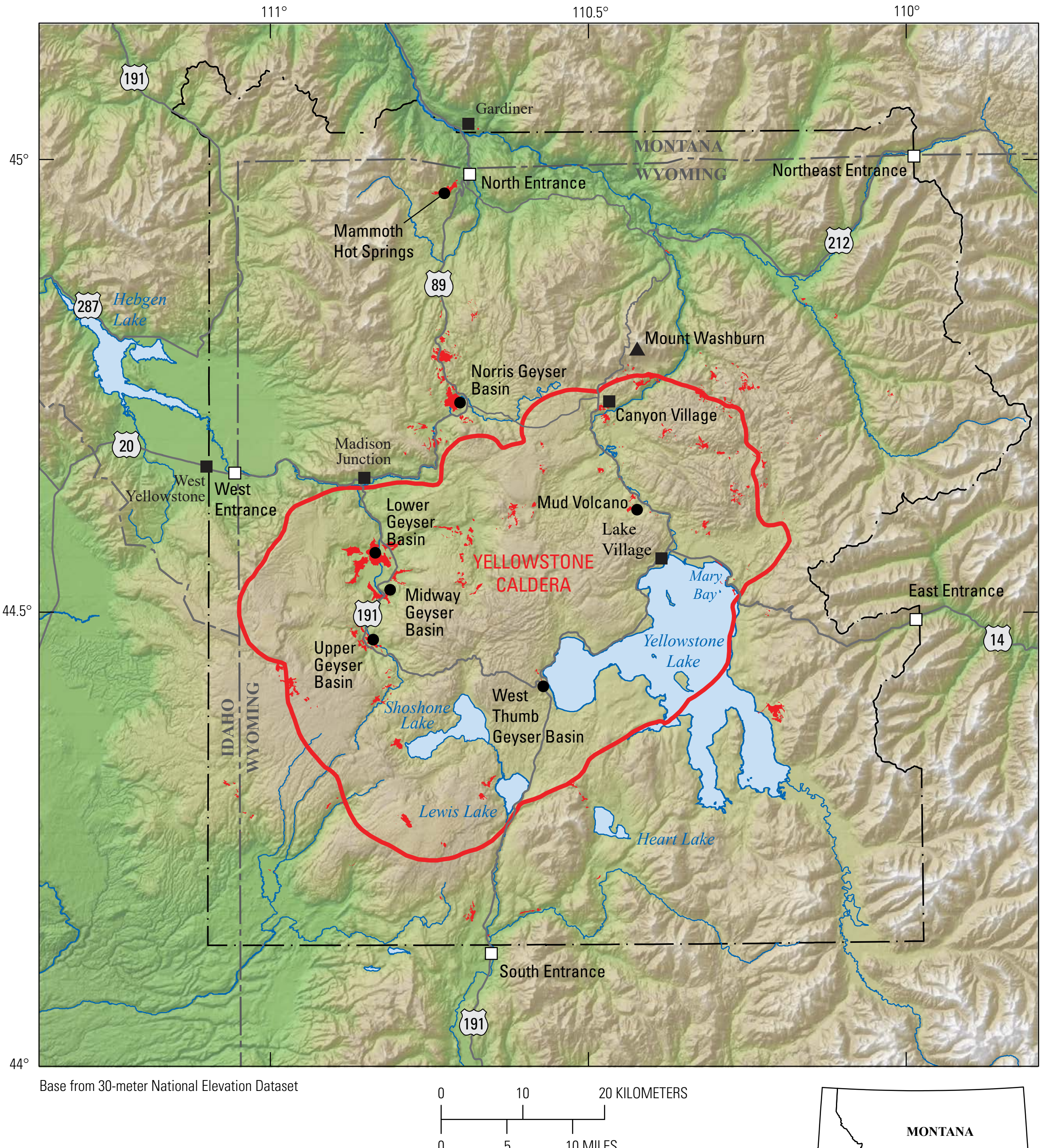
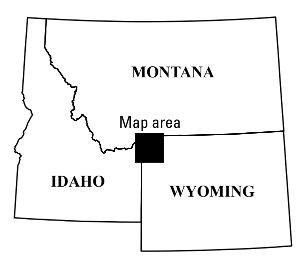
Yellowstone Volcano Observatory

2023 Annual Report

Circular 1524

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

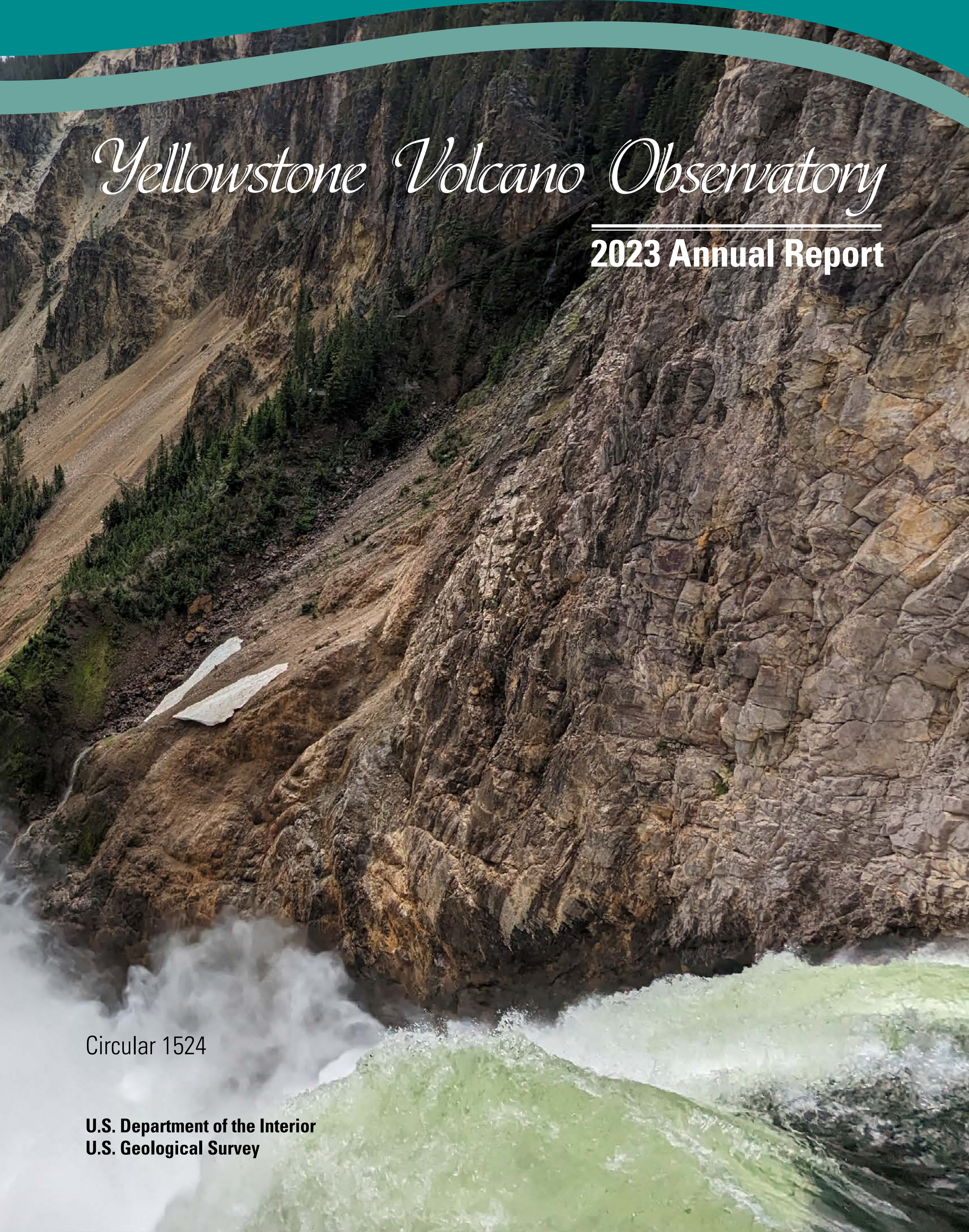




Location map showing thermal areas (in red) and noteworthy geographic features in the Yellowstone National Park region. The red line marks Yellowstone Caldera.

Cover. Photograph of Grand Prismatic spring, Yellowstone National Park, by Busara on Shutterstock.

Facing page. View from the brink of the Upper Falls of the Yellowstone River in Yellowstone National Park. Photograph by Michael Poland, U.S. Geological Survey, July 1, 2023



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U.S. Geological Survey, Reston, Virginia: 2024

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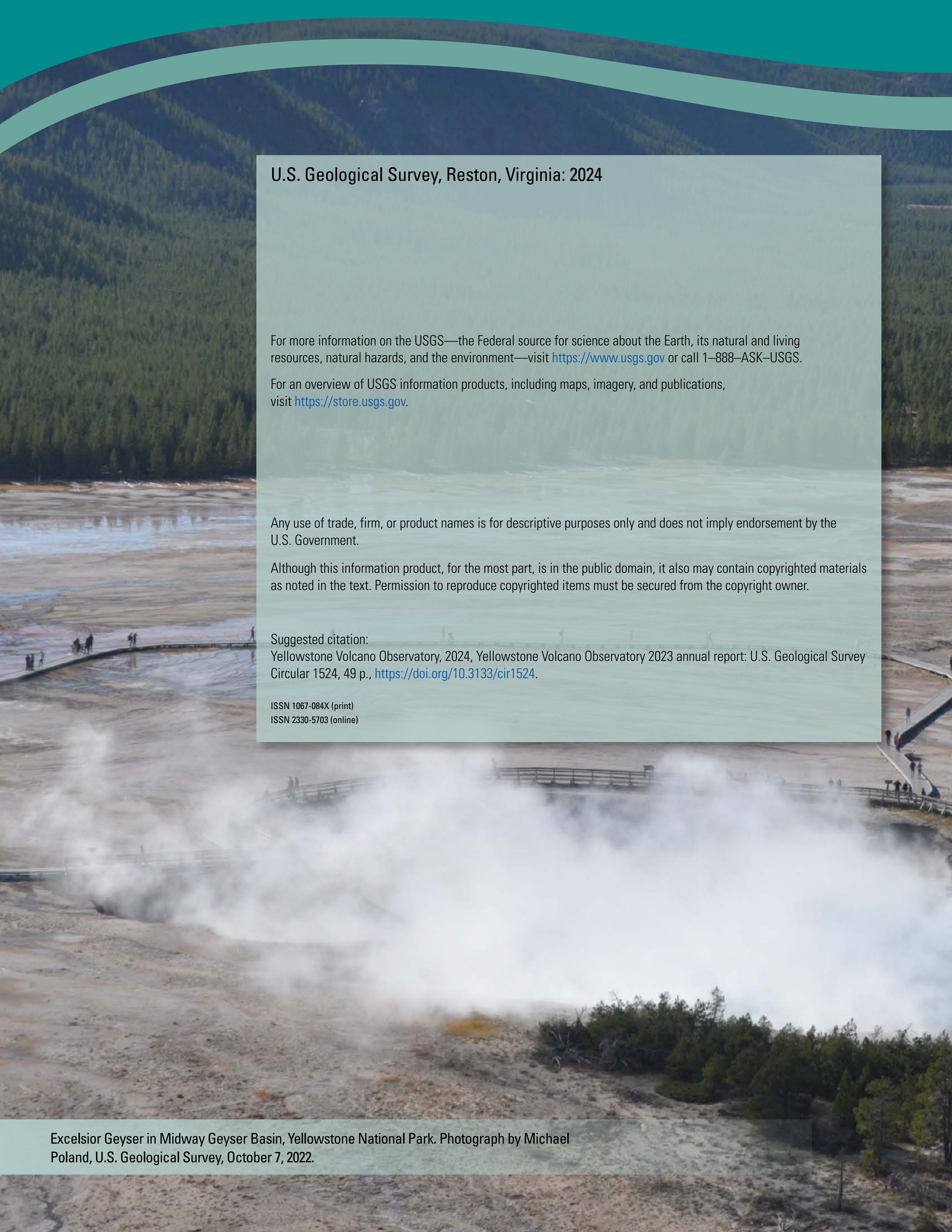

Excelsior Geyser in Midway Geyser Basin, Yellowstone National Park. Photograph by Michael Poland, U.S. Geological Survey, October 7, 2022.

