the rigorous design requirements imposed by harsh Rocky Mountain winters. For more information on the semipermanent GPS technique, see the sidebar on monitoring geodetic change (p. 12–14).

Thirteen of the 16 semipermanent GPS stations recorded data successfully for the entire time they were deployed in 2022.

The other three stations had some data loss, but all three recorded at least 25 days of useful data. Overall, the semipermanent GPS network recorded 1,951 data days out of a potential 2,209 data days, for a success rate of about 88 percent—slightly less than in 2021 (95 percent). However, a firmware problem prevented the receivers in the network from recording the complete spectrum of satellite signals needed to determine accurate positions; consequently, processing of data from 2022 will require additional effort, and results were not available at the time this report was published. For the most up-to-date station coordinates and daily time-series plots for the semipermanent GPS stations in the Yellowstone region, see the archive at https://earthquake.usgs.gov/monitoring/gps/Yellowstone_SPGPS, where the data will be posted as soon as they are available.

InSAR

Satellite InSAR uses measurements 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. 12–14).

A radar interferogram that spans the period from September 29, 2021, to October 6, 2022, shows about 3 centimeters (1.2 inches) of subsidence of the caldera, maximized near the caldera center, and about 1 centimeter (0.4 inch) of subsidence of an isolated area along the north caldera rim (fig. 11). Similar satellite deformation data spanning 2020–2021 show about 1 centimeter (0.4 inch) of uplift along the north rim of the caldera to the south of Norris Geyser Basin—a pattern similar to that seen during the onset of an uplift episode that began in 1995–1996 and lasted until 2004 (Wicks and others, 2020). This previous episode of uplift in this area lasted for about 8 years and accumulated 12 centimeters (4.7 inches) at a rate of about 1.5 centimeters (0.6 inch) per year. The interferogram spanning most of 2022, however, shows that this area subsided slightly. The north caldera deformation anomaly apparently was active only for a brief period in late 2020 or in 2021 but reversed after accumulating a very small amount of uplift.

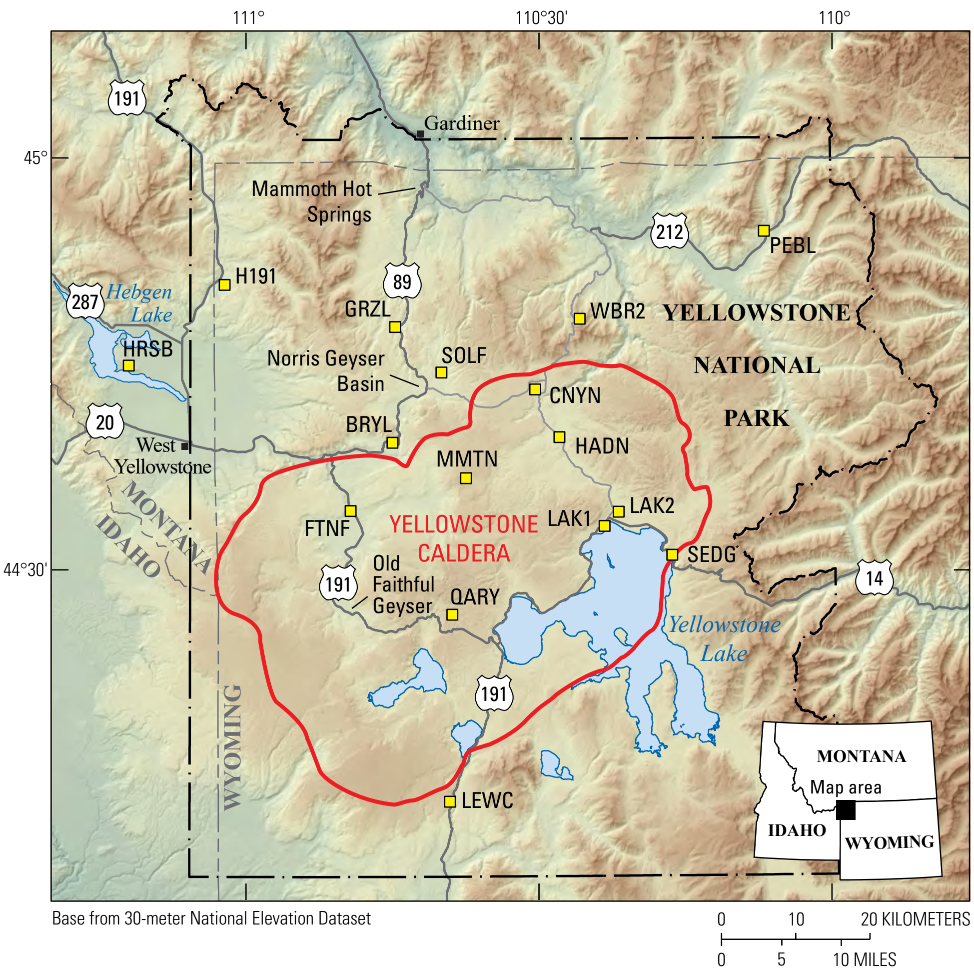


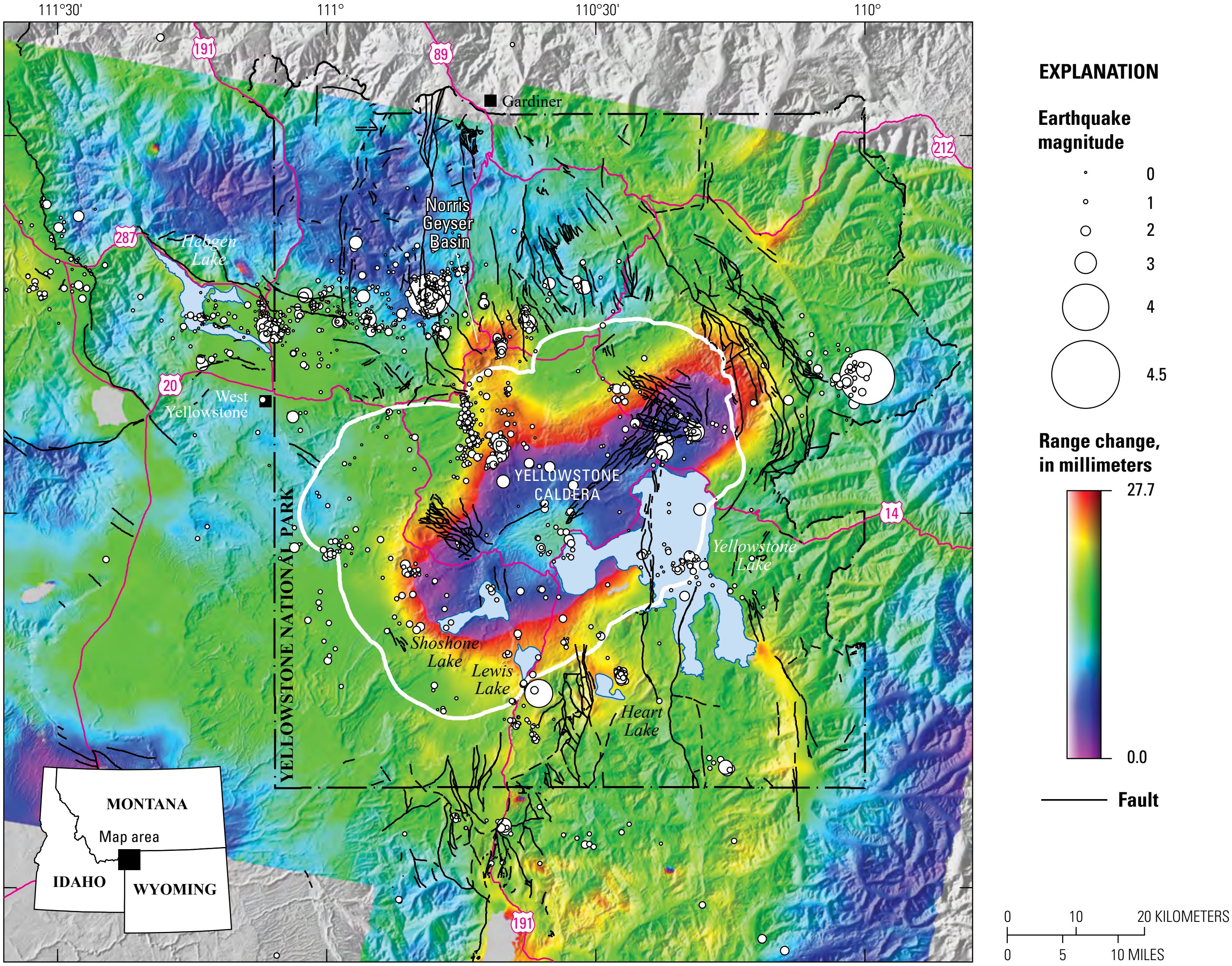
Figure 10. Map of semipermanent Global Positioning System (GPS) stations in and around Yellowstone National Park.

Geochemistry

Geochemical studies of Yellowstone National Park'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. 19). Thermal features provide a window into Yellowstone National Park'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 2022

In 2022, YVO scientists continued with gas emission measurements and collected water samples in targeted areas for laboratory analysis. An eddy covariance system was installed in the Mud Volcano area in September to collect continuous measurements of carbon dioxide (CO_2) and heat, joining the multicomponent gas analyzer system (multi-GAS) that was installed in the same area in 2021 (YVO, 2022a). Water samples were collected from the Madison Plateau to better understand the source characteristics of water that feeds the hydrothermal system in Yellowstone National Park, and an investigation into the source and fate of arsenic in thermal waters was completed.



Base from 30-meter National Elevation Dataset

Figure 11. Interferogram created from satellite radar data collected on September 29, 2021, and October 6, 2022, over the Yellowstone region 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 about 3 centimeters (about 1.2 inches) in the central part of Yellowstone Caldera and about 1 centimeter (0.4 inch) along the north rim of the caldera during the period spanned by the images. White circles show earthquakes that occurred during the time spanned by the interferogram. Circle size scales with magnitude, with the largest about magnitude 4.2.

Gas Emissions

A study of gas and heat emissions from around Obsidian Pool, in the Mud Volcano thermal area, continued in 2022. The purpose of this ongoing study is to characterize, for the first time, high-resolution real-time variation in the chemical compositions of gases, as well as fluxes of gases and heat emitted from hydrothermal features in the Obsidian Pool area. Gases emitted from the Mud Volcano thermal area have the highest magmatic contributions in the Yellowstone region, and monitoring in the area may thus provide an important comparison to prior studies at Norris Geyser Basin and Solfatara Plateau thermal area (Lewicki and others, 2017; YVO, 2019, 2021a,b,c). The multi-GAS station installed in July 2021 (station MUD in fig. 12) continued to operate through much of 2022, making high frequency (once per second) water (H_2O), carbon dioxide (CO_2), hydrogen sulfide (H_2S), and sulfur dioxide (SO_2) measurements of gas plumes emitted from hydrothermal features, along with ancillary meteorological parameters and ground

Geochemical Monitoring in Yellowstone National Park

Deep beneath the surface, gases 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 heating causes water to rise along fractures, bringing dissolved chemical components 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 made by collecting samples and analyzing the chemical makeup of the water in the laboratory.

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

temperatures. Several upgrades were made to the station MUD solar power system in 2022, including installing additional batteries and solar panels. The real-time data from the multi-GAS station MUD are available on the YVO monitoring website at https://www.usgs.gov/volcanoes/yellowstone/monitoring.

The 30-minute average H_2O, CO_2, and H_2S concentrations measured by station MUD ranged from 1 to 21 parts per thousand by volume, 461 to 1,225 parts per million by volume, and <0.1 to 2 parts per million by volume, respectively. SO_2 was not detected. Time series of 30-minute average H_2O/CO_2 and CO_2/H_2S ratios and meteorological parameters are shown in figure 13. Data gaps from January 1 to February 16 and after December 12 occurred with low atmospheric temperatures and heavy snowfall, presumably covering solar panels with snow and ice. The improved power system, however, allowed station MUD to operate on battery power for about 5 weeks after weather minimized solar charging capacity in early November. Average H_2O/CO_2 and CO_2/H_2S ratios ranged from <1 to 28 and 244 to 1,991, respectively (fig. 13*A*, *B*). During winter months, CO_2/H_2S ratios were higher and H_2O/CO_2 ratios lower, on average, reflecting plume water condensation and removal of H_2S (referred to as "scrubbing") with low atmospheric temperatures and high relative humidity (fig. 14). The bulk composition of the strongest degassing source near the station was identified by filtering data based on quality-control criteria. This composition (H_2O = 92.31 percent; CO_2 = 7.67 percent; H_2S = 0.02 percent; fig. 14) was consistent with laboratory results from a gas sample that was collected at a nearby vent in 2021 (H_2O = 91.17 percent; CO_2 = 8.81 percent; H_2S = 0.02 percent).

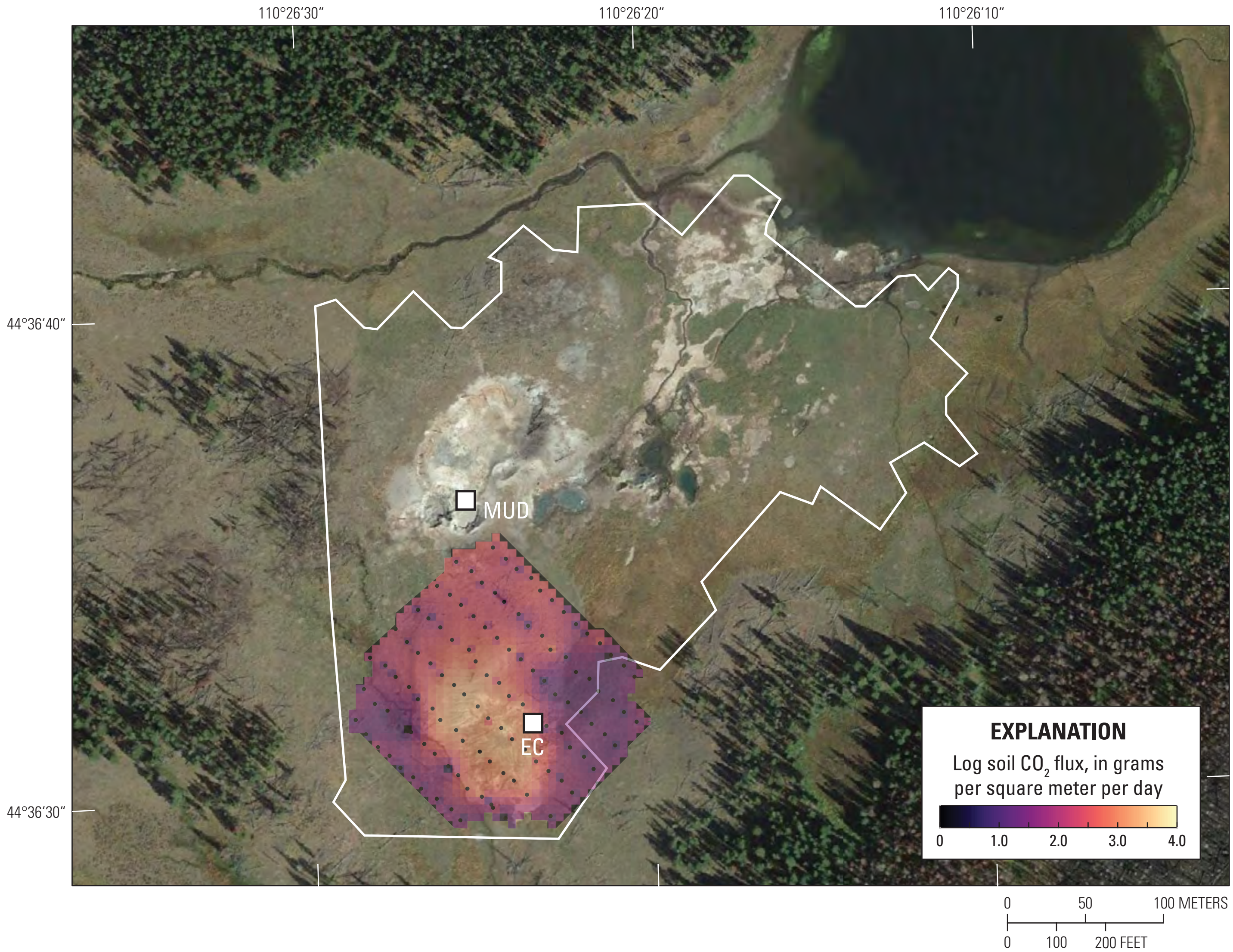


Figure 12. Map showing locations of the multicomponent gas analyzer system (multi-GAS) station MUD and eddy covariance (EC) station in the vicinity of Obsidian Pool in the Mud Volcano thermal area. Map of soil CO_2 flux simulated based on measurements made at the black dots in September 2022 is shown. White line indicates the extent of the soil CO_2 flux survey conducted across the entire Obsidian Pool area in 2021 (YVO, 2022a).

An eddy covariance station was installed on September 10, 2022, adjacent to an area of high CO_2 emissions in the Obsidian Pool area (labeled EC on fig. 12). Eddy covariance is a micrometeorological technique that measures CO_2 flux on a half-hourly basis. The system also measures sensible heat flux (owing to changes in temperature with no change in phase), latent heat flux (owing to changes in temperature associated with changes in phase [for example, evaporation]), and ancillary meteorological parameters from ground areas upwind of the station. The eddy covariance station operated until November 9, at which time it lost power because of harsh weather. Over this timeframe, the CO_2 flux was as high as 18,357 grams per square meter per day, with an average of 5,242 grams per square meter per day (fig. 15*A*). These values were substantially (more than 10×) higher than those measured in previous studies at the Bison Flat area of Norris Geyser Basin and Solfatara Plateau thermal area (Lewicki and others, 2017; YVO 2021a,b,c). Sensible and latent heat fluxes were as high as 715 and 1,268 watts per square meter, respectively (fig. 15*B* and *C*). The eddy covariance station is expected to resume data collection after atmospheric temperatures rise enough to melt snow and ice from the solar panel array.