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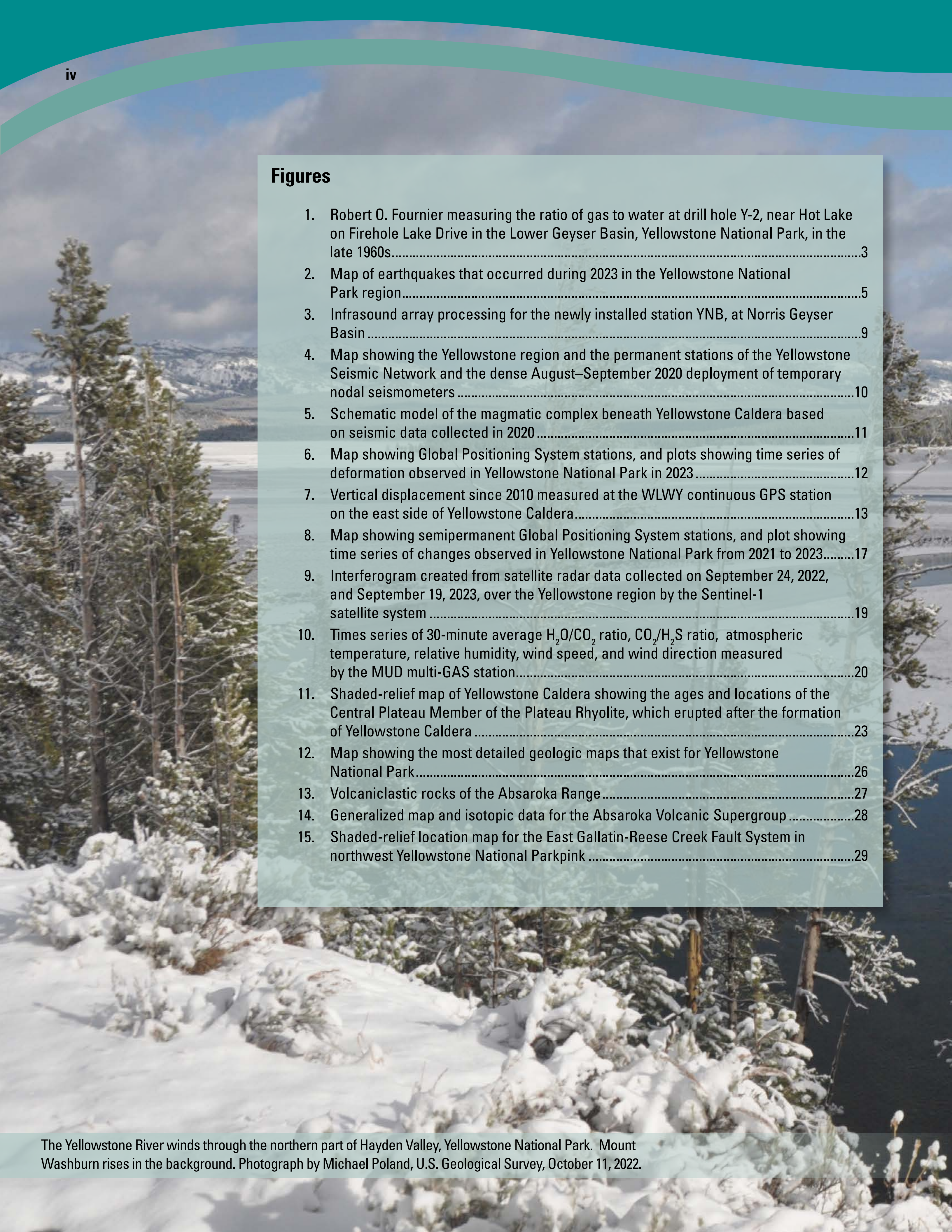

The Yellowstone River winds through the northern part of Hayden Valley, Yellowstone National Park. Mount Washburn rises in the background. Photograph by Michael Poland, U.S. Geological Survey, October 11, 2022.

Sidebars

Photograph of Morning Glory Pool spring, Yellowstone National Park, by EastVillage Images on Shutterstock.

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

https://www.usgs.gov/media/videos/pubtalk-112021-busting-myths-about-one-largest-volcanic-systems-world-top-10?utm_source=yvo-annual-report-2024&utm_medium=qr-code&utm_campaign=nh-volcanoes-fy24

Yellowstone Volcano Observatory

2023 Annual Report

By the Yellowstone Volcano Observatory

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 that includes 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 2023, focusing on the Yellowstone volcanic system. Highlights of YVO research and related activities during 2023 include

- Installation of a new monitoring station in Norris Geyser Basin that measures earthquake activity, ground deformation, meteorological conditions, and infrasound, and that represents a first attempt at specifically monitoring hydrothermal activity,
- Development of high-resolution models of the structure and composition of the magma reservoir beneath Yellowstone Caldera,
- Deployment of Semipermanent Global Positioning System (GPS) array from May to October,
- Geological studies of a major fault system in the northwest part of Yellowstone National Park,
- Refining the ages of rhyolite lava flows that erupted following the formation of Yellowstone Caldera,
- Developing a strategy for mapping volcaniclastic rocks and tracking those deposits back to their primary source areas in the Absaroka Range,
- Observations of changes in the level and color of Nuphar Lake in Norris Geyser Basin,
- Research into the age and history of Steamboat Geyser in Norris Geyser Basin and the characteristics of its eruptions, and
- Assessment of thermal output based on satellite imagery and chloride flux in rivers.

Steamboat Geyser, in Norris Geyser Basin, continued the pattern of frequent eruptions that began in 2018 with nine water eruptions in 2023, the lowest number of annual eruptions in the current eruptive sequence (compared to 32 in 2018, 48 each in 2019 and 2020, 20 in 2021, and 11 in 2022). 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. Another example is Giant Geyser, in the Upper Geyser Basin near Old Faithful, which in November 2023 erupted for the first time since a series of eruptions during 2017–2019. Also in Upper Geyser Basin, several dormant thermal features and some new ones became active in May 2023 on Geyser Hill, prompting the closure of a small section of boardwalk between Doublet Pool and Sponge Geyser. The changes were similar to those that occurred in the same area in September 2018 (YVO, 2021a). Unrest waned through June and July, and the closed section of boardwalk was reopened in August.

The number of located earthquakes in 2023—1,623—was much less than the 2,429 earthquakes located in 2022 and the 2,773 that were located in 2021 and at the lower end of the typical 1,500–2,500 earthquakes per year. Deformation patterns during 2023 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, and no significant deformation was detected in the area between the north caldera rim and Norris Geyser Basin.

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[1]This report was prepared jointly by members of the Yellowstone Volcano Observatory consortium and collaborators, including Michael Poland, Daniel Dzurisin, Shaul Hurwitz, Jennifer Lewicki, Blaine McCleskey, Patrick Muffler, Mark Stelten, R. Greg Vaughan, and Charles Wicks of the U.S. Geological Survey (USGS), Jefferson Hungerford and Kiernan Folz-Donahue of the National Park Service, Jamie Farrell of the University of Utah, James Mauch of the Wyoming State Geological Survey, Yann Gavillot of the Montana Bureau of Mines and Geology, Ken Sims of the University of Wyoming, Madison Myers and Natali Kraugh of Montana State University, Lauren Harrison of Colorado State University, and Mara Reed of the University of California, Berkeley. Liz Westby and Holly Weiss-Racine of the USGS 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

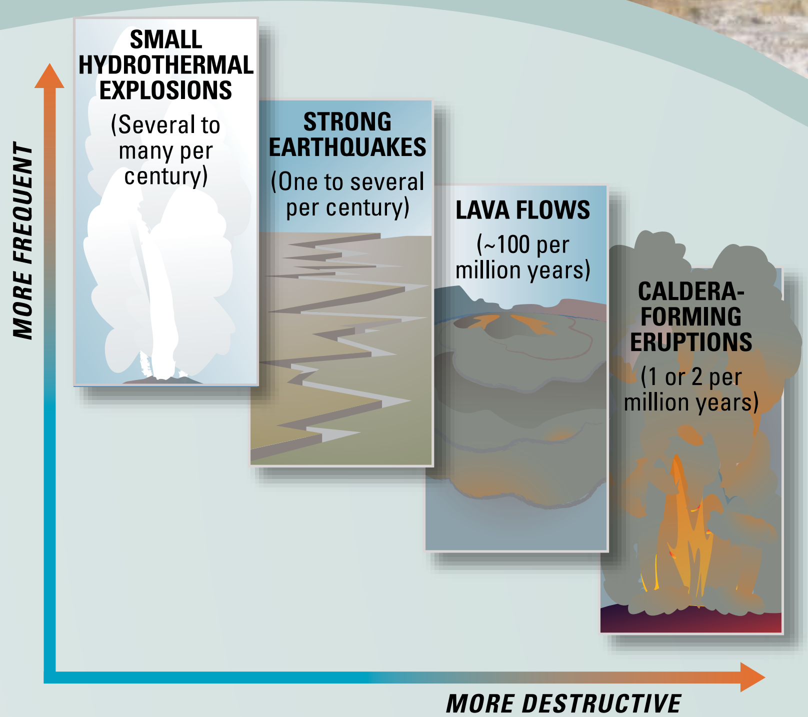
The Yellowstone Plateau in the northern Rocky Mountains of Wyoming, Montana, and Idaho is centered on a youthful, active volcanic system with subterranean magma (molten rock), boiling and pressurized waters, and a variety of active faults. This combination creates a diversity of hazards, but the most 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 16,000–14,000 years ago. Much smaller explosions, which leave craters only a few meters (yards) across, happen every few years in the Yellowstone region.

Canary Spring, Mammoth Hot Springs, in Yellowstone National Park, with Mount Everts in the background. Photograph by Michael Poland, U.S. Geological Survey, October 12, 2020.



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).

Throughout 2023, the aviation color code for Yellowstone Caldera remained at "green" and the volcano alert level remained at "normal."

YVO News

There were no organizational or planning meetings related to YVO operations in 2023, so YVO scientists focused on field work and research projects during the year. Unfortunately, the year marked the passing of Robert O. Fournier, a pioneer in the study of hydrothermal systems in Yellowstone National Park's iconic geyser basins.

Changing Contributors to YVO

In 2023, YVO contributors Lauren Harrison (USGS) and Annie Carlson (Yellowstone National Park) moved to new positions.

Dr. Lauren Harrison had been a Mendenhall postdoctoral fellow with the USGS since 2020. Lauren's research in Yellowstone National Park has numerous facets, including: the timing and cause of hydrothermal explosions in Lower Geyser Basin; the timing, extent, and characteristics of glacial activity in the Yellowstone region; and the conditions under which travertine deposition occurs within Yellowstone Caldera. Her findings provide important insights into everything from past climate conditions to present-day hazards.

Annie Carlson became the Research Coordinator for Yellowstone National Park in 2017. In that role, Annie managed about 140 individual research permits that addressed topics ranging from geophysical investigations to insect biology that is unique to hot springs. Thanks to Annie's support, YVO has been able to install and maintain new monitoring stations, and her guidance has been vital to enhancing YVO's ability study active geologic processes, like earthquake swarms, and to communicate hazards-related information to the public.

Succeeding Annie as Research Coordinator for Yellowstone National Park is Jaclyn McIlwain, who already has significant experience working with YVO in her former role as an interpretive ranger at Norris Geyser Basin. Welcome to Jaclyn! YVO looks forward to a productive collaboration.

Robert O. Fournier (1931–2023)

USGS geologist Robert (Bob) O. Fournier (fig. 1) passed away in January 2023 in Portola Valley, California, at the age of 91. In addition to being a valued friend, colleague, and mentor, Bob contributed greatly to our current understanding of the hot springs and hydrothermal systems of Yellowstone National Park, leaving a legacy of discovery that will inspire scientists for generations to come.

Bob received a B.A. from Harvard University in 1954 and a Ph.D. from the University of California, Berkeley, in 1958 with a dissertation on the porphyry-copper deposit at Ely, Nevada—a deposit that was related to the hydrothermal system associated with ancient volcanism and presaged his work on modern hydrothermal activity in the Yellowstone region. He then joined the USGS in Washington, DC, studying the solubility of silica in water as a function of temperature, a theme that would persist throughout his long and productive career.