To complement continuous gas monitoring by multi-GAS and eddy covariance, gas samples were collected for laboratory analysis, and a high-resolution survey of soil CO_2

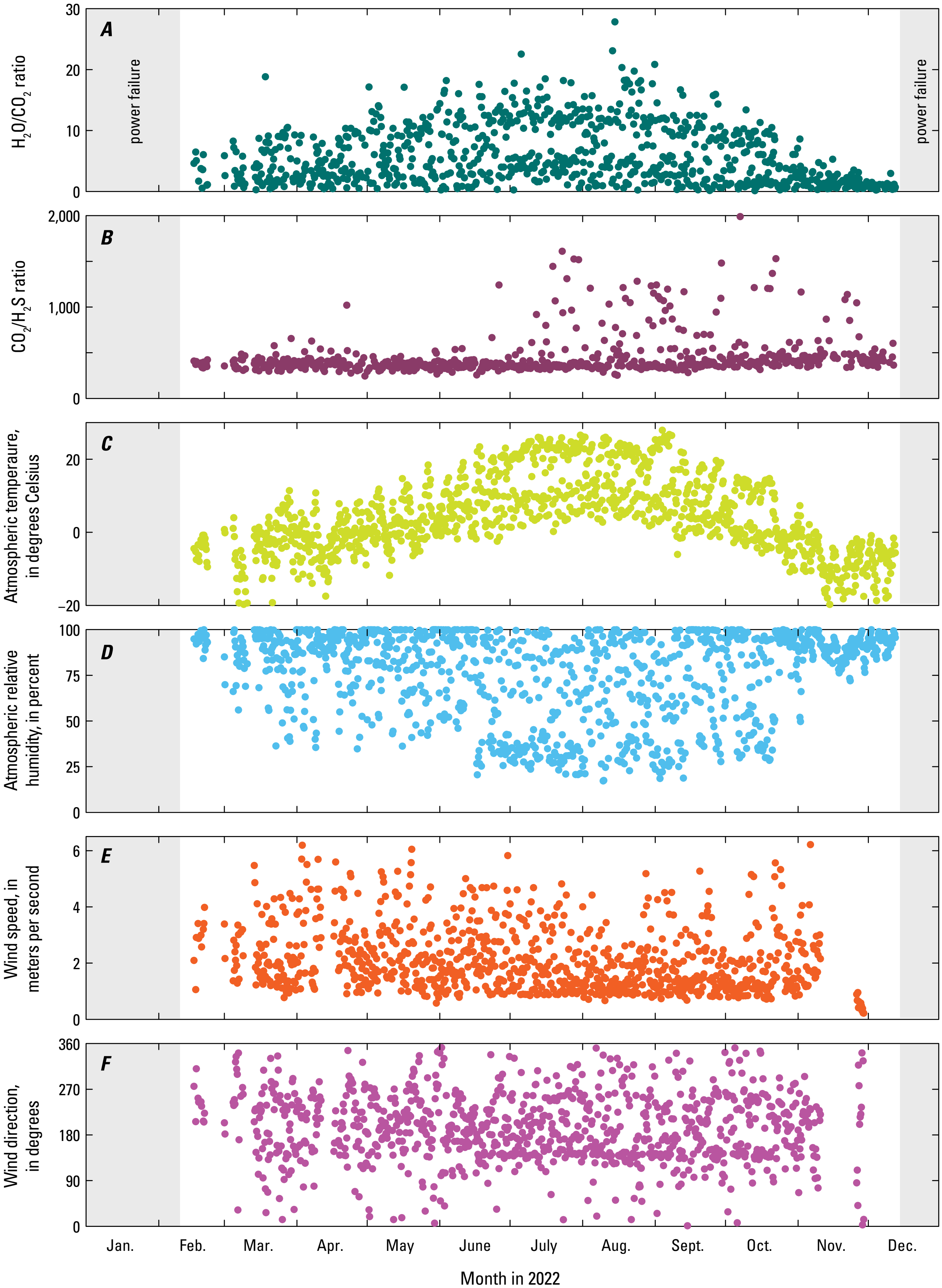


Figure 13. Times-series plots of 30-minute average H_2O/CO_2 ratio (*A*), CO_2/H_2S ratio (*B*), atmospheric temperature (*C*), atmospheric relative humidity (*D*), wind speed (*E*), and wind direction (*F*) measured at the multicomponent gas analyzer system (multi-GAS) station MUD. Gray areas denote data loss from power failure.

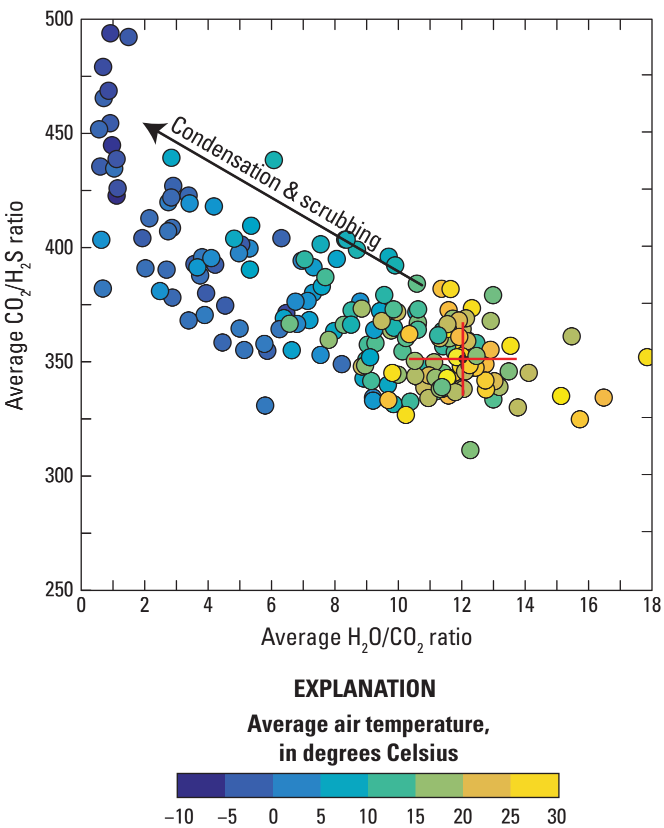


Figure 14. Plot of 30-minute average CO_2/H_2S versus H_2O/CO_2 ratios measured at the multicomponent gas analyzer system (multi-GAS) station MUD. Data are color coded for atmospheric temperature. Red cross denotes highest quality data (H_2O = 92.31 percent; CO_2 = 7.67 percent; H_2S = 0.02 percent).

flux was conducted near the eddy covariance station. The chemical and isotopic compositions of gas samples continue to indicate a large magmatic gas contribution. A simulated map of soil CO_2 flux based on 115 measurements across a region of 21,950 square meters (5.5 acres) indicates a CO_2 emission rate from the area of 7 metric tons per day (fig. 12). A survey in 2021 of a larger region in the same area found a similar soil CO_2 flux—27 metric tons per day across approximately 25 acres (YVO, 2022a).

Mixing of Shallow Meteoric and Deep Hydrothermal Water

Water from Yellowstone thermal features is a mix of fluids from two dominant sources. The first source is shallow meteoric groundwater, which is derived from rain and snowmelt, whereas the second source is deep hydrothermal fluid, which rises along fracture networks from the cooling magma reservoir beneath Yellowstone Caldera. Despite decades of investigations aimed at understanding the way these two fluids mix, there is little understanding of the depths and geometries of the subsurface fluid pathways and conduits. To address this question, geologists from the University of Wyoming used near-surface geophysical imaging methods, including resistivity and electromagnetic measurements, to study fluid migration in the Sentinel Meadows area of Lower Geyser Basin (Smeltz and others, 2022). The area was chosen as a study site because geochemical evidence indicates relatively straightforward mixing between shallow meteoric and deep hydrothermal waters, making the region an ideal natural laboratory for understanding subsurface water interactions.

Results of the geophysical investigations indicate that geologic conditions play the dominant role in how and where deep and shallow waters mix in the Sentinel Meadows area. Meteoric waters flow laterally at shallow depths through and below a nearby rhyolite lava flow, emerging near the flow's edge as cold springs. Some of this water also flows into glacial sediments that are adjacent to the rhyolite lava. Hydrothermal waters flow vertically from depth into the same glacial sediments, and this is where shallow meteoric and deep ascending hydrothermal waters meet, creating a mixed fluid that feeds the hydrothermal features in Sentinel Meadows. The farther from the lava flow, however, the less meteoric water is available to mix with the deeper hydrothermal water. As a result, the chemistry of the thermal features in Sentinel Meadows shows a distinct variation, becoming richer in the hydrothermal fluid component and poorer in the meteoric component with increasing distance from the lava flow. Similar relations may exist elsewhere in the Yellowstone region given both the large amount of meteoric water recharge and the close association of hydrothermal features and rhyolite lava flows.

Additional work on this topic also occurred in the Upper Geyser Basin area. In August 2022, USGS scientists collected samples of dilute and cold water from creeks on the Madison Plateau, west of Biscuit Basin. These samples will provide information on the source of water that is fed into the Yellowstone region's hydrothermal system and discharged as hot, and mostly boiling, water in the geyser basins. The water samples were analyzed for their oxygen and hydrogen isotopic composition and for the concentration of tritium in the water. These samples were collected under research permit YELL–05194.

Arsenic from Hydrothermal Sources in River Water

Arsenic in surface and groundwaters is a considerable public-health concern. Since arsenic is a known carcinogen, the U.S. Environmental Protection Agency set the arsenic concentration standard for drinking water at 10 parts per billion. However, thermal waters in volcanic areas commonly contain concentrations that are orders of magnitude higher than the drinking water standard, and these elevated concentrations adversely affect downstream water resources. Scientists from the USGS and Montana State University investigated arsenic in the Yellowstone hydrothermal system, finding that the arsenic is mainly derived from high-temperature leaching of rhyolite lava flows that formed during past eruptions from the Yellowstone volcanic system. Arsenic concentrations in thermal waters are as high as 4 milligrams per liter, or about 4,000 parts per billion, depending on water type, which is controlled by boiling, evaporation, mixing, and mineral precipitation and dissolution. Springs with

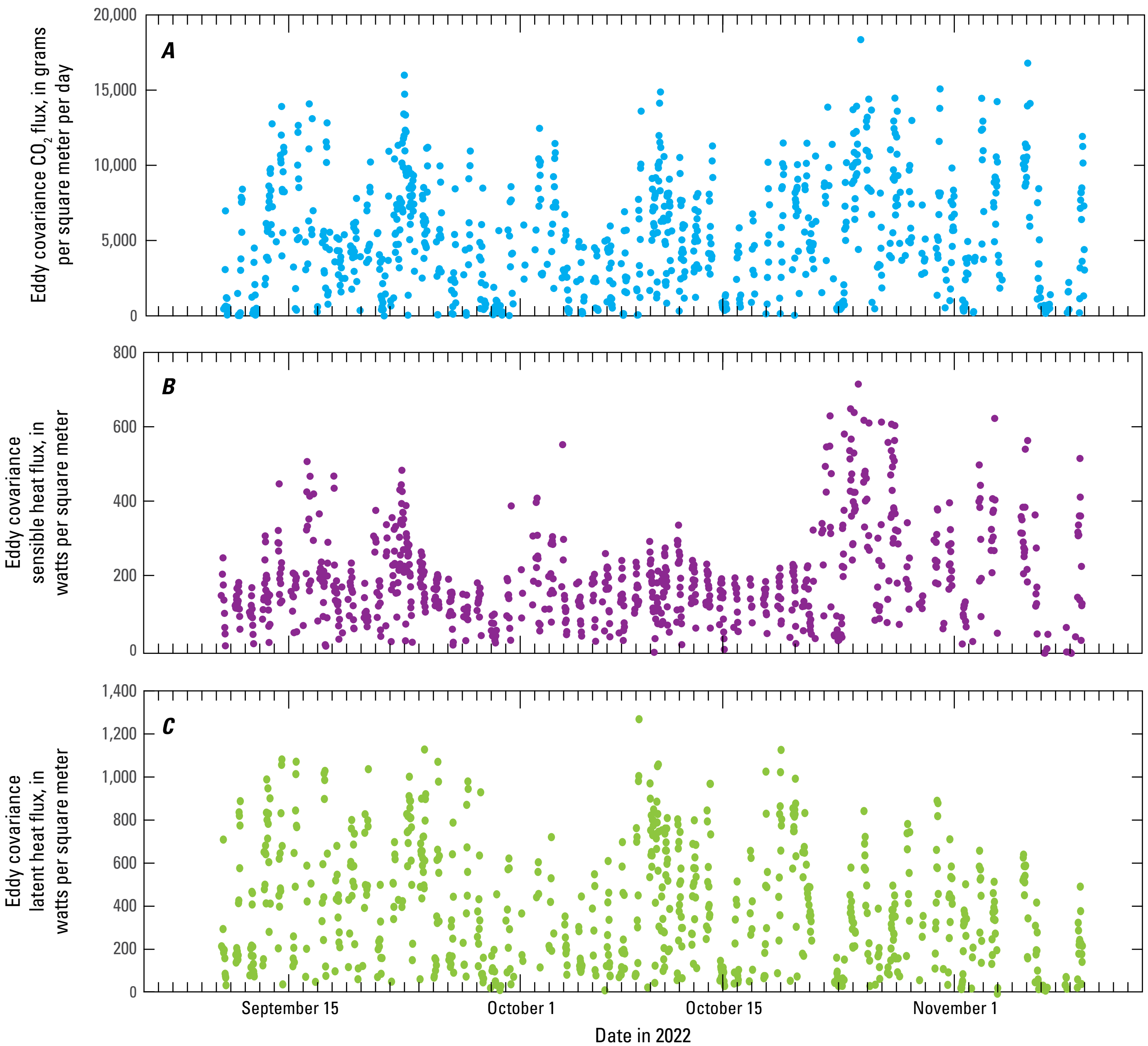


Figure 15. Time-series plots of half-hourly CO_2 (*A*), sensible heat (*B*), and latent heat (*C*) fluxes measured at the eddy covariance station in the Obsidian Pool area. Data collection stopped with power loss on November 9, 2022.

chloride-rich waters primarily in Yellowstone National Park's geyser basins have the highest concentrations of arsenic. Reduced arsenic species (arsenite and thiolated-arsenic species) are most prevalent near the orifices of hot springs. Widespread use and transformation of arsenic by thermophilic microorganisms that live in Yellowstone hot springs promotes more soluble and toxic forms of arsenic. Most of the water discharged from thermal springs eventually ends up in a nearby river, where arsenic remains soluble during downstream transport.

The discharge of arsenic from Yellowstone's thermal features impairs river water quality for many river reaches within and downstream from Yellowstone National Park. Although not immediately toxic to humans, arsenic in downstream water resources does require additional filtering at some drinking water treatment plants. There are popular swim areas in Yellowstone, including the Firehole and Boiling River Swim Areas, that are downstream of hot springs and other thermal features. To minimize the risk of illness from swimming and soaking in Yellowstone rivers, the National Park Service recommends that you avoid swallowing river water and any activities that cause water to enter your nose. Fish can also incorporate arsenic into their tissue, and although elevated in fish from Yellowstone National Park, arsenic levels are well below the threshold considered to be safe for consumption (Chaffee and others, 2007).

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 volcanic eruptions and hydrothermal explosions. 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 region (see sidebar on geology of Yellowstone Plateau on p. 26–27) 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 2022

A full field season was possible in 2022, and geologists took advantage of the opportunity to advance several ongoing projects, including investigations of the compositions and ages of rhyolite lava flows, the causes of past formation of travertine in thermal areas located within Yellowstone Caldera, the timing and mechanisms of hydrothermal explosions in the Lower Geyser Basin, and the glacial history of the Yellowstone region. In addition, geologists mapping the Sour Creek resurgent dome identified new geologic units that indicate the eruption that resulted in the formation of Yellowstone Caldera was much more complex than previously thought.

Understanding the Recent Volcanic History of the Yellowstone Region

During 2022, work continued on constraining the timing and composition of volcanism within the Yellowstone Plateau volcanic field. The goals of this work are threefold: (1) develop a robust and precise chronology of volcanism after the formation of Yellowstone Caldera 631,000 years ago using argon-argon ($^{40}Ar/^{39}Ar$) dating methods, (2) investigate the dynamics and physical state of the magma reservoir beneath Yellowstone Caldera during intra-caldera eruptive episodes through petrologic investigations, and (3) provide a robust age and chemical dataset for rhyolites that erupted after the formation of Yellowstone Caldera that will aid in determining the origins of glacial deposits within the caldera.

Work in 2022 focused on lava flows of the Central Plateau Member of the Plateau Rhyolite, which are the youngest rhyolites erupted within Yellowstone Caldera (fig. 16). To date, results indicate that post-caldera volcanism from 161,000 to 72,000 years ago was characterized by five brief eruption clusters when multiple (as many as nine) bodies of rhyolitic magma were generated and erupted in short timespans from vents spaced over large distances (more than 40 kilometers [25 miles]). Field work was conducted in September 2022 to collect samples from the oldest Central Plateau Member eruption cluster (about 161,000 years old) for chemical and paleomagnetic investigation (fig. 17). Analyses of these new samples is underway and will provide information on the duration of the five brief eruption clusters that characterize the Central Plateau Member rhyolites. These results will also provide a picture of what the magma reservoir looked like prior to these eruption clusters.