Bob is best-known for his leadership in developing various methods for determining subsurface reservoir temperatures from the chemical composition of hot-spring waters, based on both laboratory and field investigations, primarily in Yellowstone National Park. His work in the park began in 1962 when he served as a geothermal consultant to the National Park Service during bridge construction and road relocation at Beryl Hot Spring. After transferring to the USGS office in Menlo Park, California, in 1962, he joined a group led by Donald E. White to carry out research drilling in hot-spring areas of Yellowstone National Park. These unique and seminal investigations provided direct measurements of the subsurface temperature and pressure conditions beneath thermal areas, with bottom-hole temperatures reaching 240 °C (464 °F). Bob developed equipment and procedures to measure pressures and to sample water and gas from these wells, he maintained and ultimately decommissioned the wells, and he used the resulting data in his exploration of the geochemistry and dynamics of the Yellowstone hot-spring systems. His investigations in the Yellowstone region, which continued throughout his career, provided the basis for his achievements as a world-renown geothermal expert. Bob considered Yellowstone National Park his "cornerstone of reality."

Bob's field work at Yellowstone National Park was closely integrated with his ground-breaking research into chemical techniques to estimate geothermal reservoir temperatures and other characteristics. Notable were his development of "geothermometers," which use the chemical composition of thermal water measured at the surface to estimate fluid temperature in the reservoir beneath the ground. These tools have been adopted to better understand hydrothermal systems around the world. He also pioneered the use of models to estimate the

Figure 1. Robert O. Fournier (1931–2023) measuring the ratio of gas to water at drill hole Y-2, near Hot Lake on Firehole Lake Drive in the Lower Geyser Basin, Yellowstone National Park, in the late 1960s. Photograph by the U.S. Geological Survey.

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.

temperature of the hot-water component in mixed waters and to predict underground conditions in hot-spring systems—for example, whether a reservoir consists of steam or liquid water. He even developed a better understanding of the processes related to movement of fluids from plastic (ductile) into brittle rocks in the transition zone between magma at depth and the overlying hydrothermal systems.

Bob was a leader in major international geothermal efforts as well. In 1975, he chaired the U.S. Organizing Committee for the Second United Nations Symposium on Geothermal Resources, a two-week meeting in San Francisco that drew some 1,100 participants from around the world. He also led advisory panels of international experts overseeing development of the Miravalles geothermal field in Costa Rica and several geothermal fields in El Salvador. Finally, he served on many committees overseeing continental scientific drilling activities within the United States and elsewhere—efforts that led to a better understanding of the subsurface conditions in active volcanic areas.

Bob’s passion throughout his career, though, was the Yellowstone region and the spectacular hydrothermal features found there. His work built a foundation upon which scientists today can better understand the conditions beneath the surface in these areas, which is important for understanding everything from geyser activity to potentially hazardous hydrothermal explosions.

Seismology

Earthquakes have been monitored in the Yellowstone region since the 1970s (see sidebar on seismicity on p. 6–7). The Yellowstone Seismic Network is maintained and operated by the University of Utah Seismograph Stations, which records data from 47 seismic stations in the Yellowstone region. Typically, 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.

Member agencies of the Yellowstone Volcano Observatory.

Scan here to watch a video describing YVO

https://www.youtube.com/watch?v=ksYq0FWeSZQ&utm_source=yvo-annual-report-2024&utm_medium=qr-code&utm_campaign=nh-volcanoes-fy24

Scan here to view all Yellowstone monitoring sites

https://www.usgs.gov/volcanoes/yellowstone?utm_source=yvo-annual-report-2024&utm_medium=qr-code&utm_campaign=nh-volcanoes-fy24

Overall Seismicity in 2023

During 2023, the University of Utah Seismograph Stations located 1,623 earthquakes in the Yellowstone region (fig. 2), which is at the lower end of the typical range of 1,500–2,500 earthquakes per year. The total includes four magnitude 3 earthquakes, 113 magnitude 2 earthquakes, and 1,506 earthquakes with magnitudes less than 2. Only one earthquake during the year was felt, meaning that people reported some shaking. That felt event was also the largest of the year—a magnitude 3.7 earthquake that occurred beneath the north part of Yellowstone Lake on March 29 at 8:24 a.m. local time.

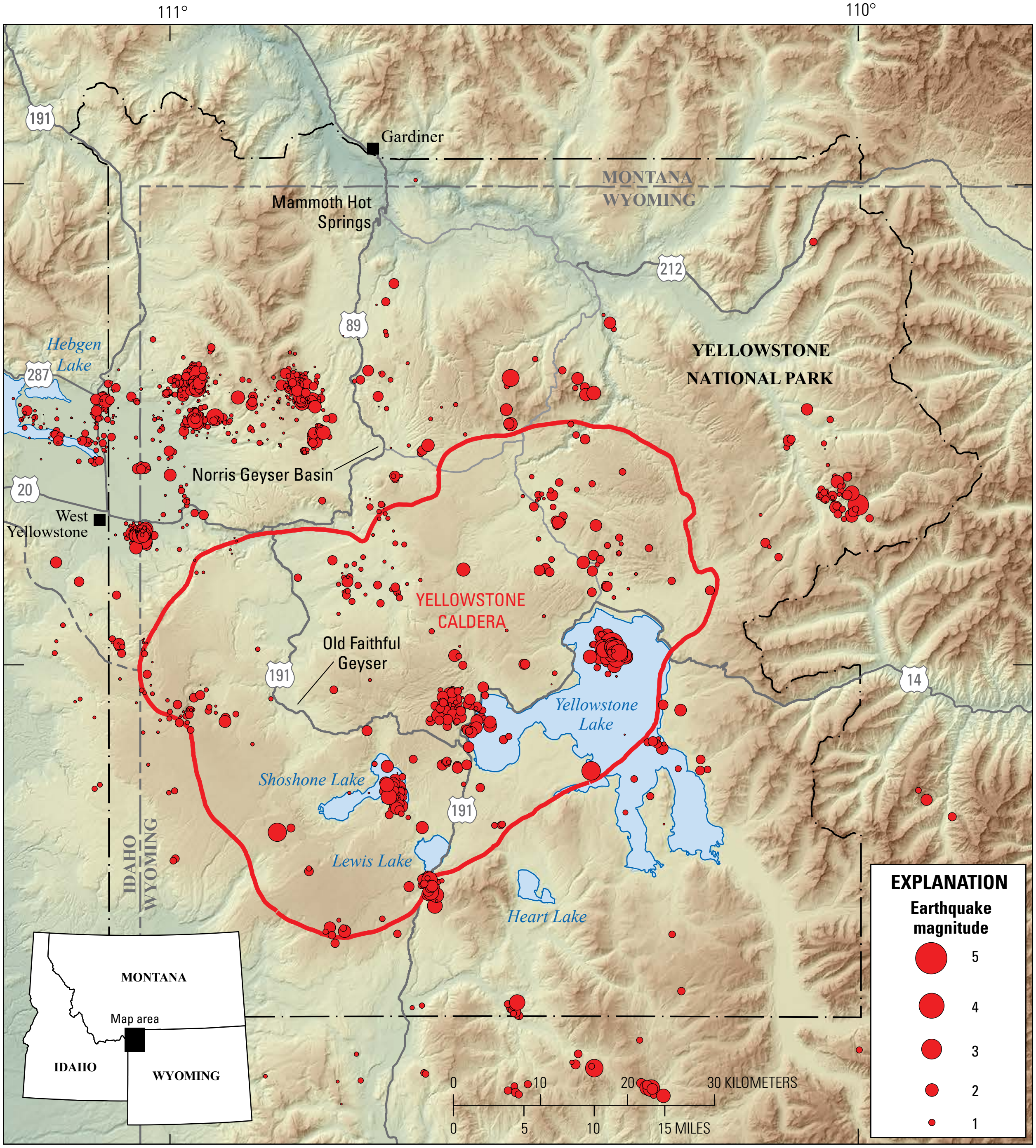


Figure 2. Map of earthquakes (red circles) that occurred during 2023 in the Yellowstone National Park region. Circle size is scaled to the magnitude of the earthquake, where larger circles represent stronger earthquakes.

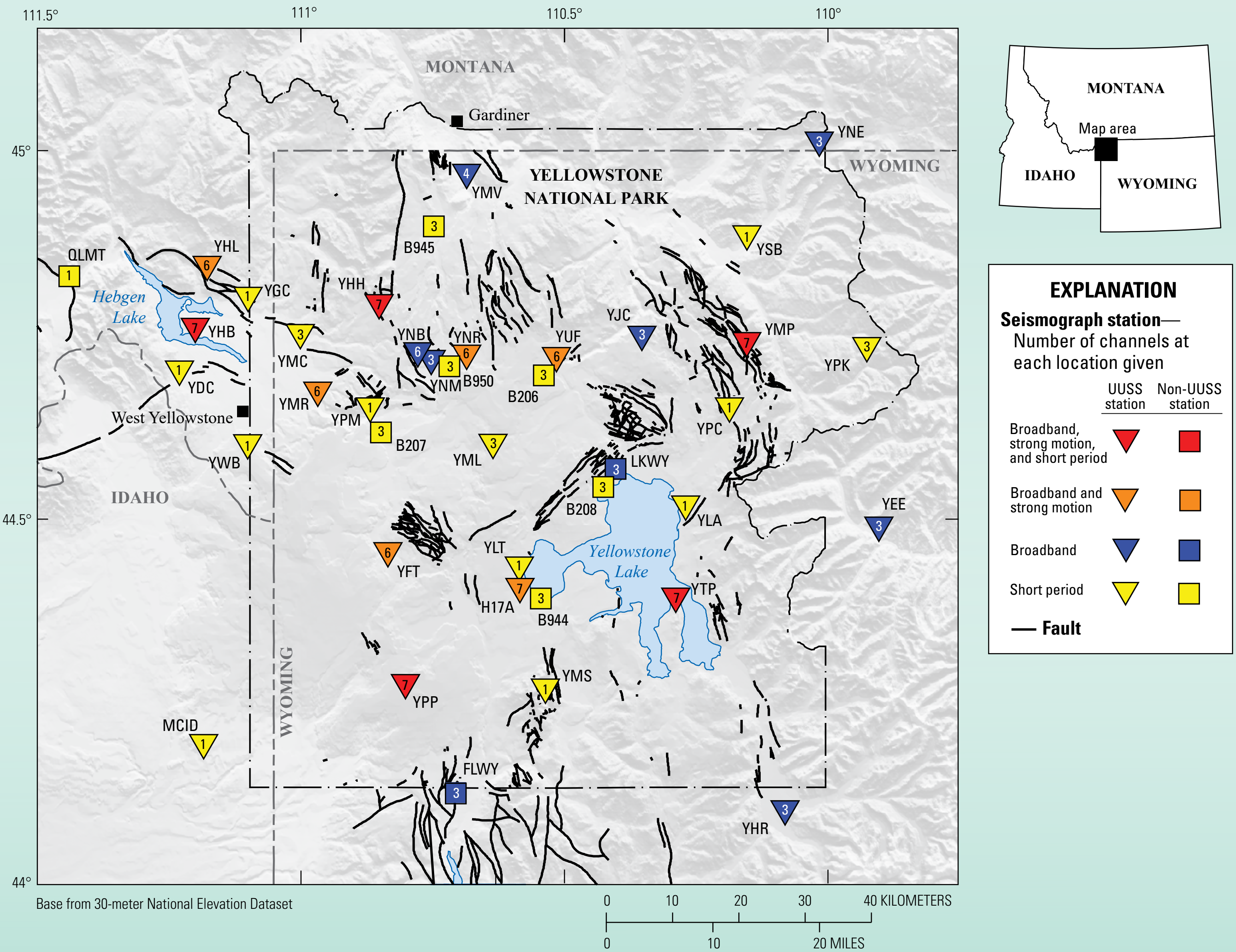
SIDEBAR

Seismicity in 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 47 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. 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