Geologic Mapping of Sour Creek Dome

The Sour Creek resurgent dome, which formed from inflation of the ground surface owing to magma accumulation shortly after the eruption that formed Yellowstone Caldera, is mapped as a heavily faulted, uplifted section of volcanic material within the eastern part of Yellowstone Caldera. The rocks in the area were previously interpreted as ash-flow units, called ignimbrite, from both the Huckleberry Ridge Tuff and Lava Creek Tuff (fig. 18*A*). The older Huckleberry Ridge Tuff eruption occurred about 2.08 million years ago and erupted about 2,500 cubic kilometers (600 cubic miles) of ash and debris, whereas the Lava Creek Tuff eruption, which resulted in the formation of Yellowstone Caldera, occurred about 631,000 years ago and erupted about 1,000 cubic kilometers (240 cubic miles) of material (Christiansen, 2001). The Lava Creek Tuff is mapped as two ignimbrite units, A and B, which are distinguished by the presence of the mineral amphibole in unit A, as well as a change in the cooling pattern between the units (Christiansen, 2001).

Recent geologic studies and age dates from ignimbrite on the Sour Creek dome, however, indicate that units previously mapped as Huckleberry Ridge Tuff are actually part of the Lava Creek Tuff, temporarily designated as units 1 and 2, and indicate that the eruption that formed Yellowstone Caldera was more complex than previously thought (Wilson and others, 2018). Field and laboratory work conducted by geologists from Montana State University during the summer of 2020 and 2021 (YVO, 2022a) confirmed this interpretation, and that the ignimbrite units on the Sour Creek dome represent a previously unknown sequence of the Lava Creek Tuff eruption.

During the summer of 2022, Montana State University geologists, accompanied by undergraduates from other universities, attempted to remap the Sour Creek dome to determine the extent of these newly recognized ignimbrites. Thirteen weeks of fieldwork revealed that all areas that were previously interpreted as Huckleberry Ridge Tuff in the Sour Creek dome are actually one of the two newly recognized Lava Creek Tuff ignimbrites, easily distinguished by the presence of scoria. Ignimbrite unit 2 appears to be extensive throughout the west half of Sour Creek dome (fig. 18*B*). Thus far, no evidence for the presence of Lava Creek Tuff units A or B has been found on Sour Creek dome, although not all areas mapped as unit B have been visited in the field yet. Another surprise awaited the geologists when they visited the informally named Stonetop Mountain flow, which had previously been mapped as an exposure of a rhyolite lava flow at the south end of Sour Creek dome. In fact, the unit is composed of two previously

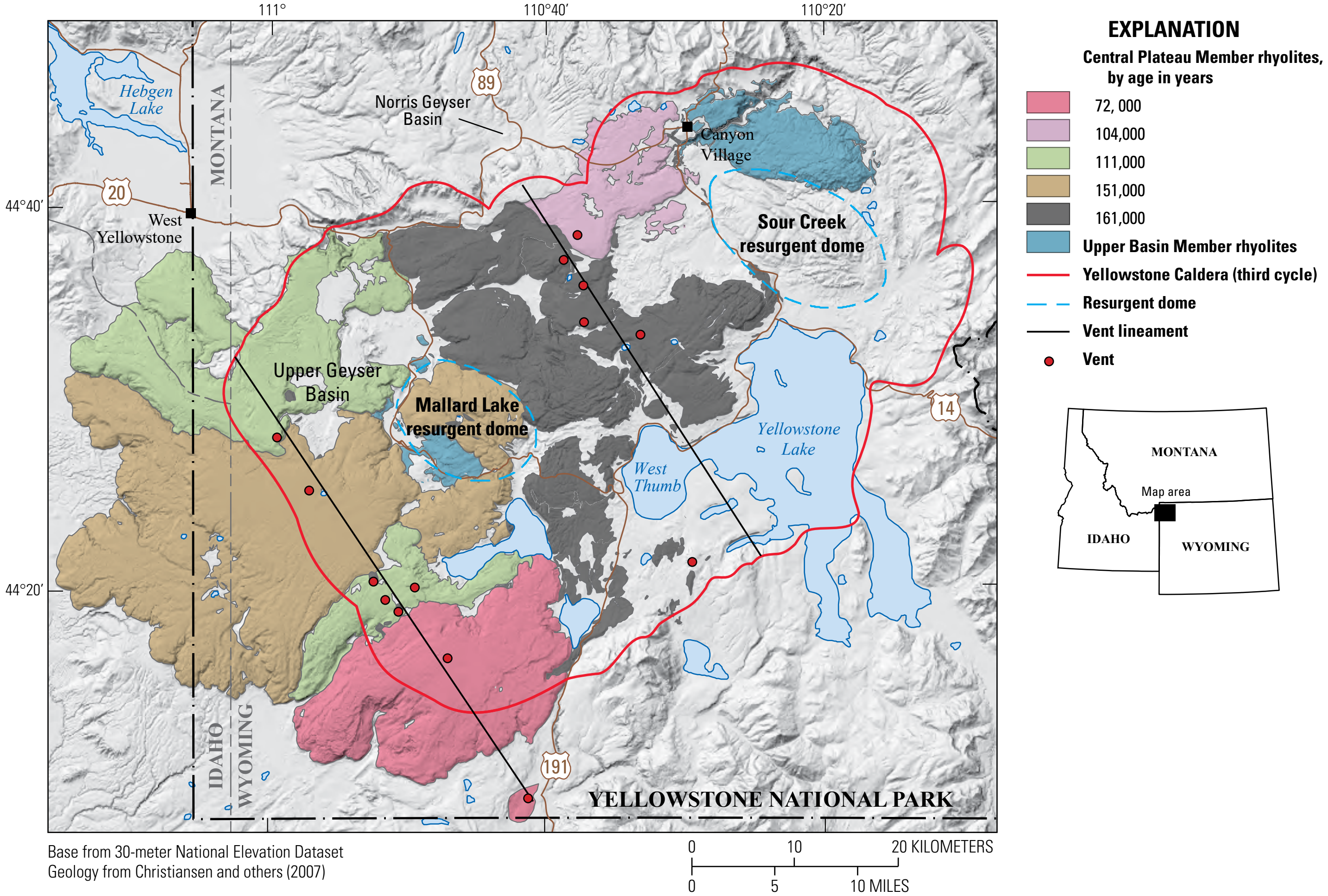


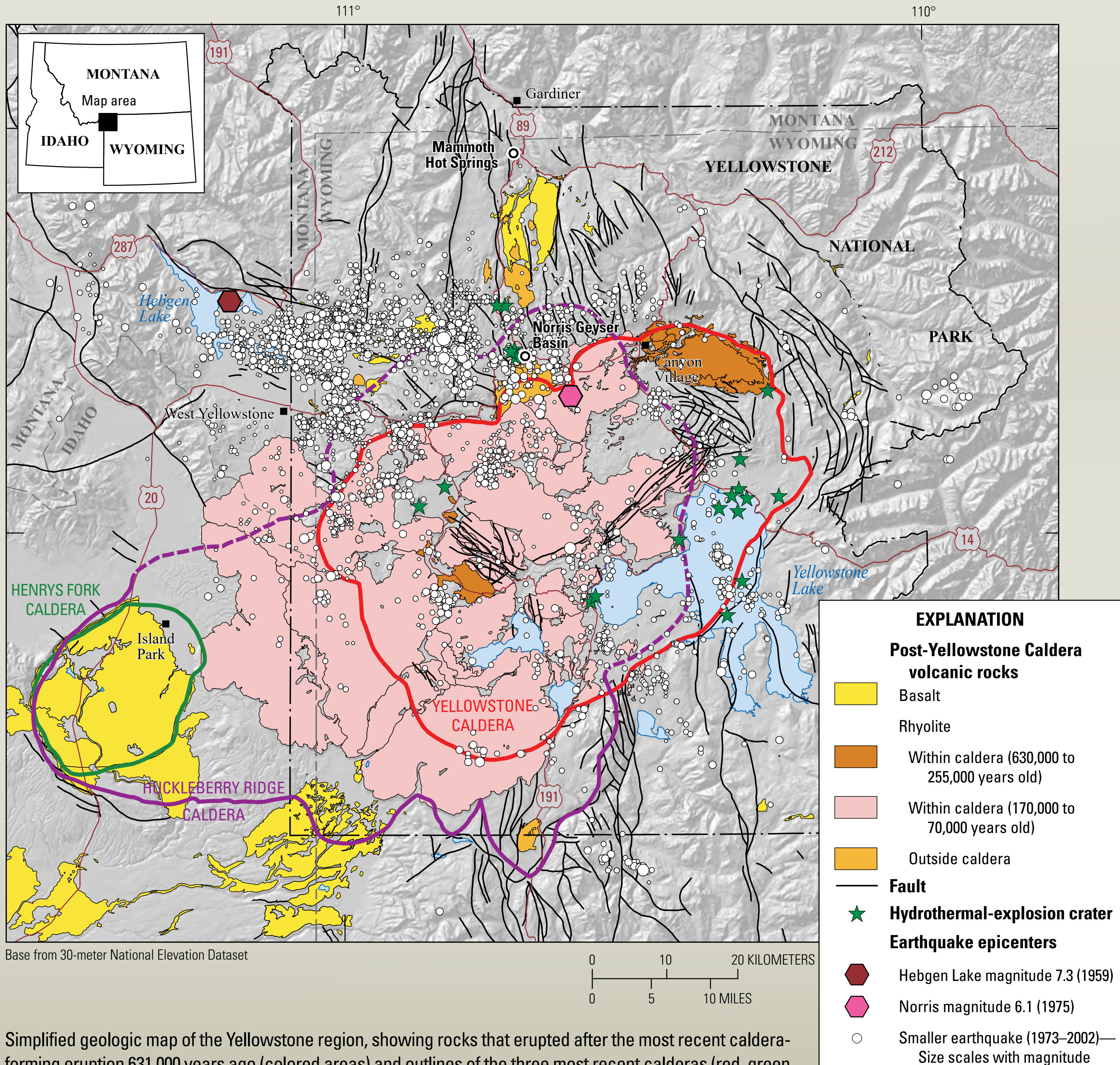
Figure 16. Shaded-relief map of Yellowstone Caldera showing the age and location of intra-caldera rhyolites that erupted after the Lava Creek Tuff. The Upper Basin Member of the Plateau Rhyolite (blue) is the first episode of post-Lava Creek Tuff volcanism, occurring from approximately 630,000 to 255,000 years before present. The Central Plateau Member of the Plateau Rhyolite erupted in a second episode and is shown by volcanic eruption age estimated via recent high-precision $^{40}Ar/^{39}Ar$ dating methods. The black solid lines represent structurally controlled vent lineaments from which the Central Plateau Member erupted (individual vent locations shown as red dots).

Figure 17. Photograph of U.S. Geological Survey scientists collecting paleomagnetic and geochemical samples from an outcrop of the West Thumb rhyolite lava flow. The outcrop is composed of jointed rhyolite (upper quarter of picture) exposed above a talus slope. Work performed under research permit YELL–2021–SCI–8204. Photograph by Mark Stelten, U.S. Geological Survey, September 13, 2022.

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 volcanic 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 more than 1,000 cubic kilometers (240 cubic miles) of magma, forming the Lava Creek Tuff, and formation of the 45×85 kilometer (28×53 mile) Yellowstone Caldera.

The three extraordinarily large explosive volcanic eruptions in the past 2.1 million years each created a giant caldera and spread enormous volumes of hot, fragmented volcanic rocks via pyroclastic density currents over vast areas. The accumulated hot ash, pumice,

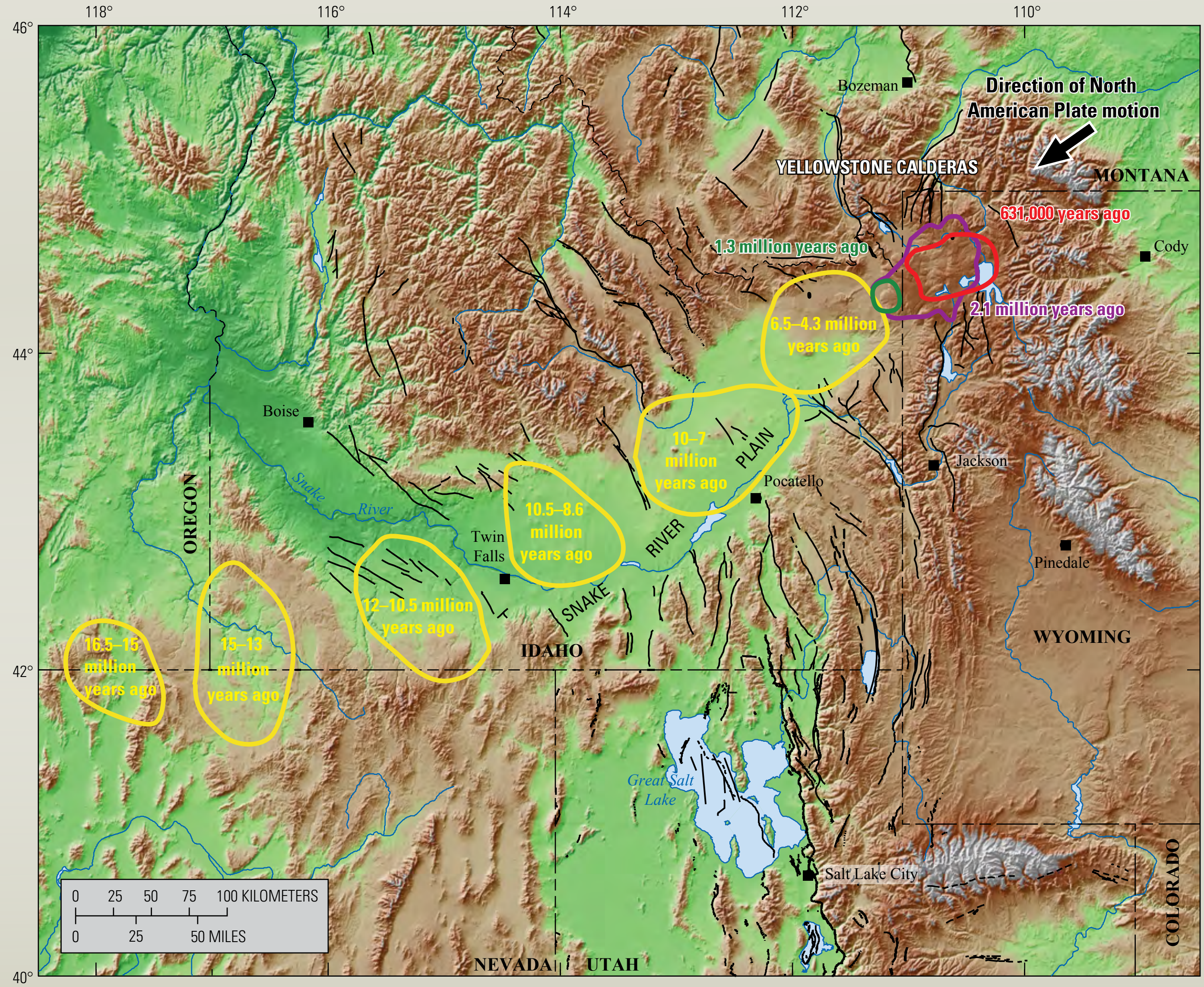


Simplified geologic map of the Yellowstone region, showing rocks that erupted after the most recent caldera-forming eruption 631,000 years ago (colored areas) and outlines of the three most recent calderas (red, green, and purple lines). Modified from U.S. Geological Survey Fact Sheet 2005–3024 (Lowenstern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

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 places, these welded ash-flow tuffs are more than 400 meters (1,300 feet) thick. The ash-flow sheets account for about half the material erupted from the Yellowstone region.

Before and after these caldera-forming events, volcanic eruptions in the Yellowstone region 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, 16,000–13,000 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.



Map showing volcanic centers where the Yellowstone Hot Spot produced one or more caldera eruptions—essentially "ancient Yellowstones"—during the 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.

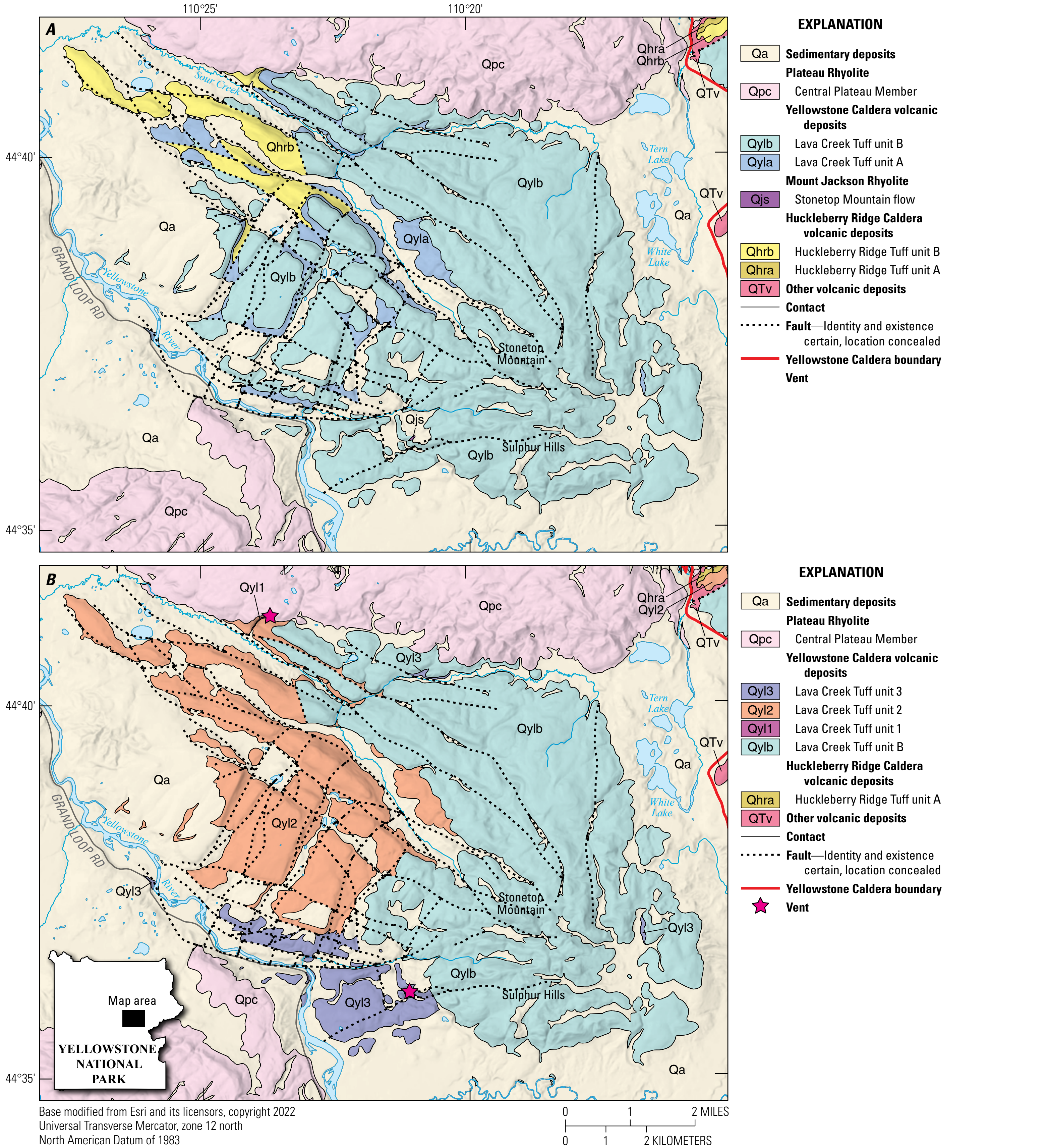


Figure 18. Preliminary geologic maps of the Sour Creek dome in Yellowstone National Park. *A*, Original map of the Sour Creek dome showing Lava Creek Tuff unit B (unit Qylb) as the primary rock in the area (modified from Christiansen, 2001). *B*, Updated geologic map of the Sour Creek dome showing the distribution of Lava Creek Tuff, including some newly recognized units. Note that the areas mapped here as Lava Creek Tuff unit B have not yet been confirmed in the field and may actually be Lava Creek Tuff unit 2 or unit 3.

Figure 19. Photographs of newly discovered ignimbrite units of the Lava Creek Tuff. *A*, Hand sample of ignimbrite unit 3. The main distinguishing factors are that unit 3 is more densely welded, has a higher crystal content, and has more plagioclase than units 1 and 2. Photograph by Ray Salazar, Montana State University, June 23, 2022. *B*, Outcrop of ignimbrite unit 4 lying atop unit 3. Yellow handheld Global Positioning System unit (10 centimeters [4 inches] long) provides a sense of scale. Photograph by Ray Salazar, Montana State University, September 7, 2022.

undocumented ignimbrites of Lava Creek Tuff age referred to as units 3 and 4 (figs. 18*B*, 19); thus, there are four previously unrecognized ignimbrite units exposed on Sour Creek dome that are associated with the formation of Yellowstone Caldera. Because these new ignimbrite units have only recently been discovered, mapping remains incomplete, and future field work is needed to understand their distribution.

Another surprising discovery at the Stonetop Mountain flow site is the presence of a structure that appears to be an eruptive vent. This vent is thought to be the source vent for the newly identified ignimbrite unit 3 (fig. 18*B*). Wilson and others (2018) have also identified another separate vent on the north end of Sour Creek dome, which is thought to have produced unit 2. These two vents, found within the Sour Creek dome, provide evidence that the east boundary of the Yellowstone Caldera as currently mapped may need to be reevaluated.

The work done by Montana State University geologists and others strongly suggests the Lava Creek Tuff eruption happened not as one large event, but rather multiple events with at least one time gap (between newly mapped units 1 and 2) long enough for cooling and reworking of previous erupted material to have taken place—possibly years or more.

Investigations into the Glacial History of the Yellowstone Plateau

The area of Yellowstone National Park hosted the largest alpine ice sheet in North America during the last glacial period, from approximately 22,000 to 14,000 years ago. Most of what is known about the timing of glacial retreat is from cosmogenic exposure dating—a way to measure how long certain minerals have been exposed to sunlight—of boulders left behind when the glaciers melted from their maximum extents. What is less known is the timing and pattern of glacial retreat across the central part of Yellowstone National Park, including the major geyser basins. Furthermore, this geologically recent glaciation sculpted the landscape we see around the region today, but some landscape features are still puzzling, including hydrothermal deposits of glacial debris, called glacial kame, and potentially large meltwater flood channels. The Yellowstone ice sheet was more than 1 kilometer (0.6 mile) thick and would have supported a large meltwater drainage system and short-lived glacially dammed lakes as it receded. In the summer of 2022, glacial meltwater channels were investigated, and samples were collected for cosmogenic exposure dating from erratic boulders moved by glacial processes on the west side of Lower Geyser Basin. In addition to dating when these boulders came to rest in their present locations to constrain the timing of glacial retreat, the path the boulder traveled to its present location was traced by matching the boulder to the rock formation from which it came. This was done using geochemistry, U-Pb geochronology, and $^{40}Ar/^{39}Ar$ geochronology.

Glacial kame is a glacial-hydrothermal deposit formed where hydrothermal heat melts overlying glaciers, causing the glacier to drop lots of poorly sorted, glacially rounded rocks and sediments in one spot that is then cemented into place by the precipitation of hydrothermal silica. This process concentrates glacial sediment rather than spreading it out, which results in the construction of hills. Once the glaciers retreat, evidence of the location of these sub-glacial hydrothermal "hot spots" is recorded by the presence of low hills of glacial kame. These deposits are particularly common in the major geyser basins in Yellowstone National Park; some of the largest glacial kame mounds are Twin Buttes in the western part of Lower Geyser Basin (fig. 20*A*). These kame hills rise to 195 meters (640 feet) above the surrounding valley floor and are composed of rounded cobbles of rhyolite transported from lava flows in the region by glaciers (fig. 20*B*). To understand when the kame formed and the flow path of the glacier that transported and deposited the rocks that built the kame, samples of kame rhyolite cobbles were collected to determine their source. Samples are in the process of being dated using $^{40}Ar/^{39}Ar$ geochronology and matched to their source lava flow, which will ultimately provide a better understanding of the timing and flow paths of glaciers that have long since disappeared.

Characteristics of Hydrothermal Explosion Craters in Lower Geyser Basin

Hydrothermal explosions are forceful eruptions from the shallow hydrothermal system that can throw rock, mud, steam, and boiling water as far as 4 kilometers (2.5 miles) from the explosion site. They are driven by superheated, confined water that flashes to steam in the shallow subsurface, and they do not involve any magma. Hydrothermal explosions can be triggered by the sudden release of pressure during landslide events, seismic activity, or the mechanical failure of a cap-like seal on the system. Yellowstone National Park has some of the largest hydrothermal explosion craters in the world, but much is still unknown about these events, including the reoccurrence interval of the largest explosions and their specific causes.

In September 2022, researchers from several universities and the USGS investigated multiple large hydrothermal explosion craters located in Lower Geyser Basin (Twin Buttes and Pocket Basin) and on the north side of Yellowstone Lake (Mary Bay and Turbid Lake). At Pocket Basin, the hydrothermal breccia deposited by the explosion was studied to better understand the dynamics and the structure of the subsurface through which the explosion occurred. All the rocks greater than 40 centimeters (16 inches) long were measured, their locations mapped, and their general compositions recorded to provide a detailed view of rock dispersal and therefore explosion energy. Wood found deposited in the hydrothermal breccia interpreted to have been from trees killed by the explosion was sampled for radiocarbon dating. Samples

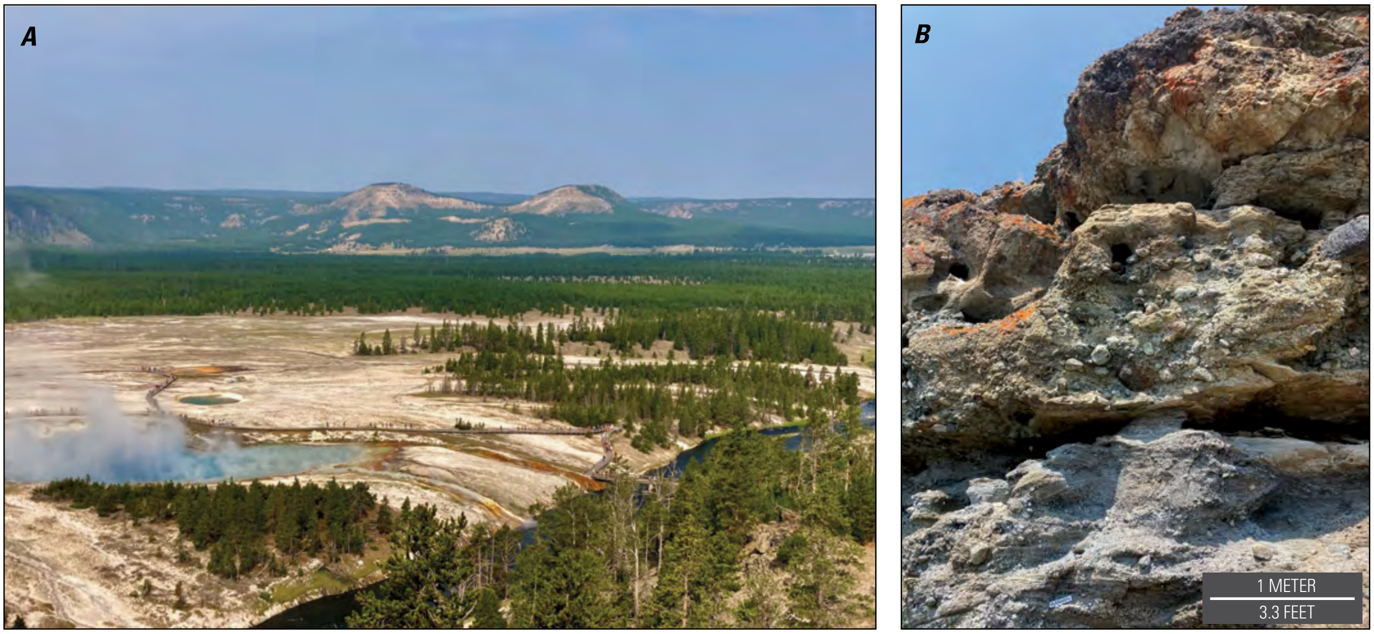


Figure 20. Photographs of Twin Buttes hydrothermal explosion crater in Lower Geyser Basin. *A*, Photograph looking to the northwest that shows Twin Buttes, the two highest hills in the distance, with Excelsior Geyser of Midway Geyser Basin in the foreground. Twin Buttes were formed when glaciers covered the area, and hydrothermal activity below the ice led to melting and the deposition and cementation of glacial sediments. A large hydrothermal explosion occurred in the area following glacial retreat. Excelsior Geyser, the large steaming spring in the foreground, was formed by a series of small hydrothermal explosions in the late 1800s. Photograph by Lauren Harrison, U.S. Geological Survey, August 2021, under permit YELL–2021–SCI–8158. *B*, Photograph of an outcrop of glacial kame on Twin Buttes. The sediment is well-rounded and poorly sorted from being carried within glaciers. Note several large, rounded cobbles of rhyolite in the cliff; cobbles like these were sampled from the entire kame deposit to determine their sources. Photograph by Lauren Harrison, U.S. Geological Survey, July 2021, under permit YELL–2021–SCI–8158.

were collected for experimental measurements into the strength and permeability of the rocks blasted by the explosion to constrain how much superheated fluid may have been stored in the subsurface prior to the event (in other words, the potential energy "fuel" for the explosion) and how much of that released energy would be consumed by fracturing the rocks. These data will constrain models of the energy, triggering mechanism, timing, and dynamics of the hydrothermal explosion that created Pocket Basin.

In August 2022, the Twin Buttes hydrothermal explosion was investigated by collecting a sediment core from a lake near Twin Buttes (figs. 21, 22), one of the five nested ponds perched within a crater that has a circumference of 600 meters (1,970 feet). If the ponds were formed by a large hydrothermal explosion, a sequence of hydrothermal explosions, or from landslides, a record of the history may be found in the sediment record accumulated at the base of the ponds. Additionally, the presence of any ashes in the pond from known volcanic eruptions in the Cascade Range since the glaciers retreated from the Yellowstone region would provide a minimum age for the timing of any large event at Twin Buttes. The 6-meter (20-foot) core that was recovered is also a valuable record of variations in the sediment type, grain size, and chemistry over the history of the pond. These variations will reveal changes in the region from past tectonic events and hydrothermal activity. In addition, the amount of organic material in the core provides insights into lake productivity during past climates. Analysis of the pollen in the core will be used to reconstruct the vegetation history of the surrounding area, and the frequency and intensity of fires through time will be studied on the basis of changes in the abundance of charcoal.

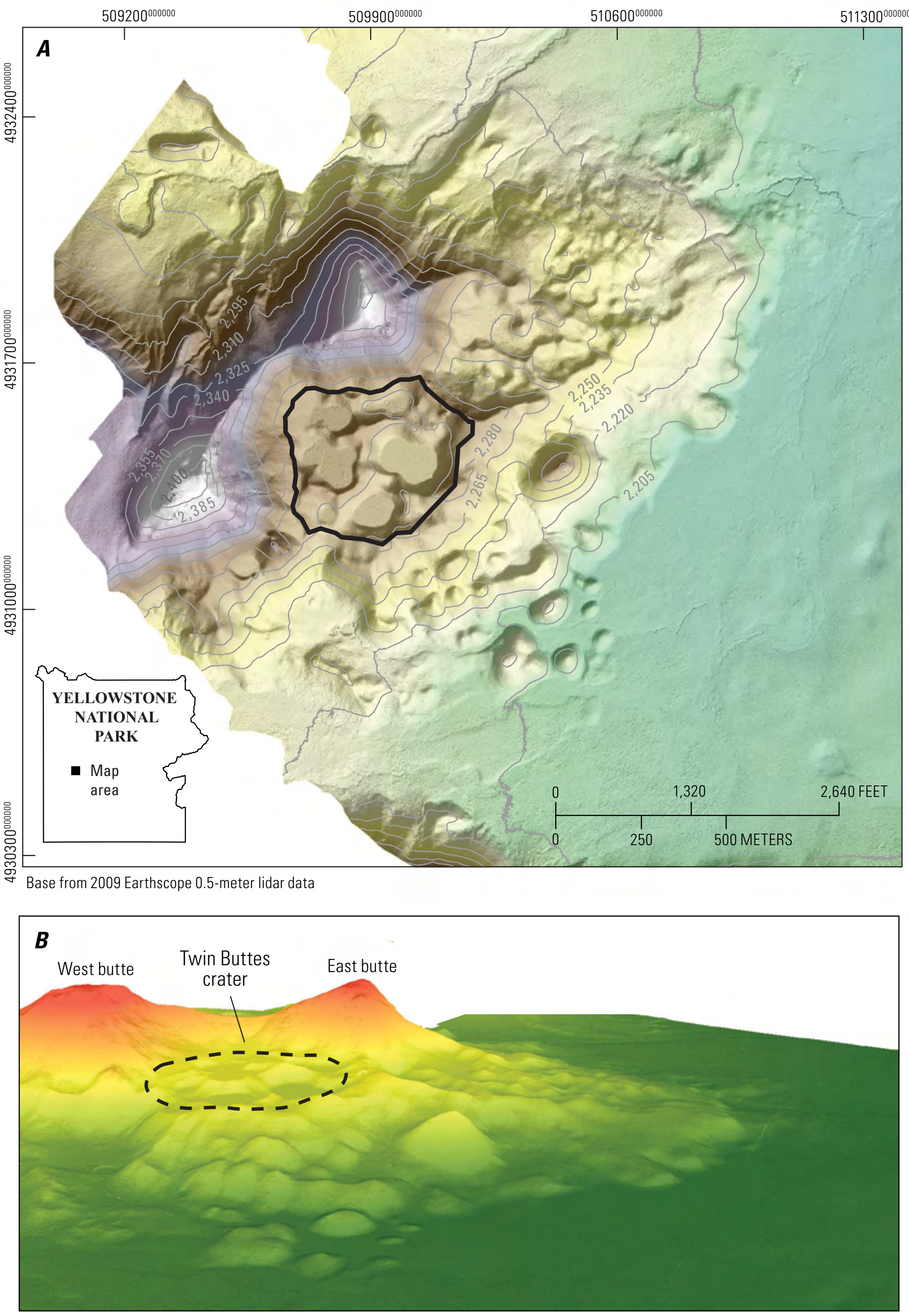


Figure 21. *A*, Color shaded relief of the Twin Buttes hydrothermal explosion crater in Lower Geyser Basin. High elevations are whites and purples, low-lying areas are greens and yellows. The explosion crater is outlined in black and contains multiple smaller craters that are currently filled with water to create small, perched lakes. Two large buttes (Twin Buttes) stand above the crater to the north and west, and the area to the east and south of the crater is surrounded by complex topography of explosion debris, slump blocks, and hills that existed before the explosion. Gray lines show elevation contours; interval is 15 meters. *B*, Oblique view of the colored digital elevation model looking north. The circumference of the explosion crater (dashed line) is 645 meters (2,120 feet).

Figure 22. Photographs of sediment core collection from a lake near Twin Buttes in Lower Geyser Basin. *A*, Dr. Cathy Whitlock, from Montana State University, examines a freshly recovered 1-meter (3.3-foot) sediment core. Cores were described and measured in the field before being carefully wrapped for transport to the laboratory. Photograph by Shaul Hurwitz, U.S. Geological Survey, August 2022, under permit YELL–2022–SCI–0009. *B*, Longitudinally split core that exhibits a change in lake productivity (laminated gray sediment on bottom transitions to dark organic-rich sediment on top). Half of the core is sampled and scanned for multiple types of data, and the other half is archived. Photograph by Lauren Harrison, U.S. Geological Survey, September 2022.

Figure 23. Photograph of travertine stalactites at Mammoth Hot Springs. Photograph by Lauren Harrison, U.S. Geological Survey, May 2022, under permit YELL–2022–SCI–8192.