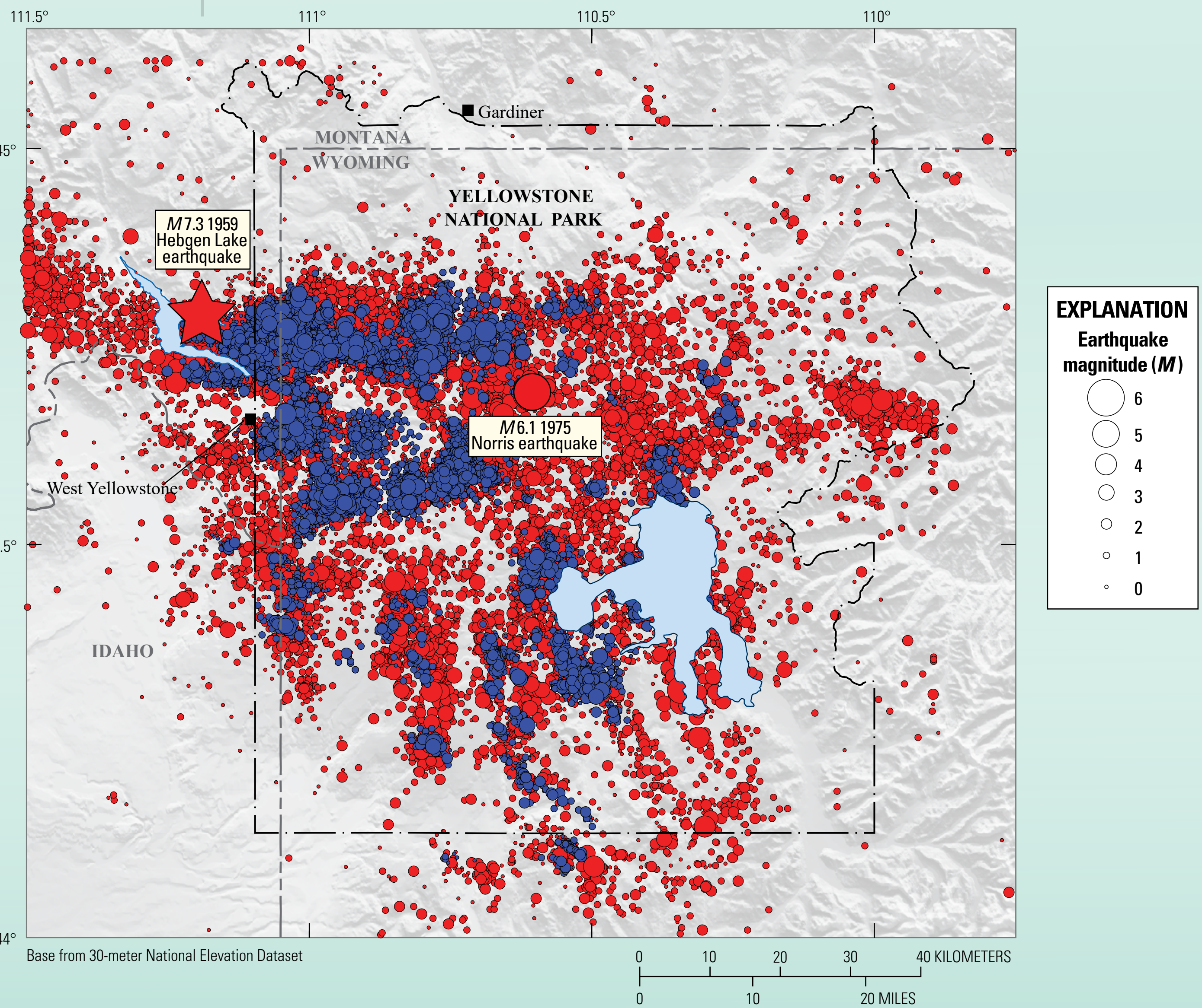


Map of seismometer station locations operated by the University of Utah Seismograph Stations (UUSS) and other agencies. Map view shows the Yellowstone Plateau earthquake catalog region.

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

Since 1973, there have been more than 60,000 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 Norris earthquake located near Norris Geyser Basin (the largest earthquake ever recorded in Yellowstone National Park). There have also been two earthquakes in the magnitude 5 range, 30 earthquakes in the magnitude 4 range, and 414 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 1973–2023. 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.

Of the total number of recorded earthquakes, about 45 percent occurred as part of 24 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 because of the coincidence of preexisting tectonic faults, magmatism, and abundant groundwater, and typically includes about half of all earthquakes that take place in the region. The largest swarm in 2023 included 138 events during March 12–14 about 6.5 km (4 mi) east-southeast of West Yellowstone, Montana. The second largest swarm of the year occurred during March 29–April 1 beneath the north part of Yellowstone Lake, with 110 located events, including the largest of the year, a magnitude 3.7 event.

During the year, in addition to annual maintenance on the Yellowstone Seismic Network, the University of Utah upgraded two Yellowstone seismic stations—YJC (Joseph's Coat) and YMV (Mammoth Vault)—to fully digital in September 2023. This work marks the beginning of a long-term project to completely update the Yellowstone Seismic Network, as described in the YVO monitoring plan for the Yellowstone Caldera system (YVO, 2022b). Future plans include updating 2–3 stations per year until all analog stations have been upgraded to digital—a modification that will also add the flexibility to include additional sensors in the future. When upgrades are completed, the network will provide state-of-the-art earthquake monitoring and offer volcano seismologists a more powerful tool to investigate many different types of earth processes that cause ground shaking, which in turn will support continued advances in understanding the Yellowstone region's magmatic, tectonic, and hydrothermal systems and associated hazards.

Seismic Studies in the Yellowstone Region

University of Utah scientists completed research projects on a number of topics during 2023, providing a better understanding of seismicity in and around Yellowstone National Park. This work included a continuation of studies on Doublet Pool, on Geyser Hill in Upper Geyser Basin. Doublet Pool is characterized by an intermittent yet rhythmic thumping that can be heard and felt. Liu and others (2023) showed that the interval between Doublet Pool's thumping episodes has varied from 2015 to 2023 and can be used to estimate variations in heat supplied to this hydrothermal feature. The data may also indicate that changes in heat are related to changes in the surficial activity of Doublet Pool and other features on Geyser Hill.

Studies also focused on improving the ability to detect microseismicity in the Yellowstone region. Armstrong and others (2023) used machine learning to identify earthquakes in the Norris Geyser Basin area that are too small to be identified using traditional techniques, and thus excluded from the routine seismic catalog. Continuing to develop these algorithms will provide a better understanding of the structures that are activated during seismic swarms in Yellowstone National Park and may eventually aid with routine earthquake location.

Not all seismicity in the Yellowstone region is associated with faulting or the hydrothermal system. Farrell and others (2023) showed that dominant daytime winds from the southwest blowing over Yellowstone Lake result in wave action that produces seismic shaking and can be recorded by seismometers in the region. These seismic phenomena are known as microseisms and have been known to occur in the oceans, but they have only recently been identified in lakes, including Yellowstone Lake.

New Monitoring Station at Norris Geyser Basin

In 2022, YVO released a monitoring plan that laid out a strategy for better understanding and tracking Yellowstone's volcanic, hydrothermal, and tectonic activity (YVO, 2022b) and addressing required monitoring under the National Volcano Early Warning System (Cervelli and others, 2021). The plan pointed out that regional monitoring was well covered, allowing for the detection of small earthquakes and subtle ground motion, but that there was little monitoring within Yellowstone National Park's hydrothermal basins. The lack of such data prevents YVO scientists from tracking activity that may be associated with hydrothermal explosions—essentially steam bursts—that are the most common volcanic hazard in Yellowstone National Park.

The monitoring plan proposed installing multi-component stations in hydrothermal basins to better track subtle geyser and hot spring activity that the regional network might miss, and that Norris Geyser Basin would be a logical starting point for such work. At the time the monitoring plan was released, the YNM seismometer, located in the Norris Museum, was the only seismic station in Yellowstone National Park located in a geyser basin, and the sensor has proven outstanding for detecting eruptions of Steamboat Geyser. Adding more monitoring stations to the Norris area would build on this start to hydrothermal monitoring.

In August and September 2023, scientists from the University of Utah, EarthScope Consortium, and USGS collaborated to install a new monitoring site in the Ragged Hills, at the center of Norris Geyser Basin. The new station incudes four monitoring instruments. First, a broadband seismometer, designated YNB, will detect subtle shaking of the earth across a variety of frequencies, including the motion caused by migration and ascent of boiling water. Second, a GPS station, designated NBWY, will detect small changes in ground motion at the site. Based on evidence from satellite data and temporary GPS deployments, this site might show localized changes related to accumulation and withdrawal of water that are not picked up by the nearby GPS site NRWY, located on a hill a few kilometers east-southeast of Norris Geyser Basin.

Largely new to the Yellowstone region is the third instrument: an array of sensors that are designed to measure low-frequency sound waves inaudible to humans, called infrasound. At the site, three sensors are deployed in a triangle-shaped pattern, which allows the data to be used to calculate the direction of any sources of infrasound, as well as the signal strength. When a geyser in the Norris area erupts, the sound of the geyser will be detected by the infrasound sensors, and the direction to the sound will be automatically calculated so that it is possible to tell which geyser is the source of the noise, even when no one is present in the basin to observe the activity. The new YNB infrasound array picked up eruptions of Steamboat Geyser on October 8, November 13 (fig. 3), and December 30, 2023. The data for all three eruptions indicate a strong onset that lasts for nearly an hour before gradually fading in intensity to background levels after about 4–5 hours. This time frame is consistent with the water phase and the most vigorous part of the steam phase of the eruptions.

Finally, a weather station will record wind speed and direction, temperature, humidity, pressure, and other parameters. This information can be helpful in understanding the sources of any seismic, deformation, or infrasound signals that might be caused by environmental conditions.

This Ragged Hills station is the first such site installed in Yellowstone National Park, with multiple types of measurements collected in a geyser basin for the specific purpose of monitoring hydrothermal activity. YVO scientists will be closely observing the data from this site over the course of 2024. If the deployment proves to be useful at detecting changes within the geyser basin, new sites could be installed in the coming years. Ideally, three such sites will ultimately be set up in Norris Geyser Basin so that the sources of even subtle deformation, seismicity, and infrasound signals can be triangulated.

High-resolution Seismic Image of the Yellowstone Magma System

Over the past few years, several new insights into the character of Yellowstone Caldera's magma reservoir have been published (for example, Huang and others, 2015; Maguire and others, 2022). These results are largely based on seismic data—particularly on the speed of seismic waves in the subsurface, which provides information about the structure and composition through which the waves traveled. Hot or partially melted rock slows down the wave propagation in comparison to solid rock, so seismic waves that move more slowly than expected might indicate the presence of hot or molten material. A single source-to-receiver travel time measurement, however, only provides the average information along the wave path. It is therefore difficult to accurately characterize underground areas that can be extremely variable and complex—for example, beneath a volcano. More data are needed. Just like a digital camera, where more megapixels give a better image, the more seismic data that are recorded, the better the resolution of the subsurface.