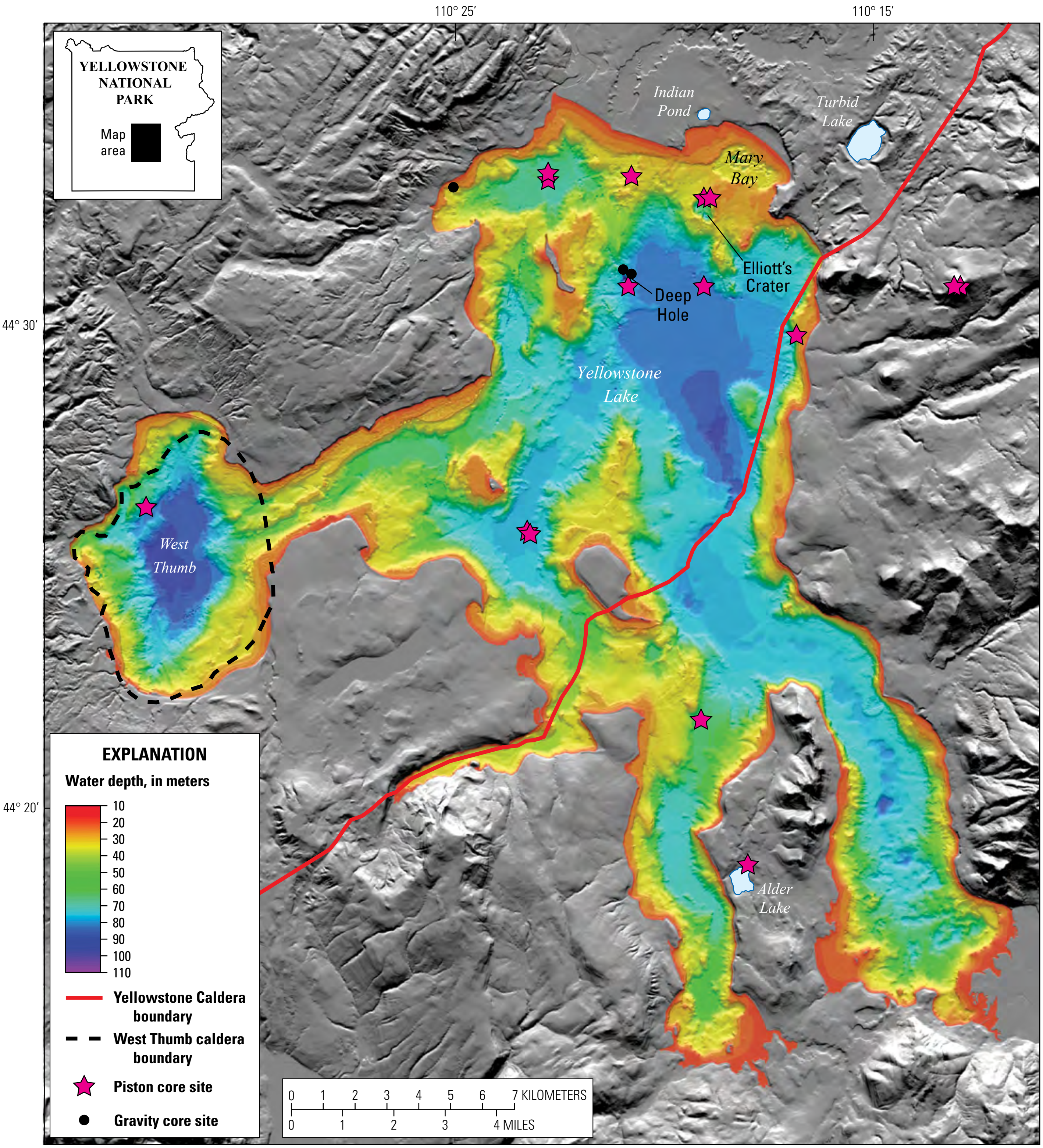
Hydrothermal Travertine Within Yellowstone Caldera

In the Yellowstone region, the location, volume, and deposition rate of travertine deposits provide a record of changing hydrothermal systems over centuries to millennia. Travertine (fig. 23) is a form of limestone that precipitates from high-temperature hot springs. The most well-known and well-studied travertine area in Yellowstone National Park is Mammoth Hot Springs. There, warm thermal waters that contain abundant CO_2 supplied by the Yellowstone magmatic system dissolve subsurface sedimentary units that formed as part of an inland shallow sea hundreds of millions of years ago. Upon surface discharge of the waters at Mammoth Hot Springs, the release of CO_2 gas to the atmosphere results in precipitation of calcium carbonates called travertine.

Smaller travertine deposits (less than 50 meters [164 feet] in horizontal extent and only a few meters [yards] thick) occur locally within the Yellowstone Caldera in Upper and Lower Geyser Basins. These deposits are not actively growing; however, they are associated with thermal features that are no longer depositing travertine or that are extinct. The existence of travertine within the caldera is puzzling because most hydrothermal systems in the caldera do not have the chemical conditions that are needed to form travertine. Investigation into the ages and chemistry of these small travertine deposits is ongoing, and in 2022 samples were collected for a new analytical technique that may provide information into the differences in the hydrothermal systems depositing travertine between Mammoth Hot Springs and within the caldera.

Yellowstone Lake Studies

Yellowstone Lake (fig. 24) is the largest high-altitude (above 2,100 meters, or about 6,900 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 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, Yellowstone National Park, Yellowstone Foundation, and Global Foundation for Ocean Exploration (Sohn and others, 2017). Although funding concluded in 2019, HD-YLAKE scientists continue to analyze data collected during the project and develop and pursue new lines of study. The overall aim of the research, which involves scientists from numerous institutions around the world, is to understand how



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

Figure 24. Bathymetric map of Yellowstone Lake showing the locations of gravity and piston cores and major hydrothermal explosion sites, including Mary Bay, Turbid Lake, Indian Pond, and the area known informally as Elliott's Crater.

Yellowstone Lake hydrothermal systems respond to geological and environmental changes by compiling observations of temporal changes in hydrothermal fluid temperature and composition, heat flow, seismicity, water-column processes, and microbial communities that inhabit the vent fields. Field strategies take a two-pronged approach: (1) geophysical and geochemical monitoring of the active hydrothermal system and (2) analyses of sediment cores to study the postglacial (approximately 14,000-year) history of sedimentary, tectonic, and hydrothermal activity beneath the lake.

Summary of Yellowstone Lake Studies in 2022

In 2022, scientific research of Yellowstone Lake focused on interpreting the records contained within numerous sediment cores collected since the 1990s from the lake bottom. The cores contain evidence of past hydrothermal explosions, faulting, and localized areas of uplift, called hydrothermal doming, over the past 14,000 years. These data provide important insights into the causes and consequences of hydrothermal explosions around Yellowstone Lake.

The Dynamic Floor of Yellowstone Lake over the Past 14,000 Years

Hydrothermal explosions caused by water flashing to steam in a confined area have emerged as one of the most important and least understood geologic hazards in Yellowstone National Park and similar volcanic and hydrothermal terrains worldwide. Hydrothermal explosions require a sudden drop in pressure, which causes rapid expansion of high-temperature fluids, fragmentation of overlying rock, ejection of debris, and crater formation. The northeastern part of Yellowstone Lake has an abundance of large (500–2,500 meters [1,640–8,200 feet] in diameter) explosion craters—the greatest concentration of such features anywhere in Yellowstone National Park and, in fact, the three largest hydrothermal explosion craters known on Earth. The craters include the partly submerged 13,000-year-old Mary Bay explosion crater (more than 2.5 kilometers [1.6 miles] in diameter), the 9,400-year-old Turbid Lake explosion crater (1.6 kilometers [1 mile] in diameter), the approximately 8,000-year-old Elliott's Crater (more than 700 meters [0.4 mile] in diameter) on the bottom of Yellowstone Lake, and the 2,900-year-old Indian Pond explosion crater (about 500 meters [0.3 mile] in diameter).

Geological and geochemical studies of 18 cores from the floor of Yellowstone Lake (fig. 24) identified 16 distinct hydrothermal explosion events ranging in age from about 13,000 years ago to about 1860 C.E. The research revealed that two distinct types of hydrothermal systems produce explosions in and around Yellowstone Lake. First, neutral- or alkaline-chloride fluids, like those that characterize Upper Geyser Basin near Old Faithful Geyser, can flash to steam after a sudden drop in pressure, producing the largest explosions in terms of energy, volume, and crater size. Second, vapor-expansion explosions in vapor-dominated thermal areas, similar to that at Mud Volcano on land, result in smaller, but possibly more frequent, explosion events.

The two largest explosion events identified in sediment cores from Yellowstone Lake had different triggers, but both involved seismic events. The Elliott's Crater explosion (fig. 25*A*) resulted from a major earthquake about 8,000 years ago that ruptured a hydrothermal dome, causing rapid decompression that prompted water to flash to steam. In contrast, the Mary Bay explosion about 13,000 years ago (fig. 25*B*) was triggered by a sudden drop (about 14 meters [45 feet]) in lake level, probably initiated by a large earthquake on the lake floor. The resulting local tsunami would have caused significant erosion of the lake's outlet, triggering rapid fluctuations in lake level. The changes in pressure on the hydrothermal system caused by the lake-level variations could have been sufficient to generate steam rapidly in the Mary Bay hydrothermal system, causing the explosion.

A key discovery of the new research is the general relation between the composition of hydrothermal fluids and the magnitude of explosions, where alkaline-chloride systems produce much larger explosions than vapor-dominated systems. This new information provides important insights into hazards associated with any future hydrothermal explosions in the Yellowstone region.

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 satellites and aircraft, and proxy measurements of chloride in Yellowstone National Park's rivers (see sidebar on monitoring thermal changes on p. 36–37).

Summary of Heat Flow Studies in 2022

The total geothermal radiative heat output from Yellowstone National Park's thermal areas in 2022, estimated from satellite thermal-infrared observations, was similar to that measured in previous years. Heat output based on chloride flux in Yellowstone National Park's rivers was lower than measured in years past, but measurement uncertainty was higher in 2022 compared to previous years owing to the historic flooding that occurred in June. Together, the thermal-infrared and chloride-flux measurements indicate that the total thermal discharge remained relatively steady.

Thermal-Infrared Remote Sensing

Most of Yellowstone's thousands of thermal features are clustered together into about 120 distinct regions. These areas are defined as having multiple thermal features, characterized by

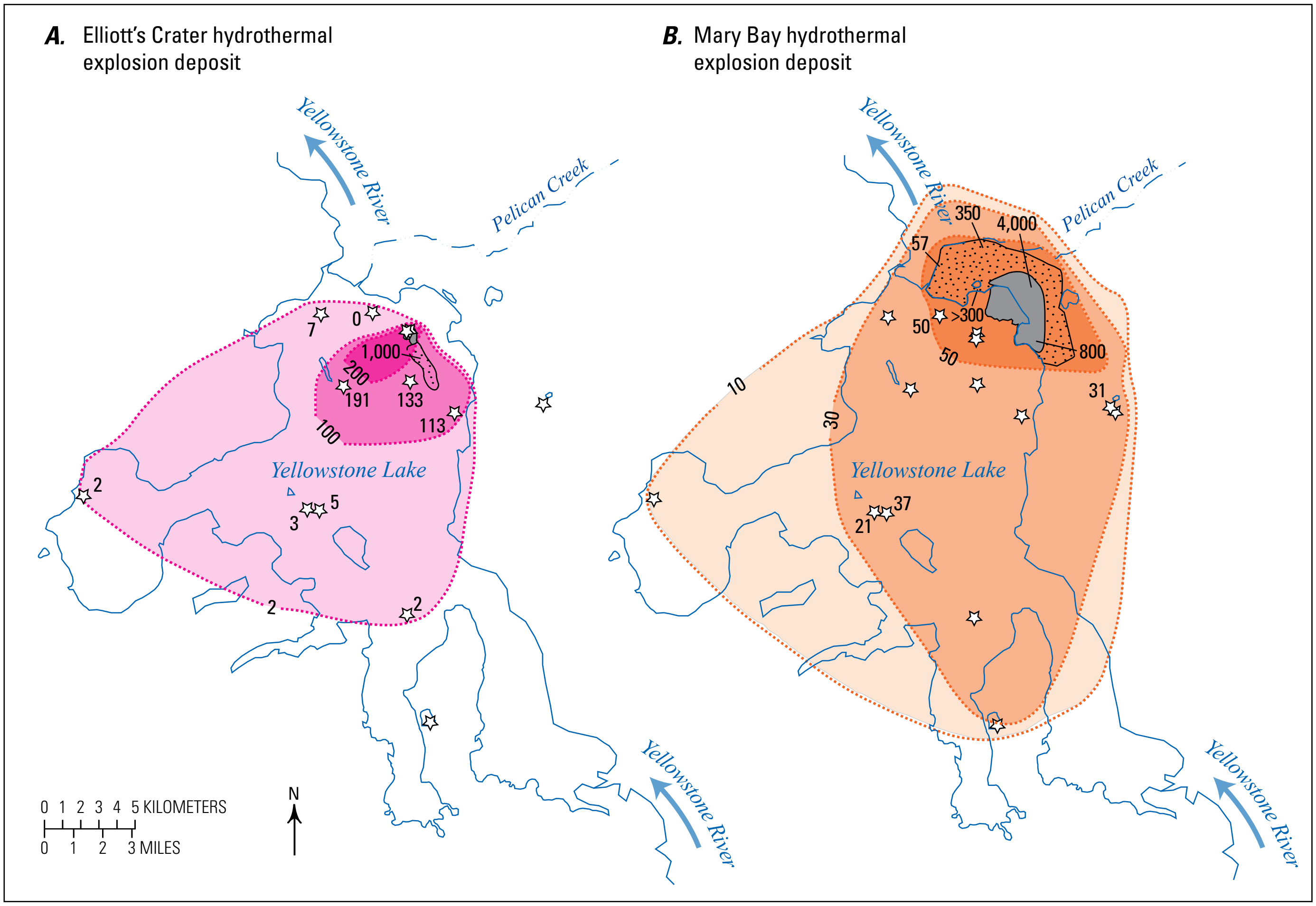


Figure 25. Simplified maps showing the areal distribution and thickness (in centimeters; 1 centimeter=0.4 inch) of hydrothermal explosion deposits from Elliott's Crater and Mary Bay explosion craters in the northern part of Yellowstone Lake. White stars represent the locations of piston cores containing lake-bottom sediment; associated numbers give the thickness at that location. Gray areas represent each explosion crater. *A*, Distribution of the Elliott's Crater hydrothermal explosion deposit. Magenta areas show the approximated extent of Elliott's Crater explosion deposits at thickness intervals of 2, 100, and 200 centimeters. An approximately 10-meter (33-foot) thick lobe of explosion breccia (dotted area) extends south-southeast from the crater and is interpreted as a subsequent directed blast from the subcrater in the southern part of the main crater. *B*, Distribution of the Mary Bay hydrothermal explosion deposit. Dotted area represents Mary Bay explosion deposits exposed on land. Orange areas show the approximated distribution of Mary Bay explosion deposits at thickness intervals of 10, 30, and 50 centimeters. Modified from Morgan and others (2023).

hydrothermally altered ground and (or) hydrothermal mineral deposits, emitting geothermal heat and (or) gases, and generally barren of vegetation or with stressed or dying vegetation. Heated bodies of water are referred to as thermal drainages—typically a lake, pond, or wetland area that is thermally emissive because it receives heated water from a nearby thermal area, a nearshore thermal spring, or underwater vents.

Analysis and interpretation of thermal-infrared remote sensing data for characterizing Yellowstone thermal areas and thermal drainages has been ongoing for several years. Satellite thermal-infrared data with moderate spatial resolution (90 to 100 meters [295 to 328 feet] per pixel) are useful for mapping, measuring, and monitoring the characteristics of most thermal areas and thermal drainages on a regional to park-wide scale. There are some thermal areas and thermal drainages that are too subtle (either too small or not hot enough) to be clearly detected with moderate-resolution data. Higher resolution thermal-infrared data would be useful for characterizing these areas; however, such data are not regularly acquired over the Yellowstone region. Fortunately, thermal areas and thermal drainages also have characteristics that can be identified with high-resolution (0.5 to 2 meters [1.6 to 6.5 feet] per pixel) visible remote sensing data. Thus, moderate-resolution thermal-infrared data and high-resolution visible data are used together to characterize Yellowstone's thermal areas and thermal drainages.

Monitoring Thermal Changes at Yellowstone National Park

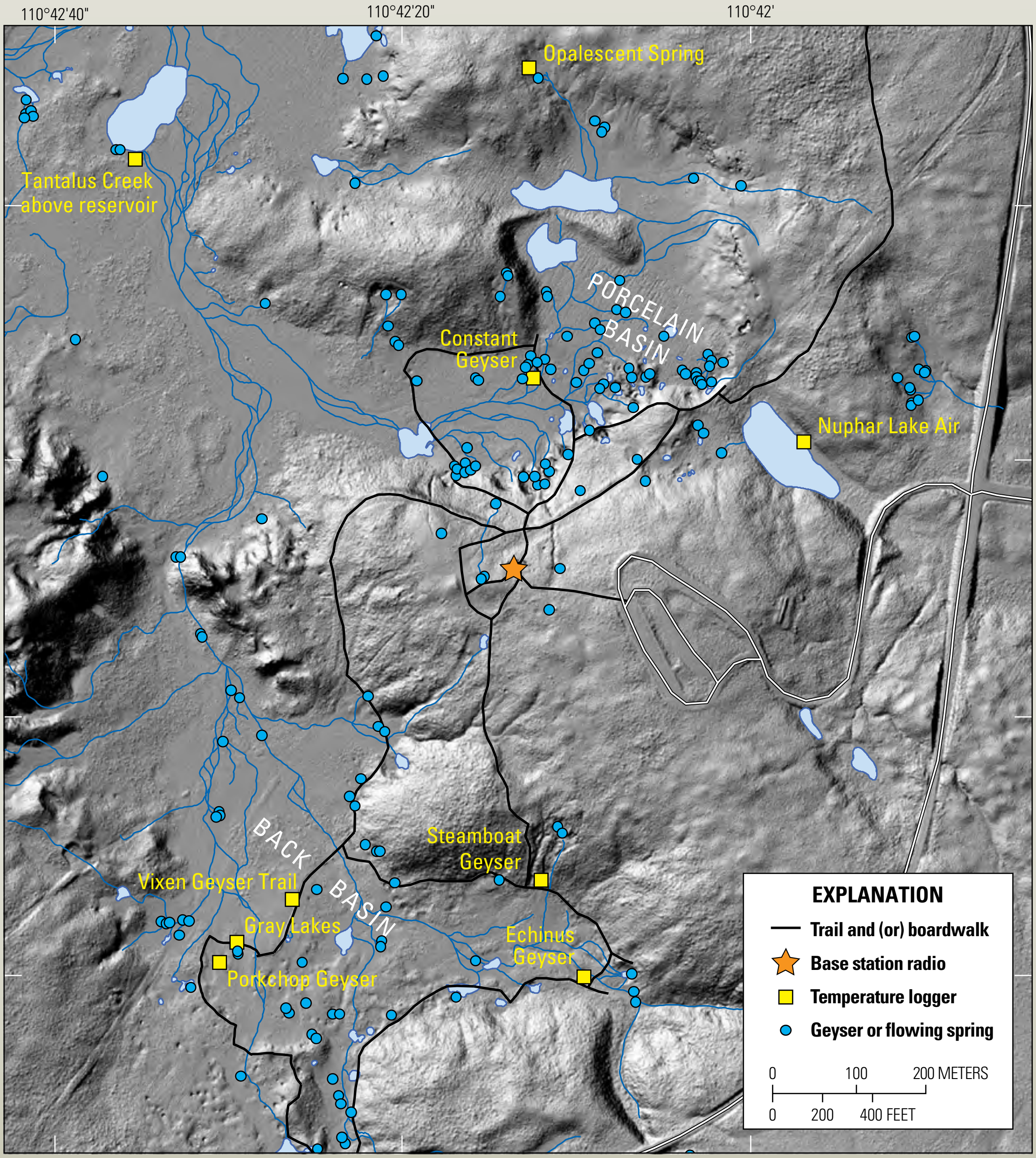
A lot of heat is released in the Yellowstone region from thermal features like hot springs, geysers, mud pots, and fumaroles. Tracking the temperatures and sizes of thermal areas is critical for monitoring Yellowstone Caldera's hydrothermal activity and for understanding and preserving these spectacular 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 anytime. These thermal probes have proven useful for detecting geyser eruptions when visual observations are impossible (because of 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 the Yellowstone region, other techniques are employed—for example, tracking the chemistry of Yellowstone National Park'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 river water because hydrothermal water has a high concentration of chloride. In fact, nearly all (95 percent) of the chloride in Yellowstone National Park rivers comes from thermal features. Thus, monitoring the chloride flux (or variability) 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 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 moderate spatial resolution, with pixels that are 90 to 100 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.

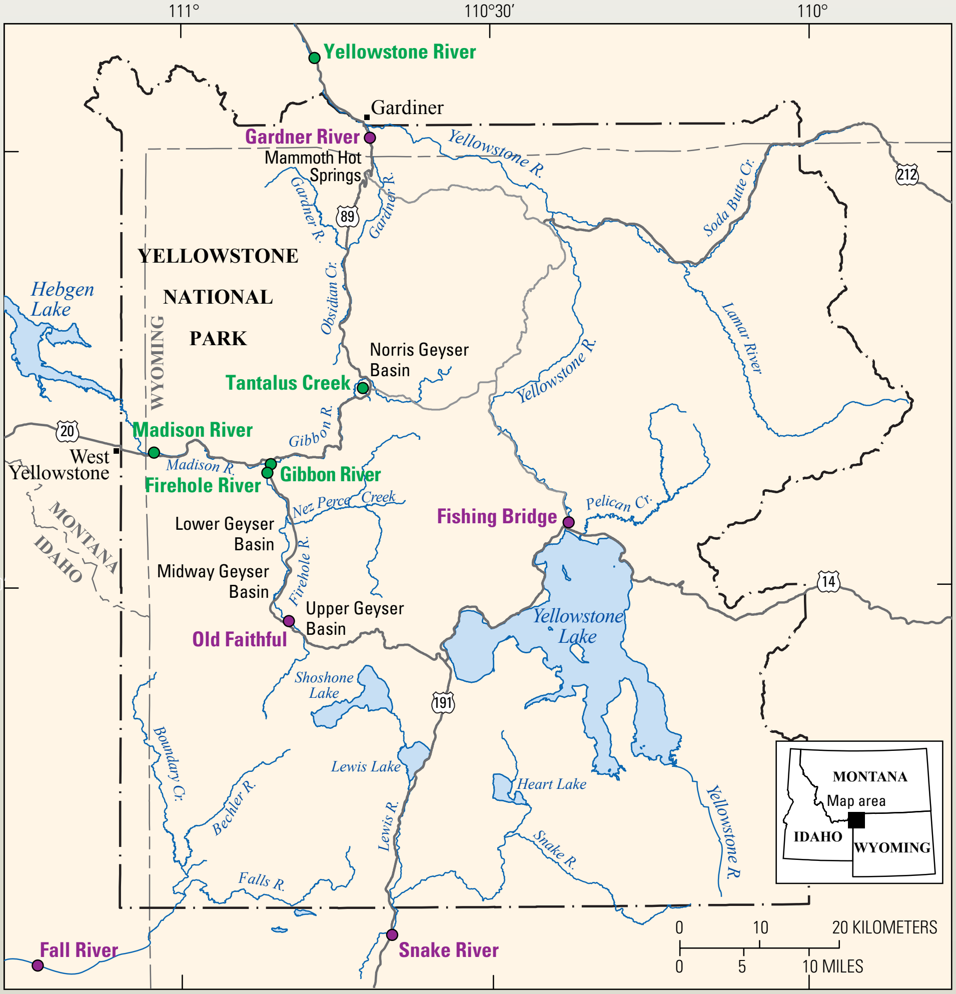
One of the challenges of thermal-infrared remote sensing is that temperature contrasts can be low, and thus challenging to discern. Hot springs and fumarole fields are relatively subtle thermal features compared to extremely hot features like active lavas or fires because the thermal features exhibit 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



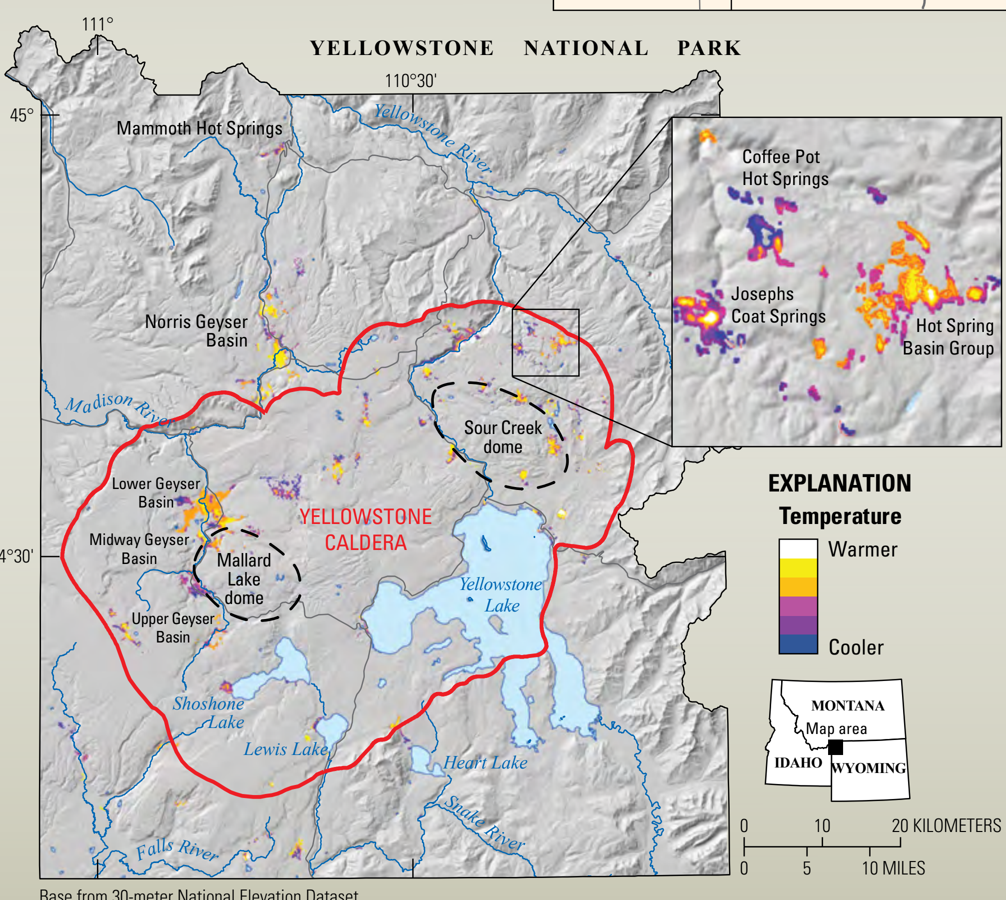
Base from 2009 EarthScope 0.5-meter lidar data

Map of temperature measurement sites in Norris Geyser Basin.

radiance and maximizes the contrast between thermal and background areas. At night, water bodies are generally warmer and more radiant than the surrounding land surface and can mask thermal areas adjacent to lakes. In Yellowstone National Park, lakes that do not receive thermal input from nearby hot springs or underwater vents are frozen from late fall 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 in 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 January 9, 2021. The warmest areas (white) are 20–30 °C (36–54 °F) above background; the cooler areas (blue) are 2–4 °C (4–7 °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 primary satellite-based thermal-infrared data used for thermal area characterization in the Yellowstone region are Landsat 8 and Landsat 9. Other moderate-resolution thermal-infrared satellite data, such as from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) or Ecosystem Thermal Radiometer Experiment on Space Station (ECOSTRESS), are not normally acquired in the area with a spatial coverage or cadence that is ideal for regular monitoring. Landsat 8 nighttime thermal-infrared data have been acquired over the Yellowstone region since its launch in 2013, nominally every 16 days. Landsat 9, which is nearly identical to Landsat 8, was launched in 2021 into an offsetting orbit; thus, together they have the potential to image the Yellowstone region at night every 8 days. In 2022, a total of 33 nighttime scenes (23 from Landsat 8 and 10 from Landsat 9) were acquired. Of these, 25 were too cloudy. However, there was a clear nighttime thermal-infrared scene acquired in the winter on January 28, 2022; those data were processed and analyzed for this report (fig. 26).

The results of the January 28, 2022, thermal-infrared data analyses were similar to those from previous years in that the same regions tended to be the warmest and most radiant. The thermal areas with notably high pixel temperatures, 30 to 41 °C (54 to 73 °F) above background, were Sulphur Hills and Midway Geyser Basin. These two thermal areas also had the highest geothermal radiant emittance values, ranging from 120 to 163 watts per square meter. The thermal area with the highest total geothermal radiative power output (in megawatts), which tends to be the largest in area, was Lower Geyser Basin, emitting about 295 megawatts. Other large areas with notably high geothermal radiative power output include Norris Geyser Basin, Hot Spring Basin, Astringent Creek, and Roaring Mountain, with outputs ranging from 100 to 195 megawatts. The total geothermal radiative power output summed for all of Yellowstone National Park's thermal areas was 2.2 gigawatts. This value, calculated only for the portions of thermal areas that were warmer than 2 standard deviations above the mean temperature of the background, is within the range of values reported from the previous few years (1.8 to 2.5 gigawatts).

Chloride Flux Monitoring

Measuring the thermal output of Yellowstone Caldera's large magmatic system is not straightforward, as thousands of thermal features are spread across more than 9,000 square kilometers (3,500 square miles). Since thermal-water discharge eventually enters nearby rivers, one way to capture and integrate the contributions from this broad area is to monitor river chemistry. Nearly all the chloride in rivers that drain Yellowstone National Park comes from emerging hot-spring water heated underground by underlying magma. By monitoring the chloride flux, the hydrothermal discharge and heat flux from the Yellowstone region can be estimated, and variations (both short and long term) can be used to identify changes in the deep hydrothermal system, earthquake activity, geyser eruptions, and other natural events (like floods and the effects 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 stations can make measurements of specific conductance every 15 minutes.

Monitoring the chloride (and other geothermal solutes) flux in the major rivers draining Yellowstone National Park continued in 2022. 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. 36–37). 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.

The use of specific conductance as a proxy for chloride requires knowledge of the relation between specific conductance, chloride, and other geothermal solutes (sulfate, fluoride, bicarbonate, silica, potassium, lithium, boron, and arsenic), and the relation needs to be confirmed annually. Water samples were collected during two 2022 field trips to assess the solute-specific conductance correlations.

Quantifying the chloride flux was challenging in 2022 because of the historic flooding that occurred in northern Yellowstone National Park from June 10–13. A specific conductance probe was buried under about 1.2 meters (4 feet) of debris at the Gardner River monitoring site (fig. 27), and excessive fouling caused by large amounts of suspended sediment occurred at other locations, especially the Yellowstone River at the Corwin Springs monitoring site just north of Yellowstone National Park. Furthermore, river discharges were the largest on record, and errors associated with discharge measurements were greater than normal because of extrapolation to rating curves and changing streambeds. Finally, the water composition during the storm event was likely different than normal flow conditions, and the specific conductance proxy may not have been valid during the period of extreme discharge. Consequently, the error in the annual chloride flux is expected to be close to ±15 percent.

In 2022, the total chloride flux leaving Yellowstone National Park was 44±7 kilotons, which was determined by summing the flux from the Madison, Yellowstone, Snake, and Fall Rivers. This is lower than historical measurements of 51±5 kilotons (based on data collected during 1983–2003 and 2013–2021), although the difference might not be significant given the uncertainty in the measurements and calculation. The percentages of the total flux from the Madison (45 percent), Yellowstone (32 percent), Snake (12 percent), and Fall (11 percent) Rivers for 2022 are shown in figure 28*A*. The

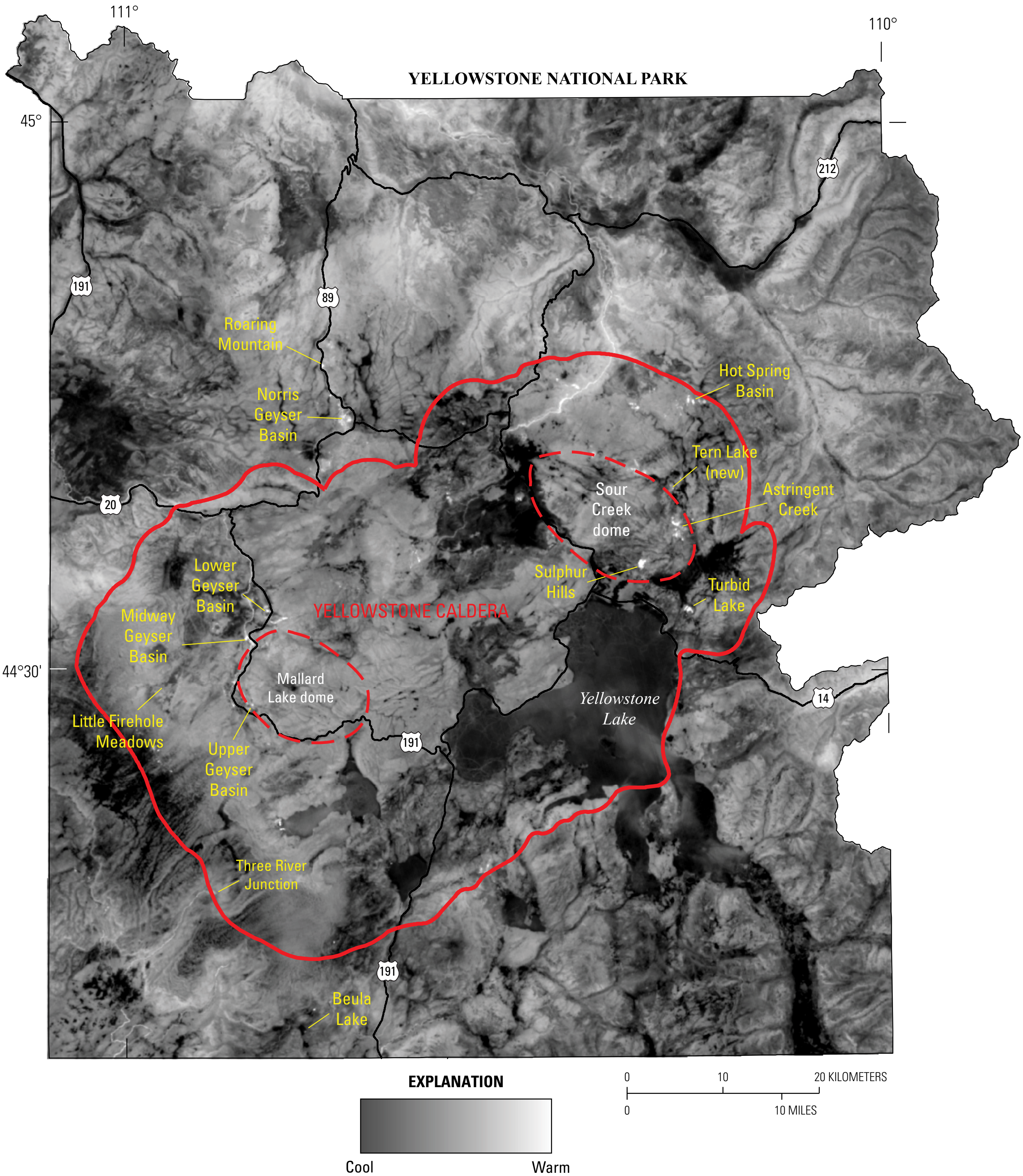


Figure 26. Landsat 8 nighttime thermal-infrared image of Yellowstone National Park from January 28, 2022. Satellite-based thermal-infrared data show areas on the surface that are warmer versus cooler, and they can be used to estimate surface temperature and the geothermal radiative heat output from the Yellowstone magmatic and hydrothermal system. The warmest areas (lightest in shade) in this image are as much as 41 °C (73 °F) above background. Geologic structures are indicated in red; thermal areas are labeled in yellow.