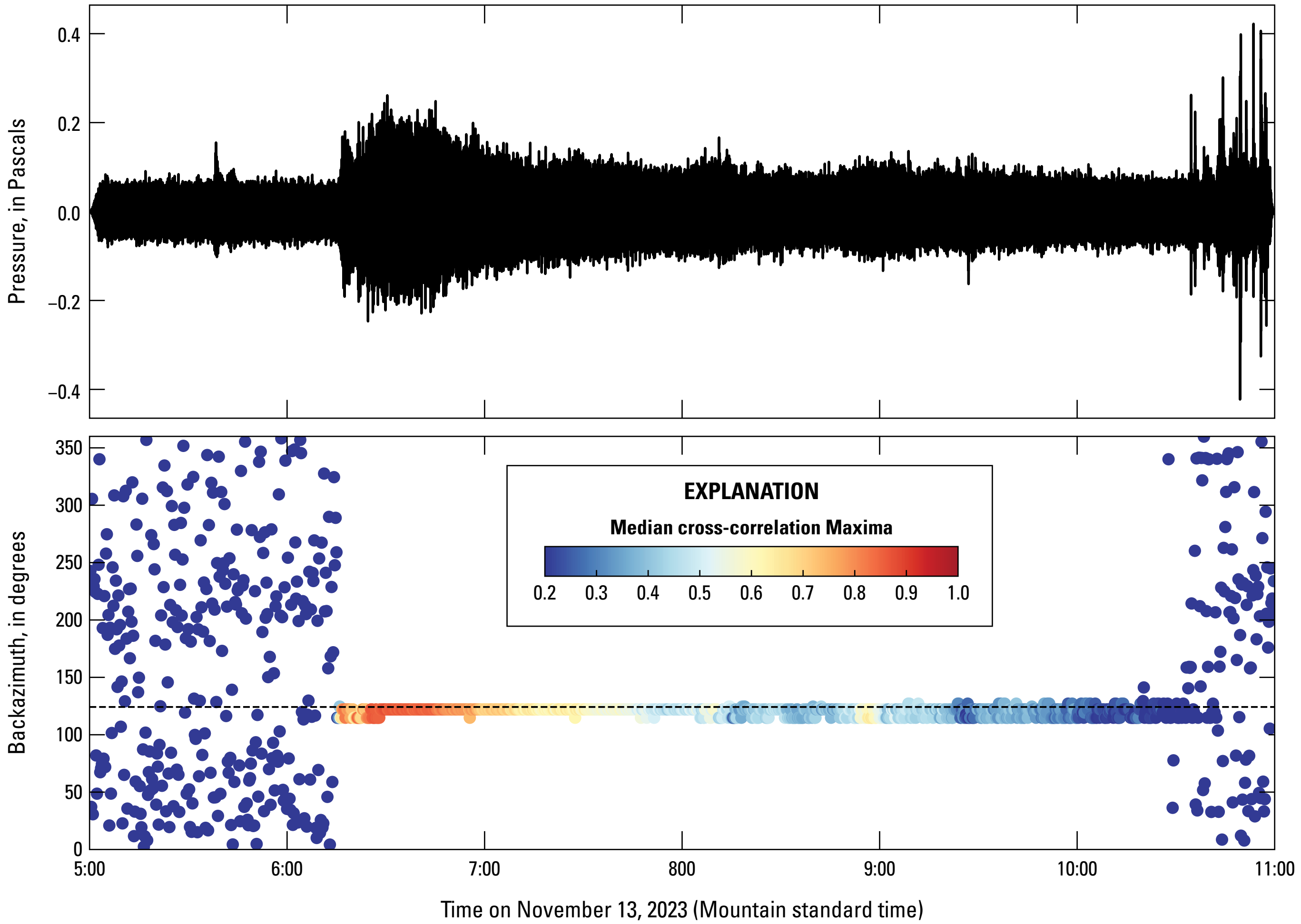


Figure 3. Infrasound array processing for the newly installed station YNB, at Norris Geyser Basin. Top panel shows the pressure waveform from one of the three elements that comprise the array, filtered between 1 and 15 Hz. Bottom panel shows the backazimuth from the station to the source. The direction from the station to Steamboat Geyser is indicated by the black horizontal dashed line. The colors represent how well the 3 elements in the array agree (Median Cross-Correlation Maxima, MdCCM), where values closer to 1.0 (red) indicate highly correlated, strong signals.

Data from the current seismic network in the Yellowstone region provide a general picture of the magmatic system beneath Yellowstone Caldera, which consists of two reservoirs stacked atop one another—one containing viscous rhyolite magma at depths of 5–19 kilometers (about 3–12 miles), and a second holding more fluid basaltic magma at 20–50 kilometers (about 12–30 miles) beneath the surface, both of which are mostly solid. To better understand the structure of the subsurface magma plumbing, the University of Utah, in collaboration with the University of New Mexico and Yellowstone National Park, conducted a temporary deployment of 650 autonomous seismic sensors, or "nodes," along roads and trails (fig. 4) from August to September 2020. These nodes passively recorded seismic waves generated by the ocean, known as microseisms. Although the energy from microseisms is small, it is detectable by modern seismometers even very far from the coast and has characteristics that make it ideal for studying the crustal structure beneath Yellowstone Caldera.

Data collected during the 2020 temporary deployment indicate that seismic velocity is especially slow near the top of the magma reservoir at 5 kilometers (3 miles) depth, suggesting that more melt may be concentrated in this area of the magma reservoir. The three-component (vertical and horizontal) data provided by the nodal seismometers also indicated that waves moving horizontally propagated about 20 percent faster than those moving vertically in the upper part of the magma reservoir. This indicates the presence of horizontally elongated areas of localized magma storage, called sills, and means that magma is stored in a sheet-like manner, instead of evenly distributed within the rock matrix. After accounting for the textural fabrics, the melt fraction can be more accurately estimated to be up to 28 percent in this region of the magma reservoir.

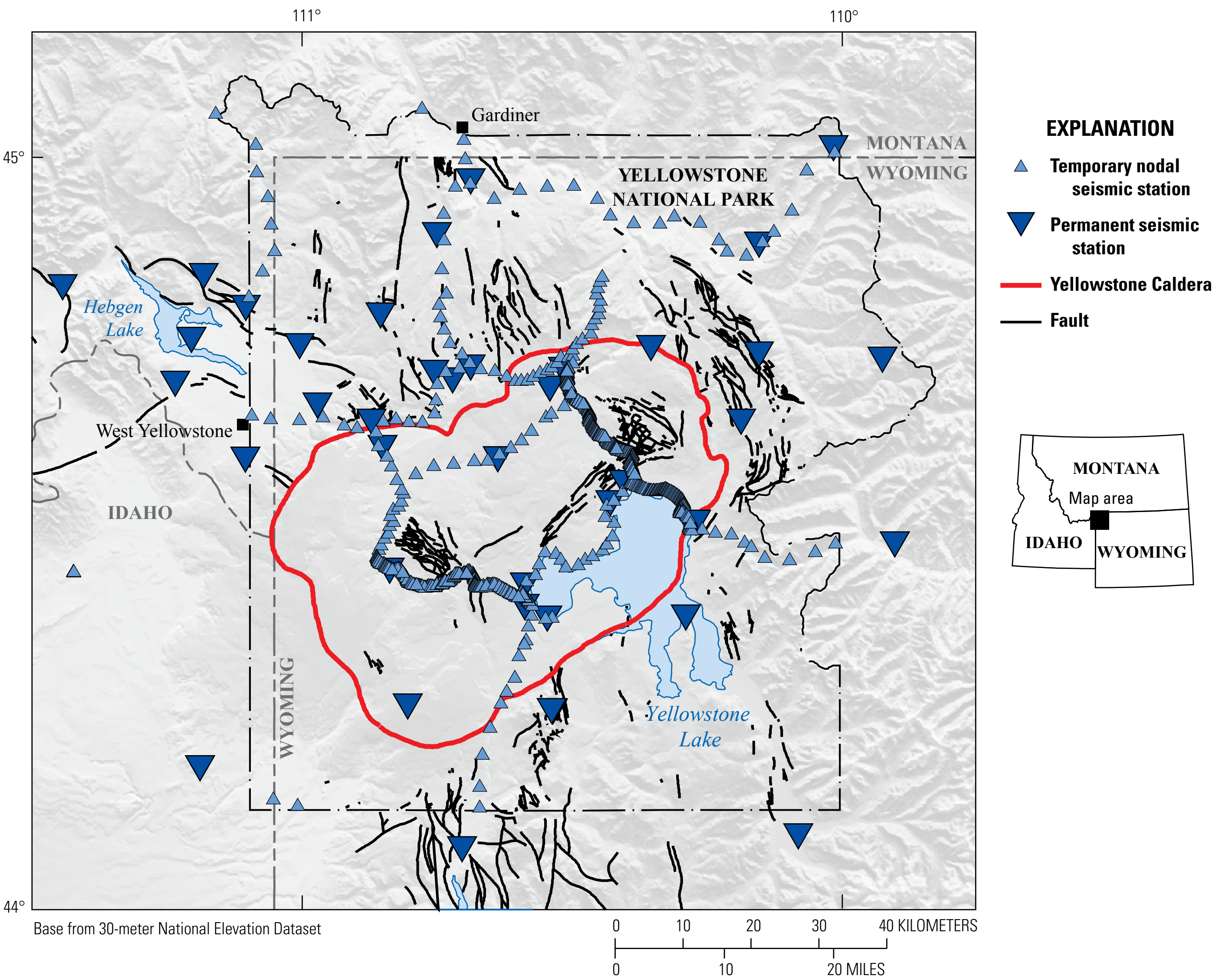


Figure 4. Map showing the Yellowstone region and the permanent stations of the Yellowstone Seismic Network and the dense August–September 2020 deployment of temporary nodal seismometers (YVO, 2021c).

The new data provide a more complete picture of the Yellowstone magmatic system, with horizontal lenses of partial melt near the top of the complex separated by layers that are poor in melt (fig. 5). Additional work using the 2020 dataset will occur in the coming years and could provide an even more refined view of the upper part of the magma system beneath Yellowstone Caldera.

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. 14–16). 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, and can provide insights into the physical processes responsible for changes measured at the surface.

[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.

Overall Deformation in 2023

Ground deformation throughout 2023 resembled that of 2021 and 2022. Subsidence of Yellowstone Caldera occurred at a rate of 2–3 centimeters (about 1 inch) per year (fig. 6), continuing the trend that, except for a brief period of uplift in 2014–2015, has persisted since 2010 (fig. 7). 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. 7), caused by seasonal groundwater and snowmelt conditions. In 2021, satellite deformation data identified 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, showed slight subsidence in this area, indicating that the episode of uplift in this region was brief and small, and no deformation of this area was identified in 2023. 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, with no significant changes in 2023 (fig. 6).

In 2023, 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 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 2023. The borehole instruments near Madison Junction and Norris Geyser Basin began experiencing communication failures in 2023, and telemetry upgrades are planned in 2024.

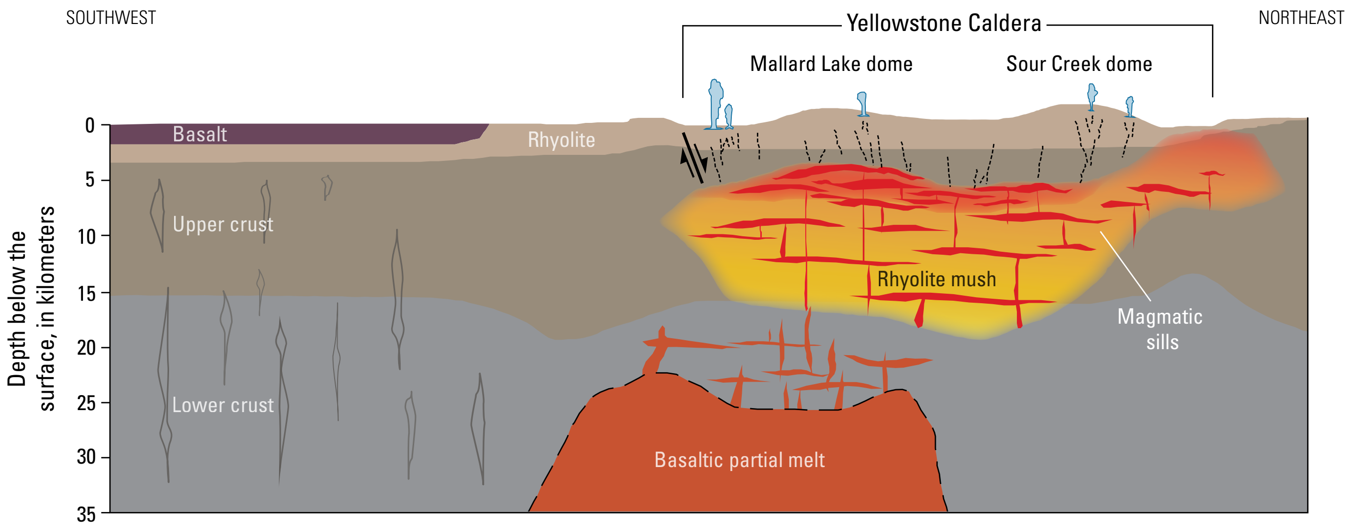


Figure 5. Schematic model of the magmatic complex beneath Yellowstone Caldera based on seismic data collected in 2020. The presence of magmatic sills with higher amounts of melt—about 28 percent—compared to their surroundings is revealed by data collected from a dense deployment of about 650 3-component (capable of measuring vertical and horizontal motion) seismometers in Yellowstone National Park during August–September 2020. Adapted from Wu and others (2023).