Figure 27. Photograph of Gardner River chloride flux monitoring site before and after the June 2022 flooding in Yellowstone National Park. *A*, Site prior to June 2022 storm. Note that the riverbank is near the base of the fallen tree. Photograph by Blaine McCleskey, U.S. Geological Survey, May 21, 2014. *B*, Site after June 2022 storm. The specific conductance probe is buried under about 1.2 meters (4 feet) of debris. Photograph by Blaine McCleskey, U.S. Geological Survey, September 5, 2022.

2022 chloride fluxes measured at every monitoring site were lower than most historical (beginning 1983) fluxes (fig. 28*B*). Continued chloride flux monitoring will determine if the observed decrease in hydrothermal discharge from the thermal areas lasts.

Geysers, Hot Springs, and Thermal Areas

Yellowstone National Park 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 Geyser that exist in comparative isolation, follow patterns that allow their activity to be forecast. However, most of Yellowstone National Park's geysers, springs, and other thermal features have unpredictable behavior. Thermal features occur in clusters, forming about 120 distinct regions called thermal areas that are found throughout Yellowstone National Park (see sidebar on p. 36–37).

Summary of Geyser Activity and Research in 2022

The most noteworthy geyser activity in Yellowstone National Park during 2022 continued to be water eruptions from Steamboat Geyser, the tallest active geyser in the world. Fewer eruptions occurred in 2022 compared to the previous 4 years, indicating that the geyser's current period of activity, which started in 2018, may be waning. Research efforts during the year focused on the eruptive history of Steamboat Geyser, interactions between geysers in Lower Geyser Basin, gas and thermal emissions from the new thermal area near Tern Lake, documentation of small thermal areas in the area of Little Firehole Meadows, and reactivation of a small thermal feature in the southwestern part of Yellowstone National Park. Yellowstone National Park geologists also expanded the telemetered thermal logging system to new geysers in the Upper Geyser Basin and continued regular monitoring of hydrothermal features in the park.

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 328 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 (fig. 29) 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 [YVO, 2021a]). That trend continued in 2019 with 48 major eruptions, shattering the record set during the previous year—a record that was equaled with 48 major eruptions in 2020 (see YVO 2019 and 2020 annual reports [YVO, 2021b,c]). In 2021, however, there were only 20 major water eruptions (see YVO 2021 annual report [YVO, 2022a]), and there were only 11 eruptions in 2022—impressive numbers by most measures except when compared to the preceding years. It is unclear if fewer eruptions in 2021 and 2022 is an indication that the current episode of frequent activity is coming to an end.

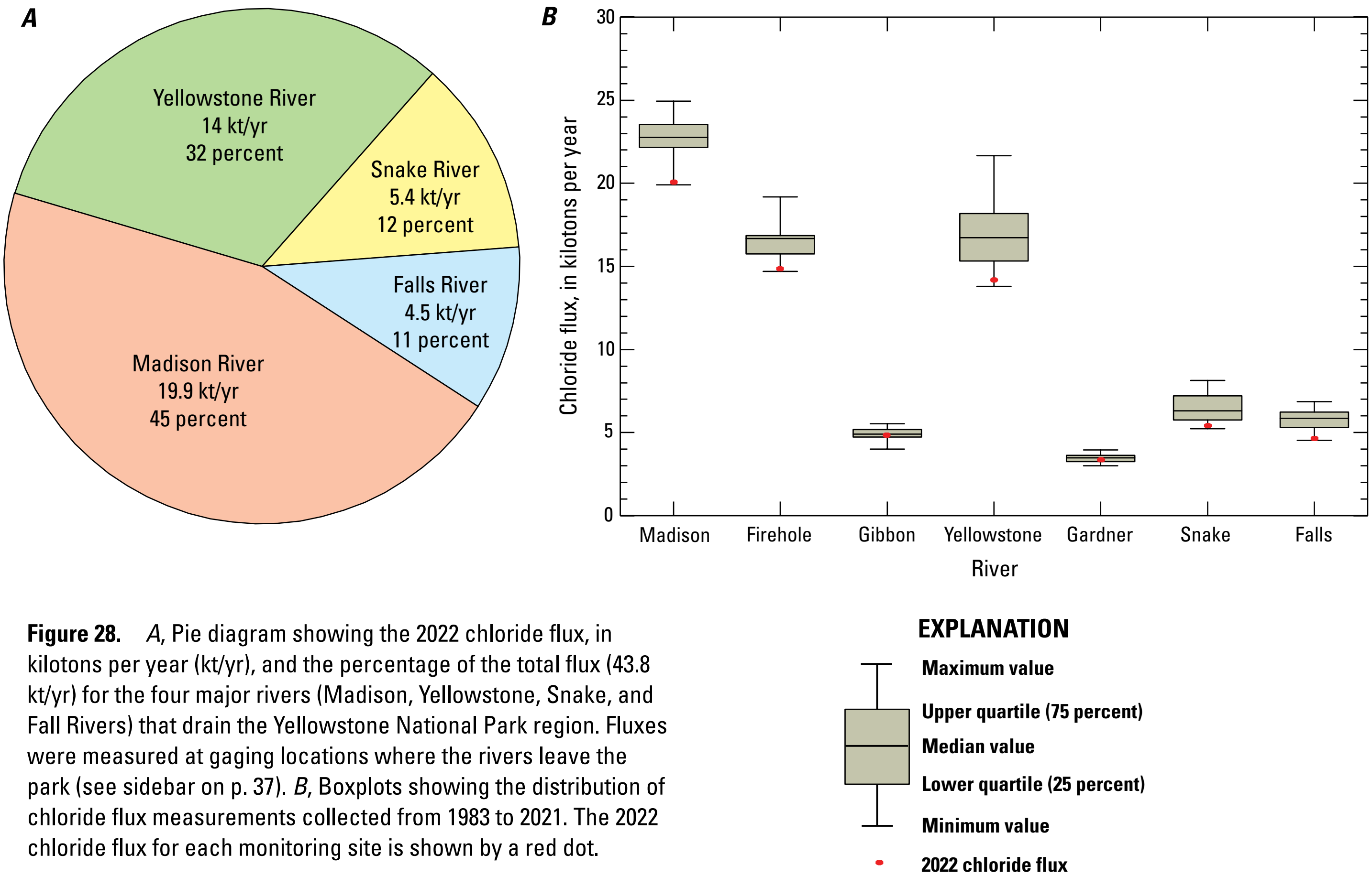


Figure 28. *A*, Pie diagram showing the 2022 chloride flux, in kilotons per year (kt/yr), and the percentage of the total flux (43.8 kt/yr) for the four major rivers (Madison, Yellowstone, Snake, and Fall Rivers) that drain the Yellowstone National Park region. Fluxes were measured at gaging locations where the rivers leave the park (see sidebar on p. 37). *B*, Boxplots showing the distribution of chloride flux measurements collected from 1983 to 2021. The 2022 chloride flux for each monitoring site is shown by a red dot.

Each eruption of Steamboat Geyser followed the same general pattern: gradually increasing minor activity over hours to days, culminating in a major water eruption that lasts 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, a pool at Cistern Spring, located about 100 meters (300 feet) downslope, drains within a day after each eruption and then gradually refills over the following days.

As in 2021, the intervals between geyser eruptions in 2022 were longer and more variable than in previous years. The shortest interval between eruptions was slightly more than 10 days, which occurred in June, and the longest interval was almost 90 days, which occurred during June–September. In previous years, the shortest intervals between eruptions occurred in summer months, presumably owing to abundant groundwater from spring snowmelt (see 2020 YVO annual report [YVO, 2021c]). This pattern was broken in 2021 (see 2021 YVO annual report [YVO, 2022a]), but was partly reestablished in 2022, with the shortest

Figure 29. Photograph of Steamboat Geyser shortly after a major water eruption on September 19, 2022. In 2022, 11 major water eruptions occurred—fewer than in the preceding 4 years and with more variable intervals between eruptions. Photograph by Kiernan Folz-Donahue, National Park Service.

intervals in May–June. How the current episode of frequent eruptions may end is unknown, but the trend of the past 2 years suggests it will continue to diminish in 2023.

As in past years, 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://www.usgs.gov/volcanoes/yellowstone.

In May 2022, scientists from the USGS, Lone Pine Research, Yellowstone National Park, and the University of California, Berkeley, collected fossilized wood samples from around Steamboat Geyser. The wood samples, which are tree remnants, were collected for radiocarbon dating to determine when the trees grew, which will help to indicate times of geyser inactivity. The age of the wood samples will also provide information about the possible date the geyser formed, as well as how the geyser may have responded to regional precipitation patterns over decades to centuries. Written documents suggest that Steamboat Geyser formed in 1878, but evidence for or against prior possible geyser eruptions is lacking. Additionally, cores from live trees surrounding the geyser's active sinter mound were collected to search for damaged or absent rings from years associated with sustained episodes of geyser eruptions, such as the sequence that began in March 2018. All samples were collected under the National Park Service Geology Programs Milestones Permit 2016-9, and results from the study are expected in 2023.

Interactions Among Geysers in Upper Geyser Basin

Scientists from the University of Maryland, together with geologists from Yellowstone National Park and the USGS, examined and quantified possible correlations in geyser eruptions in Upper Geyser Basin, which is home to the greatest concentration of geysers in the world. Prior research suggested that individual geysers are not isolated but rather are hydraulically connected to other geysers and thermal springs through the subsurface. To quantify such connections, several mathematical techniques were combined to characterize the collective eruptive behavior of a set of 10 geysers over 18 months (April 2007 to September 2008). Model results predicting a geyser's eruptive activity improved by a factor of 15 when the eruptions of all geysers in the network were considered compared with the eruption time series of a single geyser alone. Results also revealed that on average, cone-type geysers (fig. 30*A*) had larger effects on other geysers than did fountain-type geysers (fig. 30*B*), and that geysers located close together had stronger effects on one another than did geysers located farther away from each other (Fagan and others, 2022). The study's findings emphasize the subsurface interconnectedness of thermal features in the Upper Geyser Basin.

Reconnaissance Study of New Tern Lake Thermal Area

In September 2022, a group of seven scientists from the USGS and McGill University collected water, gas, and tree core samples from a relatively new thermal area that has been developing west of Tern Lake since about 2000 (fig. 31) (YVO, 2021a,b). Soil CO_2 concentrations were measured using a portable fluxmeter to collect soil CO_2 concentrations. The total CO_2 flux of the small (0.03 square kilometer [7.4 acres]) Tern Lake thermal area was calculated from 195 measurement points (fig. 32*A*), resulting in a total flux of 12.4 metric tons per day of CO_2. When compared to other nearby acid-sulfate thermal areas, such as Mud Volcano (0.4 square kilometer [99 acres] in area, with a CO_2 emission rate of more than 290 metric tons per day [Werner and Brantley, 2003]), the Tern Lake thermal area emitted around half as much CO_2 per unit area. The emissions of this area make up a small part of the total CO_2 emissions from the thermally altered, acid sulfate areas of the Yellowstone Plateau volcanic field, which is approximately 20 kilotons per day (Hurwitz and Lowenstern, 2014). Soil temperature data were collected at a depth of

Figure 30. Photographs showing examples of cone and fountain geysers in Yellowstone National Park. *A*, Lone Star Geyser is a good example of a cone-type geyser. Photograph by Jacob W. Frank, National Park Service, June 25, 2012. *B*, Great Fountain Geyser exemplifies fountain-type geysers. Photograph by Neal Herbert, National Park Service, November 10, 2016.

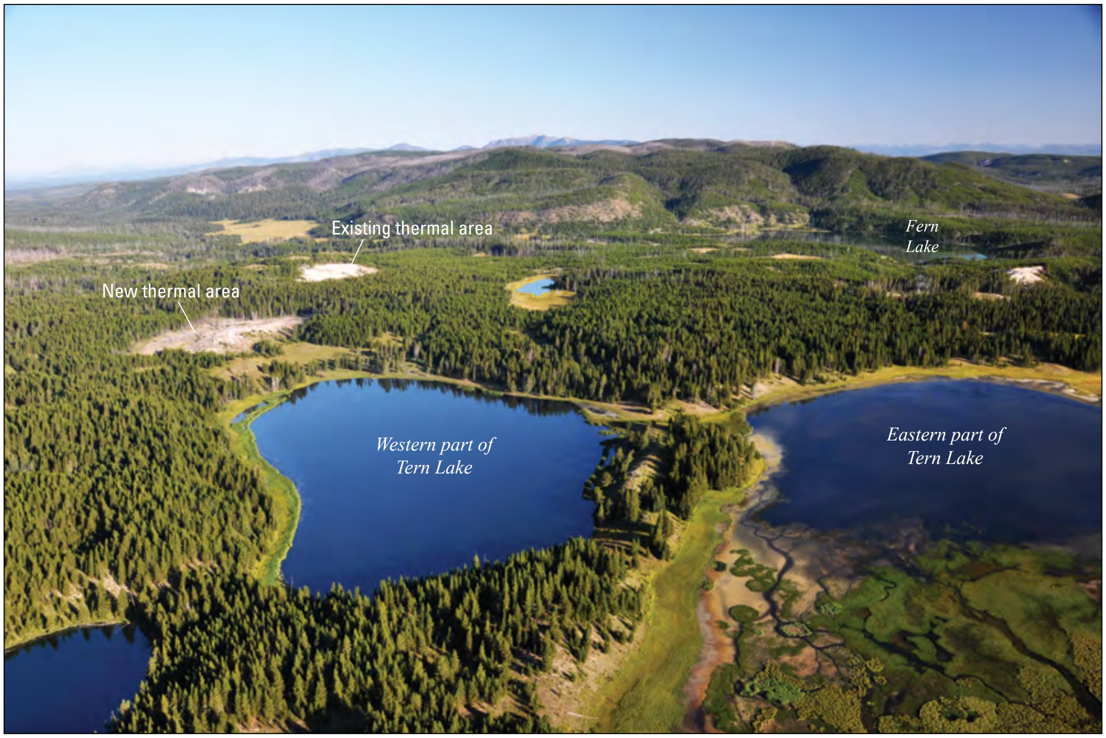


Figure 31. Aerial view looking north at the thermal area near Tern Lake that has been developing since about 2000. Photograph by Michael Poland, U.S. Geological Survey, on August 19, 2019.

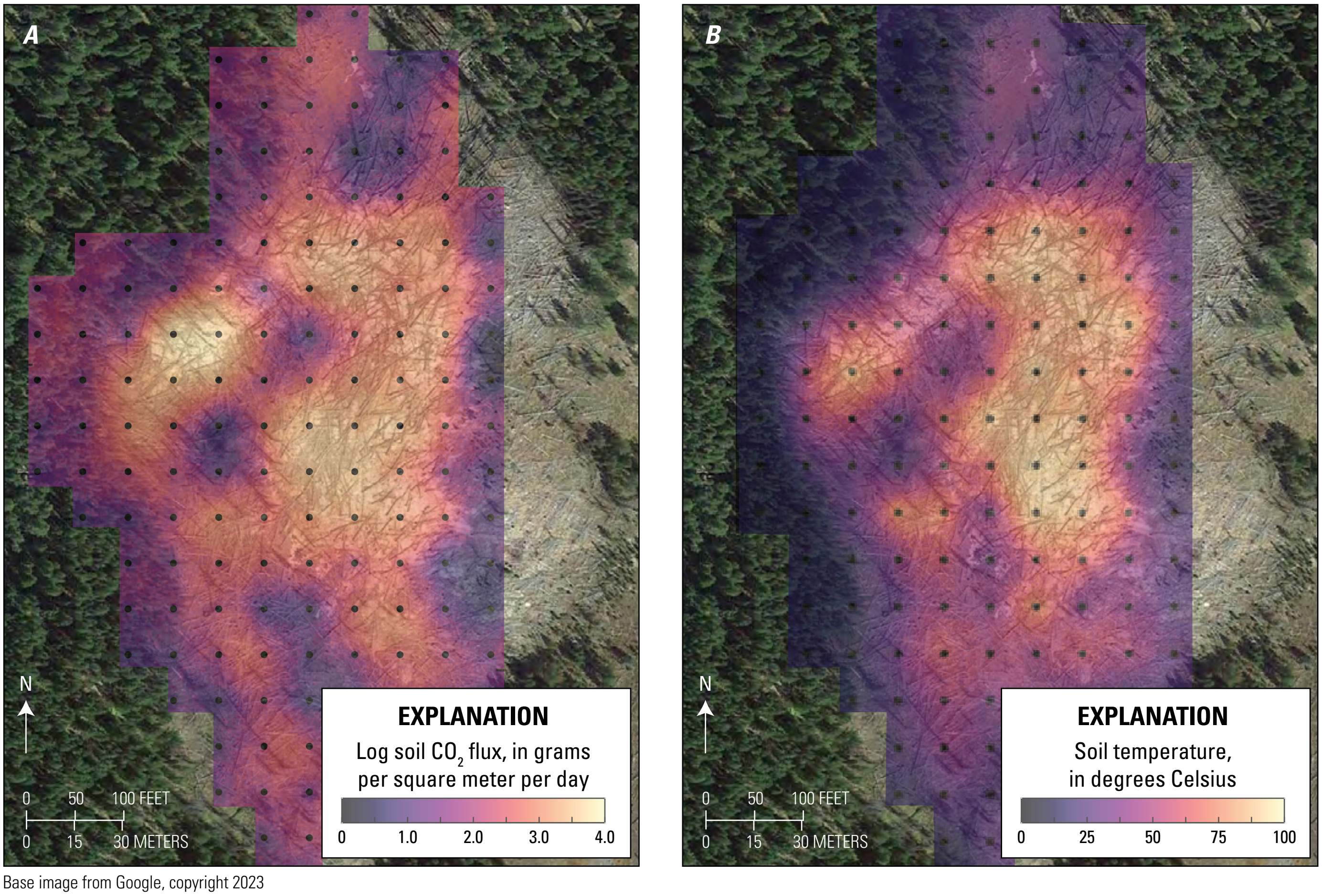


Figure 32. Maps of soil CO_2 concentration and temperature measured at a new thermal area near Tern Lake in Yellowstone National Park. *A*, Map of log soil CO_2 flux simulated based on measurements made at the black dots in September 2022. *B*, Map of soil temperature at a depth of 20 centimeters (8 inches). Location of Tern Lake thermal area shown in figures 26 and 31.

20 centimeters (8 inches) at the soil CO_2 measurement locations, and the highest temperatures (generally about boiling for that elevation) correspond to the areas of highest CO_2 concentrations (fig. 32*B*). Tree cores were also collected around the new thermal area to provide insight on the gas emission history of the area, as recorded by trees incorporating CO_2 into their rings.

In addition to work at the new thermal area, scientists took advantage of the proximity of other sites to collect gas samples from the Fern Lake, Ponuntpa Springs, and Sour Creek thermal areas. Water samples were collected from Pelican Creek, Astringent Creek, Fern Lake outlet, Broad Creek, and Sour Creek to quantify the thermal discharge from several areas in the Mirror Plateau. In addition, thermal water samples were collected from several springs in Hot Springs Basin and Ponuntpa Springs thermal areas. Water samples will be analyzed for many constituents, including mercury, arsenic, and rare earth elements. All water samples were collected under the Yellowstone National Park Research Permit YELL–05194, and gas samples were collected under permit YELL–2022–SCI–5406.

Recognition of Previously Unmapped Thermal Areas near Little Firehole Meadows

Mapping thermal areas in Yellowstone National Park is a work in progress, partly because changes occur frequently and also because some thermal areas are in remote wilderness regions that are not easily accessible. Satellites with thermal-infrared instruments can directly sense emitted surface radiance and differentiate most thermal areas from the background, but their moderate spatial resolution (90- to 100-meter [about 300 feet] pixels) limits the ability to detect thermal areas that are small or have temperatures insufficiently above background. Routinely acquired high-spatial-resolution airborne and commercial satellite data do not yet have thermal-infrared capabilities, but the sub-meter- to meter-scale (3 feet or less) pixels in those datasets enable detection and accurate characterization of the visible signs of thermal areas, including vegetation stress and mortality, mineral deposits, hydrothermal alteration, snow-free zones in winter, steaming, bubbling or boiling water, and variable water levels (although even these visible signs are not always obvious).

About 7 kilometers (4.3 miles) west of Biscuit Basin in Upper Geyser Basin is a small thermal area that was recently discovered. Located on the north side of Little Firehole Meadows, north of a small tributary to the Little Firehole River, there is a small hillside, barren of vegetation, with bright, hydrothermal mineral deposits or hydrothermally altered rocks, about 1,000 square meters in area (0.25 acres) (fig. 33*A*). It is too small and not hot enough to be detected with moderate-resolution thermal-infrared data, but high-resolution visible wintertime data going back to 2008 show that it is consistently warm enough to prevent snow accumulation in the winter. The archived high-resolution data also indicate that this thermal area has been consistent in size since 2006 and thus is not a newly emerging area like the one identified in 2018 near Tern Lake (Vaughan and others, 2020; YVO, 2021a) (fig. 31). Interestingly, there are several small ponds and wetlands near this thermal area, informally named the Little Firehole Meadows thermal area, that are also perennially free of snow in the winter (fig. 33*B*, *C*). These sites remain to be investigated in the field, but could be small, warm thermal drainages. The discovery of this existing, but newly mapped, thermal area was prompted by the mapping of a low-resistivity region using airborne electromagnetic surveys conducted in 2016 (Finn and others, 2022). More work is needed to characterize these subtle thermal areas, including field work to accurately measure surface and subsurface temperatures, catalog individual thermal features, and sample any emitted gases or water.

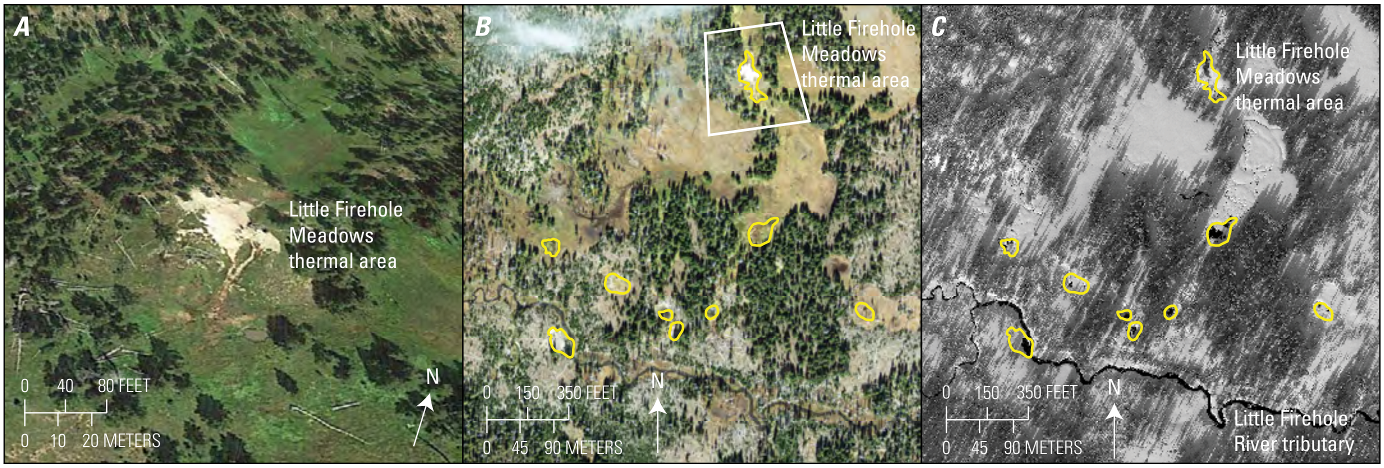


Figure 33. Images of newly mapped thermal areas near Little Firehole Meadows. *A*, Small newly mapped thermal area located on the north side of Little Firehole Meadows (see fig. 26 for location). This Google Earth oblique perspective view has 2× vertical exaggeration. *B*, National Agriculture Imagery Program natural color image from September 24, 2015, showing suspected thermal areas outlined in yellow. *C*, WorldView-1 image from January 17, 2020, showing numerous small ponds and wetland areas that are consistently and conspicuously warm (the same areas outlined in yellow as in part *B*), as indicated by the lack of snow. These locations have yet to be investigated in person as possible thermal drainages.

Tracking Changes in Thermal Features in Southwest Yellowstone National Park

The YVO annual reports from 2020 (YVO, 2021c) and 2021 (YVO, 2022a) described an unnamed thermal pool in the southwestern part of Yellowstone National Park that had gone dry in late 2019 or early 2020. It appears that sometime during the first half of 2021 this feature returned to its prior normal state, with three interconnected boiling hot spring pools, each 3 to 5 meters (10 to 16 feet) across, with runoff that flows over a colorful sinter mound into Ferris Fork, which feeds into the headwaters of the Bechler River at Three River Junction about 1.5 kilometers (1 mile) downstream. A combination of field photographs by backcountry rangers and archived high-resolution airborne and commercial satellite remote sensing data (fig. 34) were used to document the approximate timing of these changes. Photographs from a Yellowstone National Park backcountry ranger from July 2021 (fig. 34*F*) showed that the feature had returned to normal, and a high-resolution airborne image from the National Agriculture Imagery Program from July 2022 (fig. 34*E*) confirms this. Over the last 20 years, the apparent recent draining and cooling of this feature appears to be a unique event and remains unexplained. In the future, a combination of field and aircraft observations and commercial satellite images could be an effective way to continue monitoring changes to this and similar remote backcountry thermal features.

Monitoring Hydrothermal Features in Yellowstone National Park

During the 2022 field season, the Yellowstone National Park Geology Program team continued its work operating telemetered and manual thermal logger networks. The telemetered thermal logger system in the Upper Geyser Basin consists of sensors placed in geyser outwash channels that record changes in water temperature at 1-minute intervals. Rapid changes in water temperature represent geyser eruptions. The goal of the project is not only to document geyser eruptions and provide more accurate forecasts for visitors, but also to make the data publicly available via National Park Service data repositories. In 2021, a pilot system was set up to track activity at Old Faithful, Castle, Lion, Beehive, and Grand Geysers in Upper Geyser Basin. In 2022, monitoring began at nearby Daisy, Oblong, Riverside, and Artemisia Geysers.

The Yellowstone National Park Geology Program also monitors 63 hydrothermal features around the park with thermal sensors attached to loggers that are manually downloaded 3 to 4 times per year. These datasets are in the process of being published for public use. Given the time interval between logger visits to download data and maintain the stations, there can be substantial data loss from logger failure or damage, commonly caused by animals. A long-term goal over the coming years is to convert more of these manually downloaded logger stations to telemetered stations, and to better mitigate data loss caused by animal damage and mechanical failures.

Communications and Outreach

Thanks to easing of restrictions from the COVID-19 pandemic, it was possible to hold an in-person public event in Gardiner, Montana, for the first time since 2019. In May, YVO scientists presented a summary of recent research and monitoring results from geological, geochemical, and geophysical studies of the Yellowstone region, and also met with community members and visitors to answer questions individually. YVO also continued to produce monthly video updates of activity (posted on "USGSVolcanoes" Facebook and Twitter pages, the USGS YouTube channel, the USGS Multimedia Gallery, and the multimedia section of the YVO website) and weekly Yellowstone Caldera Chronicles articles, which are posted to social media pages and published by several regional news outlets. In addition to the monthly activity updates distributed via the Volcano Notification Service (https://www.usgs.gov/programs/VHP/volcano-updates), YVO issued an Information Statement following the May 11, 2022, magnitude 4.2 earthquake, which was widely felt in the region (see "Seismology" section).

Scan here to view the Caldera Chronicles online

A Monitoring Plan for the Yellowstone Volcanic System

In 2022, the Yellowstone Volcano Observatory published a new monitoring plan for seismic, magmatic, and hydrothermal activity in Yellowstone—the "Volcano and Earthquake Monitoring Plan for the Yellowstone Caldera System, 2022–2032" (YVO, 2022b). The plan, which is downloadable from https://doi.org/10.3133/sir20225032, builds on a previous monitoring plan that was published in 2006 (YVO, 2006).

The 2006 monitoring plan covered the 2006–2015 period and was intended "to provide Yellowstone National Park and its surrounding communities with a modern, comprehensive system for volcano and earthquake monitoring." The plan was ambitious, with numerous goals stretching across several disciplines. For example, YVO proposed new seismic monitoring sites and upgrading existing sites with digital broadband sensors capable of better detecting seismic activity. The plan also suggested installation of new continuous GPS stations, continuous gas-monitoring sites, and temperature-monitoring stations.

Many of the 2006–2015 monitoring plan goals were met, thanks in part to resources provided by the Plate Boundary Observatory component of the National Science Foundation EarthScope program—a nationwide effort to improve deformation and seismic monitoring in the United States (in 2018, the Plate Boundary Observatory was incorporated into the newly formed Network of the Americas)—and the 2009

Figure 34. Images of an unnamed thermal feature in the Three River Junction thermal area in southwest Yellowstone National Park (see fig. 26 for location). *A*, WorldView-3 satellite image from September 2014. *B*, National Park Service (NPS) aerial photograph from 2017. Images *A* and *B* were acquired before the feature went largely dry in late 2019 or 2020. *C*, WorldView-3 satellite image from June 2020. *D*, NPS field photograph by Hillary Robison from July 2020. Images *C* and *D* were taken during the period that the feature was largely dry. *E*, NPS field photograph by Erik Muzzey from July 2021. *F*, National Agriculture Imagery Program (NAIP) image from July 2022. Images *E* and *F* were taken after the feature refilled and returned to its normal behavior.

American Recovery and Reinvestment Act. The seismic network was modernized and new seismic, GPS, borehole tiltmeter, and borehole strainmeter stations were installed, including in remote areas of Yellowstone National Park. Continuous gas monitoring equipment was tested in multiple locations, and a real-time telemetered temperature-monitoring network was established at Norris Geyser Basin. All these data are available on the YVO website at https://www.usgs.gov/volcanoes/yellowstone.

The new monitoring plan covers the 2022–2032 period and divides monitoring goals into two categories: backbone and hydrothermal. Backbone monitoring refers to region-wide surveillance. Thanks to work done during the previous 15 years, the backbone monitoring network is already quite strong. In the coming decade, YVO will focus on continuing to upgrade continuous GPS and seismic monitoring, as well as installing additional stations in places that currently lack continuous observations. Another important goal is improving hydrological monitoring, including better tracking of the chemistry, flow patterns, and physical properties of groundwater, rivers, and lakes.

Hydrothermal monitoring refers to tracking activity associated with Yellowstone's thermal and geyser basins. To date, continuous seismic and deformation monitoring has largely avoided the geyser basins because they are "noisy." To accurately locate small earthquakes, it is inadvisable to install a seismometer next to a geyser, where eruptions and hot water moving through the subsurface might create noise that would obscure earthquake activity. In fact, there is currently only one seismometer in Yellowstone National Park located in a geyser basin—station YNM in Norris Geyser Basin. But hydrothermal regions are important sources of hazard in Yellowstone National Park. Even small steam-driven outbursts, like the 1989 explosion of Porkchop Geyser, could have serious effects on anyone that might be nearby. Volcanologists still do not have a good understanding of whether hydrothermal explosions have detectable precursors, but additional monitoring in these regions should provide more insights into this question.

The improvements proposed in the "Volcano and Earthquake Monitoring Plan for the Yellowstone Caldera System, 2022–2032" will ensure that the technology used to track seismic, magmatic, and hydrothermal activity in the Yellowstone region during the next decade remains at the cutting edge of volcanology. The monitoring strategy will also continue to take advantage of Yellowstone National Park's status as a premiere natural laboratory to better understand how volcanoes work.

Scan here to view the 2022 YVO monitoring plan

Summary

In 2022, measurements from monitoring stations in and around Yellowstone National Park indicated background levels of seismicity, deformation, and thermal emissions. The number of located earthquakes (2,429) was within the range of annual seismicity that is typical for the region. GPS measurements indicated no significant deformation at Norris Geyser Basin throughout the year, and Yellowstone Caldera continued to subside at rates of a few centimeters (about 1 inch) per year, as it has since 2015. Heat flux estimates from both satellite imagery and river chemistry indicated no major changes with respect to previous years, although the June flooding resulted in greater uncertainty on river chemistry heat flux measurements, which are based on the chloride content of rivers that drain Yellowstone National Park. Geyser activity was normal, and 11 major water eruptions occurred at Steamboat Geyser, the second straight year of a decrease in the frequency of eruptions from the world's tallest geyser. A thermal feature in the southwestern part of Yellowstone National Park, which went dry in late 2019 or early 2020, was confirmed to have resumed its normal mode of hydrothermal discharge sometime in 2021 based on field observations and satellite imagery.

The easing of restrictions during the COVID-19 pandemic allowed for more field work in 2022 than had been possible during the previous 2 years. Temporary deployments of seismometers in Norris and Upper Geyser Basins collected information that will be used to better understand geyser plumbing systems, and an eddy covariance station for measuring CO_2 and thermal emissions was deployed alongside an existing continuous gas monitoring station near Mud Volcano in September. Geologic investigations focused on better understanding the age and history of hydrothermal explosion craters and glaciation in the Lower Geyser Basin and improving age constraints on post-caldera rhyolite lava flows. In addition, detailed investigations of the Sour Creek resurgent dome identified several units of the Lava Creek Tuff, indicating that the eruption that resulted in the formation of Yellowstone Caldera about 631,000 years ago was much more complex than previously thought. Water and gas samples were collected from numerous sites in the Yellowstone region, including a thermal area that has developed since about 2000 near Tern Lake. Studies of sedimentary cores collected from Yellowstone Lake provided a window into the mechanisms of hydrothermal explosions, which are an underappreciated hazard in Yellowstone National Park. New research results will be highlighted in future editions of YVO's weekly series of online articles, Yellowstone Caldera Chronicles, which are available at https://www.usgs.gov/volcanoes/yellowstone/caldera-chronicles, as well as in annual reports, monthly updates and videos, and public presentations.

YVO was also able to engage in several in-person activities in 2022, including the first coordination meeting of the consortium since 2018, a scientific meeting to investigate the characteristics, causes, and consequences of distributed volcanism, and a public event in Gardiner, Montana. The year, however, also saw the passing of Robert Christiansen, founding Scientist-in-Charge of the Yellowstone Volcano Observatory and the geologist who unraveled much of the volcanic history of the Yellowstone region. We are all better scientists thanks to his example and better people for having known him, and we continue our efforts to honor the memory of the mentor, colleague, and friend we all knew as "Chris."

2022 Publications

Fagan, W., Swain, A., Banarjee, A., Ranade, H., Thompson, P., Staniczenko, P., Flynn, B., Hungerford, J., and Hurwitz, S., 2022, Quantifying interdependencies in geyser eruptions at the Upper Geyser Basin, Yellowstone National Park: Journal of Geophysical Research, v. 127, no. 8, article e2021JB023749, https://doi.org/10.1029/2021JB023749.

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Electric Peak and the Gallatin Range in the background, with the headwall scarp of the Silver Gate landslide in the foreground. Photograph by Michael Poland, U.S. Geological Survey, October 7, 2022.

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