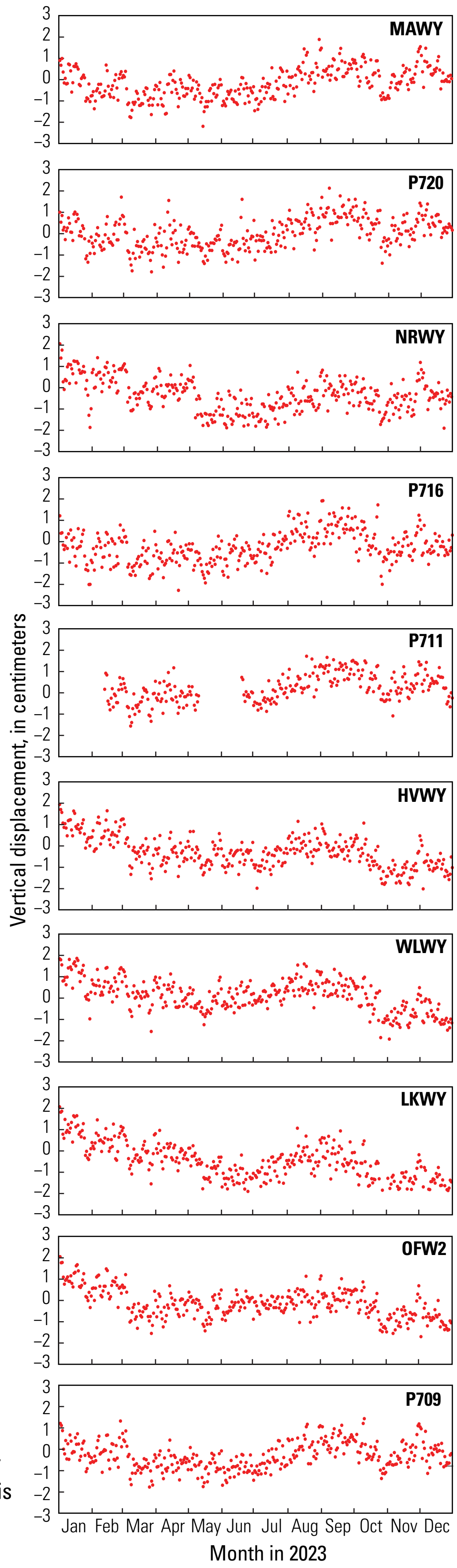


Figure 6. Map showing Global Positioning System (GPS) stations, and plots showing time series of deformation observed in Yellowstone National Park in 2023. Solid red line indicates boundary of Yellowstone Caldera. Vertical displacement (up or down movement of the ground) throughout the year is plotted for ten selected GPS stations (green dots) located around the national park. The GPS stations in bold on the map have their data displayed in the plots on the right. 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 2023 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). All stations show slight uplift during the summer months, which is a seasonal signal due to changing groundwater and snowmelt conditions. Gaps during time series indicate periods when GPS stations were not operational.

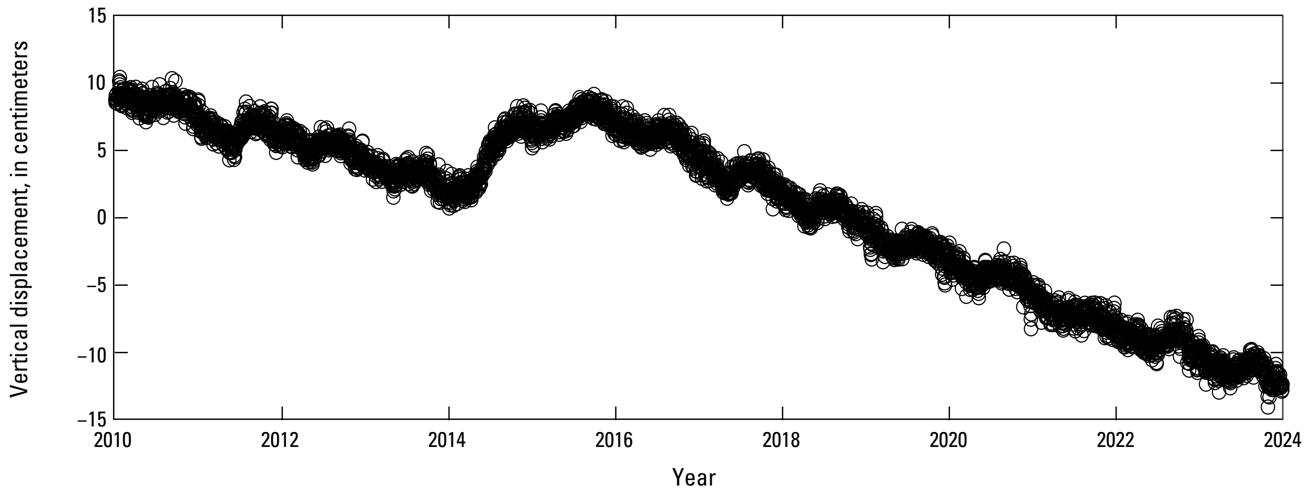


Figure 7. Vertical displacement (up or down movement of the ground) since 2010 measured at the WLWY continuous GPS station on the east side of Yellowstone Caldera (see fig. 6 for station location). Each black circle represents a single day of data. The station measured subsidence during 2010–2023 except 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 due to seasonal groundwater and snowmelt conditions.

Continuous GPS Results

Throughout 2023, surface deformation measured by 16 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. 6). During summer months, the subsidence stalls, and can even reverse slightly, with up to about 1 centimeter (0.4 inch) of uplift interrupting the ongoing subsidence. This seasonal variation is observed during most summers and is related to groundwater and snowmelt conditions and is not due to the magmatic or hydrothermal systems. During 2023, the seasonal pause in subsidence was manifested as slight uplift at most GPS stations in Yellowstone National Park, beginning in late May and lasting until early October.

At Norris Geyser Basin, there was little net deformation in 2023. 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. Similar to the GPS stations in the Caldera, seasonal uplift near Norris Geyser Basin began in late June, accumulating about 1 centimeter (about 0.4 inch) by early October. Little change occurred through the remainder of the year. As noted previously ("New Monitoring Station at Norris Geyser Basin"), a new GPS site, designated NBWY, was installed along with meteorology, seismic, and infrasound sensors in the Ragged Hills area of Norris Geyser Basin in August-September 2023. The GPS site is intended to assess deformation within the geyser basin itself, which probably differs significantly from that recorded by station NRWY, located only 3 kilometers (1.8 miles) to the east-southeast but that is well outside the geyser basin. The site did not collect sufficient data for rigorous analysis in 2023, but a year-long comparison between NBWY and NRWY in 2024 may yield interesting results.

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

As in 2022, the Yellowstone semipermanent GPS (SPGPS) network in 2023 comprised 16 stations in the park and one (HRSB) in the adjacent Hebgen Lake Ranger District of Gallatin National Forest (fig. 8). One of the stations in the park, WRBN, still exists but has not been deployed since 2021; instead, nearby and easier-to-access WBR2 has been deployed since 2019. Twelve of the other 16 stations were deployed in early May 2023. At that time, snow prevented access to WBR2 on Mount Washburn, LEWC near Lewis Falls, MMTN on Mary Mountain, and HRSB on Horse Butte. Those four stations were deployed in late June. Also in June, the GPS equipment at each of the May-deployed stations, which had been used for several years, was replaced with a more recent design by a different manufacturer. The equipment change resulted in small offsets (a few millimeters to about two centimeters) in some of the time series data; these can be corrected during subsequent analysis. To quantify the offsets at WBR2, LEWC, and HRSB, the older equipment was deployed for a few days in June and then replaced with the newer equipment. Only the new equipment was deployed in 2023 at backcountry station MMTN; any equipment-related offset there will be difficult to assess.

When they were visited in June, all of the stations that had been deployed in May were operating normally and recording data. All 16 stations were also undisturbed and recording data when they were retrieved in late September. These temporary deployments are intended to complement the continuous GPS (CGPS) network, which operates year-round, and to take advantage of generally benign summertime conditions to

SIDEBAR

Monitoring Geodetic Change in the Yellowstone Region

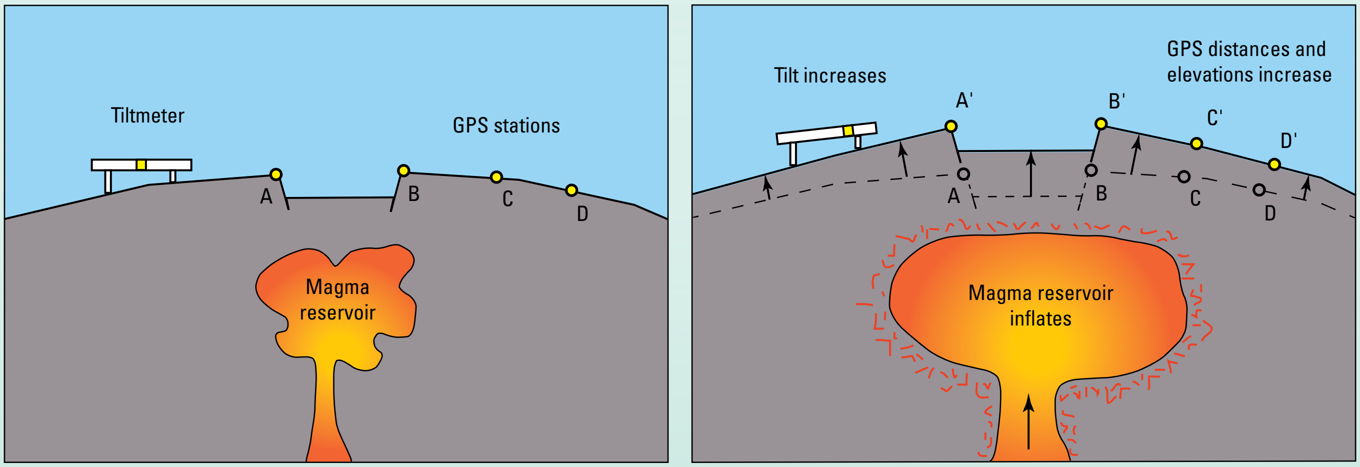
Subtle changes to the shape of a volcano's surface, called deformation, can be caused by the accumulation, withdrawal, or migration of magma, gas, or other fluids (usually water) beneath the ground, or by movements in Earth's crust owing to motion along faults. Typically, this deformation is very small 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. 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 16 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 GAGE archives, where they are made publicly available at https://earthscope.org.

Semipermanent GPS sites are temporary stations that are deployed in the late spring and collected in the early fall. Measurements from these portable sensors significantly 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 Yellowstone National Park.

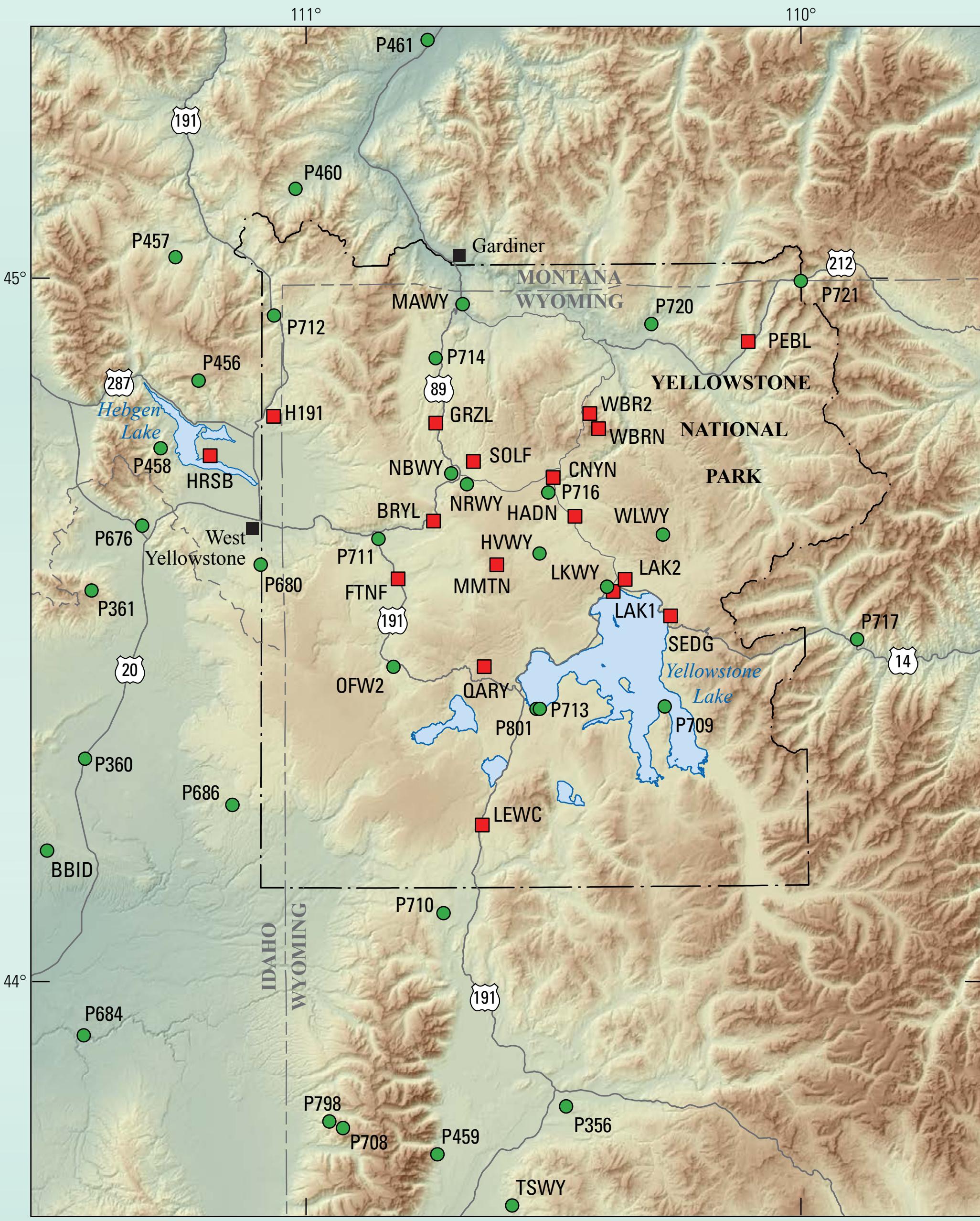
Yellowstone Volcano Observatory scientists also use satellite measurements, called interferometric synthetic aperture radar (InSAR), to take a broad snapshot of deformation. Two radar images of the same area that were collected at different times from similar vantage points in space are compared against 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 bad 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.

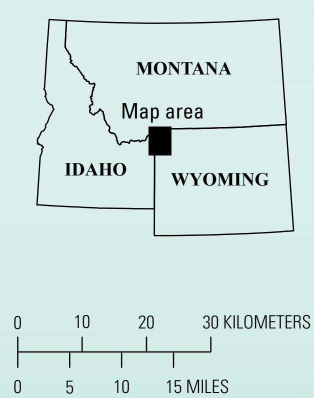
Measurements of changes in Earth's gravity field are another means to study processes that occur underground, hidden from sight. For example, gravity will increase slightly if more magma accumulates in a shallow reservoir, or if porous rock fills with groundwater. By combining gravity measurements (which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

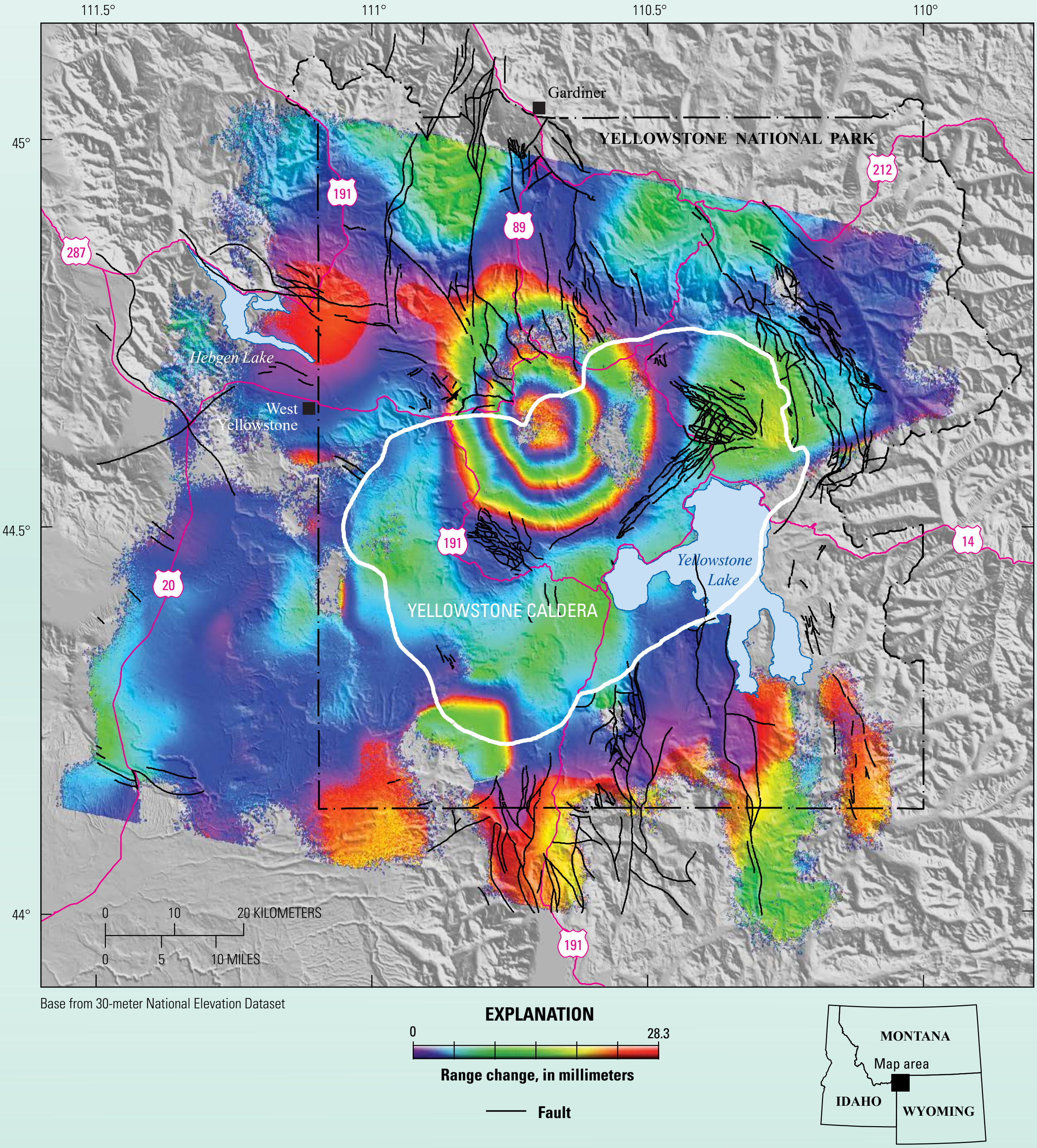
Scan here to watch a video describing deformation in Yellowstone National Park

https://www.youtube.com/watch?v=y0yq3DtR5Y4&utm_source=yvo-annual-report-2024&utm_medium=qr-code&utm_campaign=nh-volcanoes-fy24



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

Monitoring Geodetic Change in the Yellowstone Region



Map showing 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).

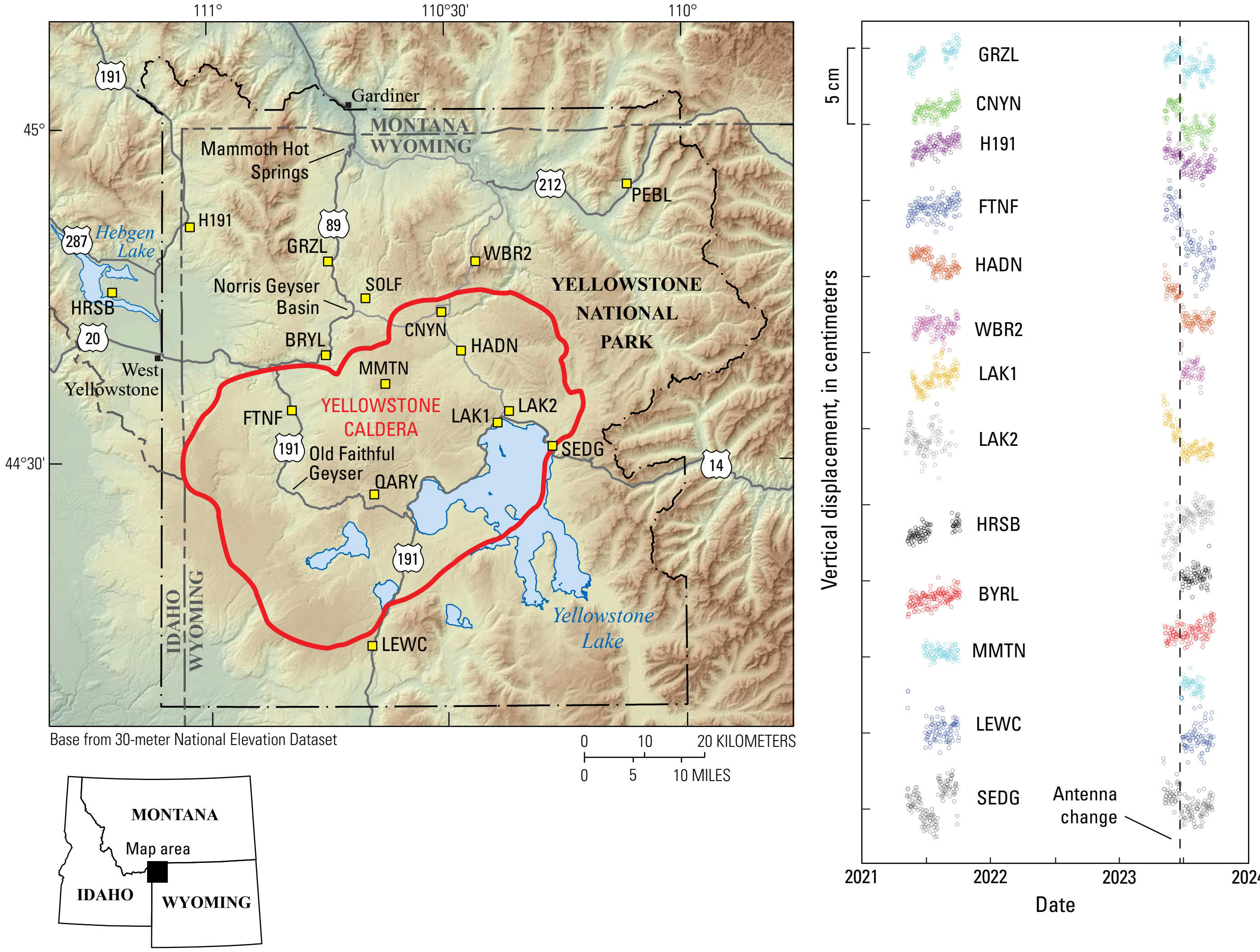


Figure 8. Map showing semipermanent Global Positioning System (GPS) stations, and plot showing time series of changes observed in Yellowstone National Park from 2021 to 2023 (no data were collected in 2022). Vertical displacement (up or down movement of the ground) is plotted for 13 selected semipermanent GPS stations (yellow squares) located around or just outside the park. The distance between tick marks on the vertical axis is 5 centimeters (cm) (about 2 inches). Downward trends indicate subsidence and upward trends indicate uplift. Dashed vertical line in 2023 marks time when older GPS receivers and antennas were swapped for newer equipment, which caused a vertical offset in most time series that does not reflect real ground motion.

collect data while avoiding harsh Rocky Mountain winters. For more information on the SPGPS technique, see the sidebar on monitoring geodetic change (p. 14–16).

All 16 of the SPGPS stations recorded useful data for the duration of their deployments (essentially 100 percent data retrieval). In past years, some data were lost as a result of equipment failures or disturbance by wildlife. In 2022, all of the data were compromised by a firmware problem. With that hopefully singular exception, it appears that 15 years of experience has produced a reliable and hardened station configuration while maintaining a small (and temporary) footprint on the landscape (about ten square feet, or one square meter, per station).

Both SPGPS and CGPS stations record not only ground deformation caused by volcanic and tectonic processes, but also unrelated short-term signals. These include seasonal effects, like changes in lake and groundwater levels that cause variable loading of the surface (YVO, 2019), as well as noise that occurs when a GPS antenna is covered with snow or ice, which is especially common near the start or end of the deployments. Such signals are easier to identify on records from CGPS stations than from SPGPS stations, which are deployed for only part of the year. For this reason, unless the deformation rate is unusually high, data from SPGPS stations are best compared from year to year, ignoring small variations during any one year.

From 2021 to 2023, most of the SPGPS stations recorded only small seasonal effects or weather-related noise, with little net change (fig. 8). Exceptions are BRYL, HADN, and MMTN, which are well positioned to detect ground deformation in the central part of Yellowstone Caldera. Each of those stations shows a few centimeters of net subsidence over that two-year time period, which is consistent with results from CGPS stations (see “Continuous GPS Results” section) and InSAR (see “InSAR” section). Apparent subsidence at WBR2 is likely to be an artifact associated with the equipment change described above; that station is located on the flank of Mount Washburn, on the topographic rim of Yellowstone Caldera, where InSAR shows no measurable deformation. Also consistent with the CGPS and InSAR results, the SPGPS data show no appreciable deformation in the vicinity of Norris Geyser Basin.

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

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. 14–16).

A radar interferogram that spans the period from September 24, 2022, to September 19, 2023, shows about 3 centimeters (1.2 inches) of subsidence of Yellowstone Caldera, maximized near the caldera center (fig. 9). This pattern of caldera deformation is similar to that of the preceding several years. No deformation is apparent outside the caldera, including in the area between Norris Geyser Basin and the north caldera rim. Interferograms spanning 2020–2021 show about 1 centimeter (0.4 inch) of uplift in that area (YVO, 2022a), followed by an equivalent amount of subsidence in the same area during 2021–2022 (YVO, 2023). The region between the caldera and Norris Geyser Basin has seen significant deformation in recent decades related to both magma and water accumulation and withdrawal (Wicks and others, 2020). An uplift episode that began in 1995–1996 and lasted until 2004 accumulated 12 centimeters (4.7 inches) at a rate of about 1.5 centimeters (0.6 inch) per year and was probably caused by magma accumulation at a depth of 14 kilometers (8.7 miles). More localized episodes of uplift and subsidence in 2013–2014 and 2016–2018 appear to be caused by water and gas accumulation and drainage at shallower depths of about 2–3 kilometers (1.2–1.9 miles), but the area did not deform significantly in 2023.

Geochemistry

Geochemical studies aim at better understanding the interface between hydrothermal and magmatic systems in the Yellowstone region, with the ultimate goal of investigating processes that are hidden from direct observation (see sidebar on geochemical monitoring on p. 21). Thermal features provide a window into the subsurface characteristics of Yellowstone National Park, not only through the chemical composition of the emitted waters, but also from the composition and flux of gases possibly emanating from subsurface magma.

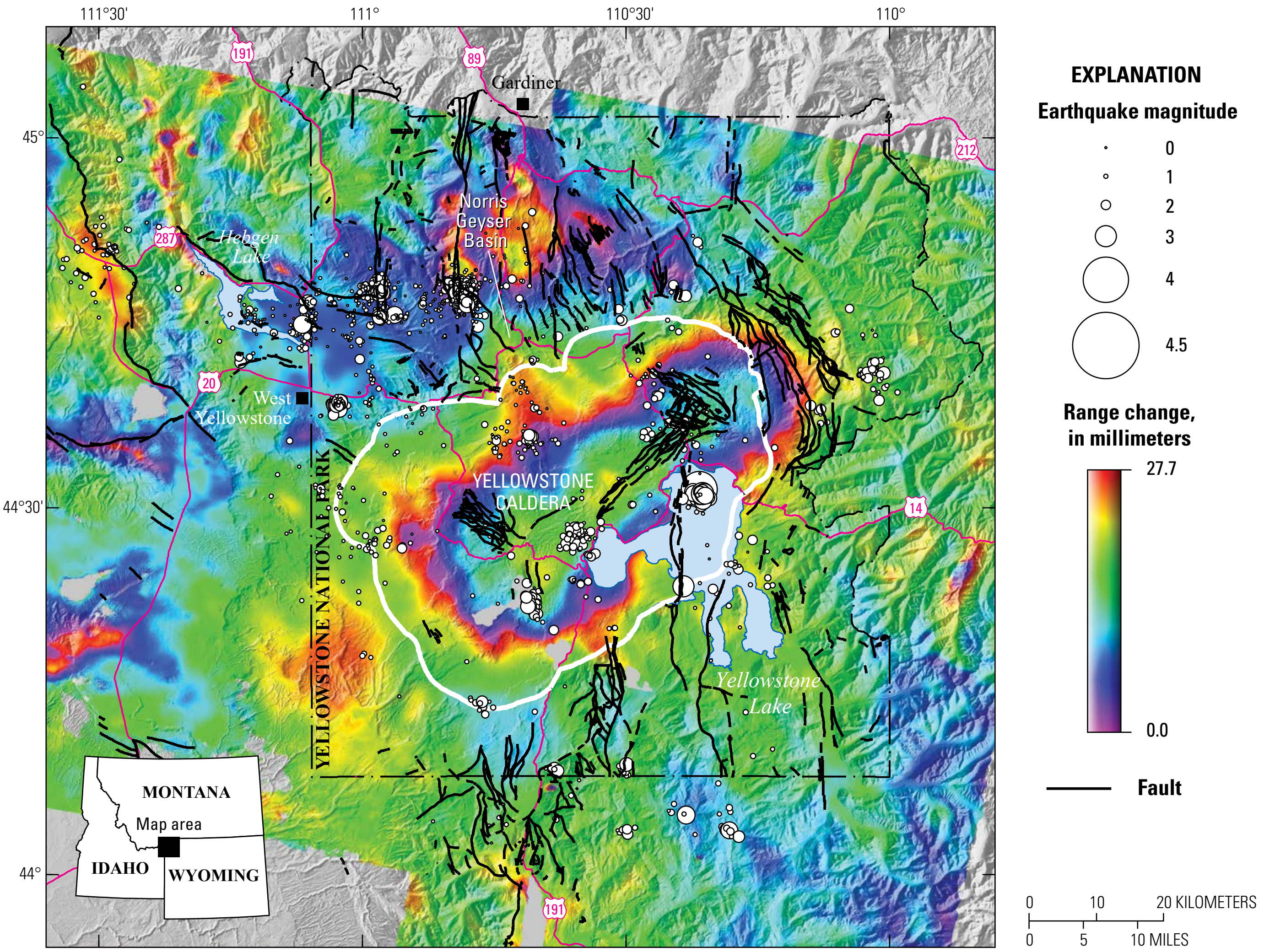
Summary of Geochemistry Activities in 2023

In 2023, YVO scientists continued with gas emission measurements and water sampling in targeted areas for laboratory analysis. The multicomponent Gas Analyzer System (multi-GAS) that was installed in the Mud Volcano area in 2021 (YVO, 2022a) continued to collect water vapor, hydrogen sulfide, and carbon dioxide concentrations throughout 2023. The eddy covariance station that was installed in summer 2022 was removed for repairs after experiencing a power failure in late 2022. Research results included an analysis of the feedback between geological and biological processes in hot springs at Norris Geyser Basin.

Gas Emissions

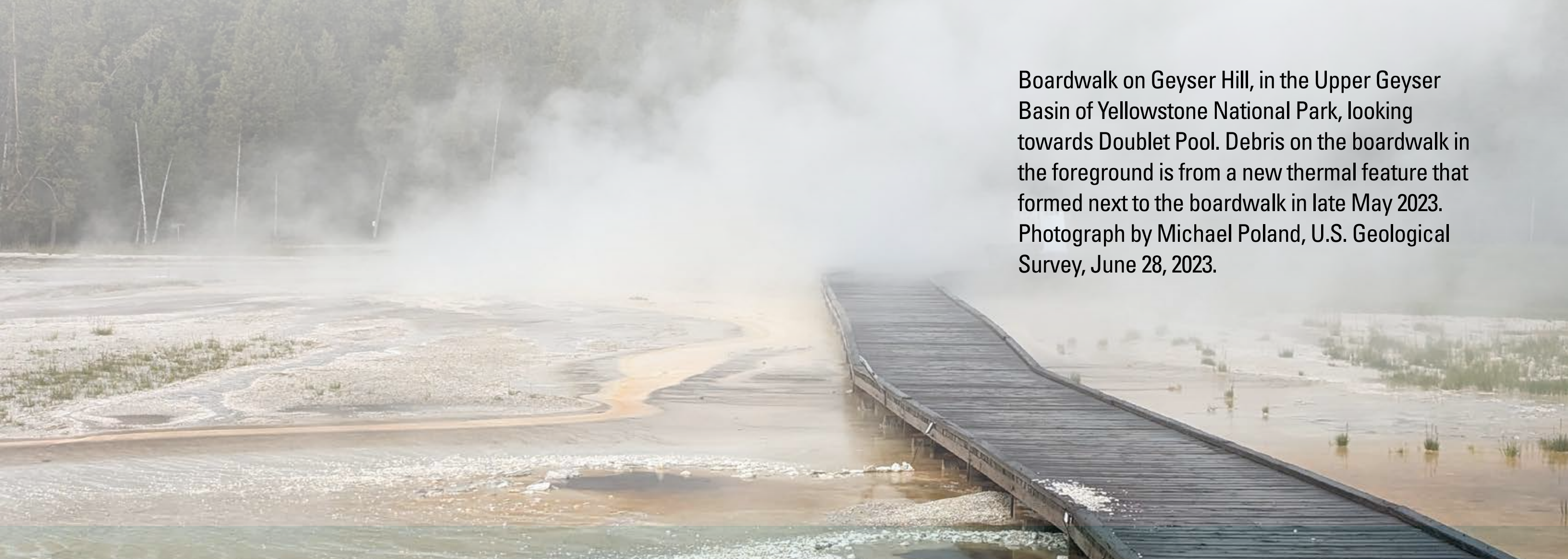
A study of gas and heat emissions from around Obsidian Pool, in the Mud Volcano thermal area, continued in 2023. The purpose of this ongoing study is to characterize, for the first time, high-resolution real-time variation in the chemical compositions of gases, as well as fluxes of gases and heat emitted from hydrothermal features in the area of Obsidian Pool. Gases emitted from the Mud Volcano thermal area can then be compared to those measured during 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”) continued to operate through much of 2023, 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 temperatures. Consistent with observations in 2022 (YVO, 2023), the 30-minute average H_2O, CO_2, and H_2S concentrations measured by MUD ranged from 1 to 20 parts per thousand by volume, 463 to 1,296 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 fig. 10. Data gaps from January 1 to February 12 and March 4 to 15 occurred with low air temperatures and heavy snowfall, presumably covering solar panels with snow and ice. Average H_2O/CO_2 and CO_2/H_2S ratios ranged from <1 to 23 and 255 to 2401, respectively (figs. 10*A* and 10*B*). These results were similar to observations in 2022 (YVO, 2023). During winter months, CO_2/H_2S ratios were higher and H_2O/CO_2 ratios lower, in general, reflecting plume water condensation and H_2S scrubbing with low air temperatures and high relative humidity (figs. 10*A*–10*D*).

The eddy covariance station—designed to measure CO_2 and heat flux—that was installed at the Obsidian Pool site in September 2022 (YVO, 2023) stopped working due to a power failure in November 2022, and no gas and heat flux data were collected in 2023. The equipment was removed for repairs in September 2023.



Base from 30-meter National Elevation Dataset

Figure 9. Interferogram created from satellite radar data collected on September 24, 2022, and September 19, 2023, 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 during the period between the image acquisition times. Fringes outside the caldera are mostly related to atmospheric artifacts and do not reflect real ground motion. White circles show earthquakes that occurred during the time spanned by the interferogram. Circle size scales with magnitude, with the largest about magnitude 3.7.



Boardwalk on Geyser Hill, in the Upper Geyser Basin of Yellowstone National Park, looking towards Doublet Pool. Debris on the boardwalk in the foreground is from a new thermal feature that formed next to the boardwalk in late May 2023. Photograph by Michael Poland, U.S. Geological Survey, June 28, 2023.

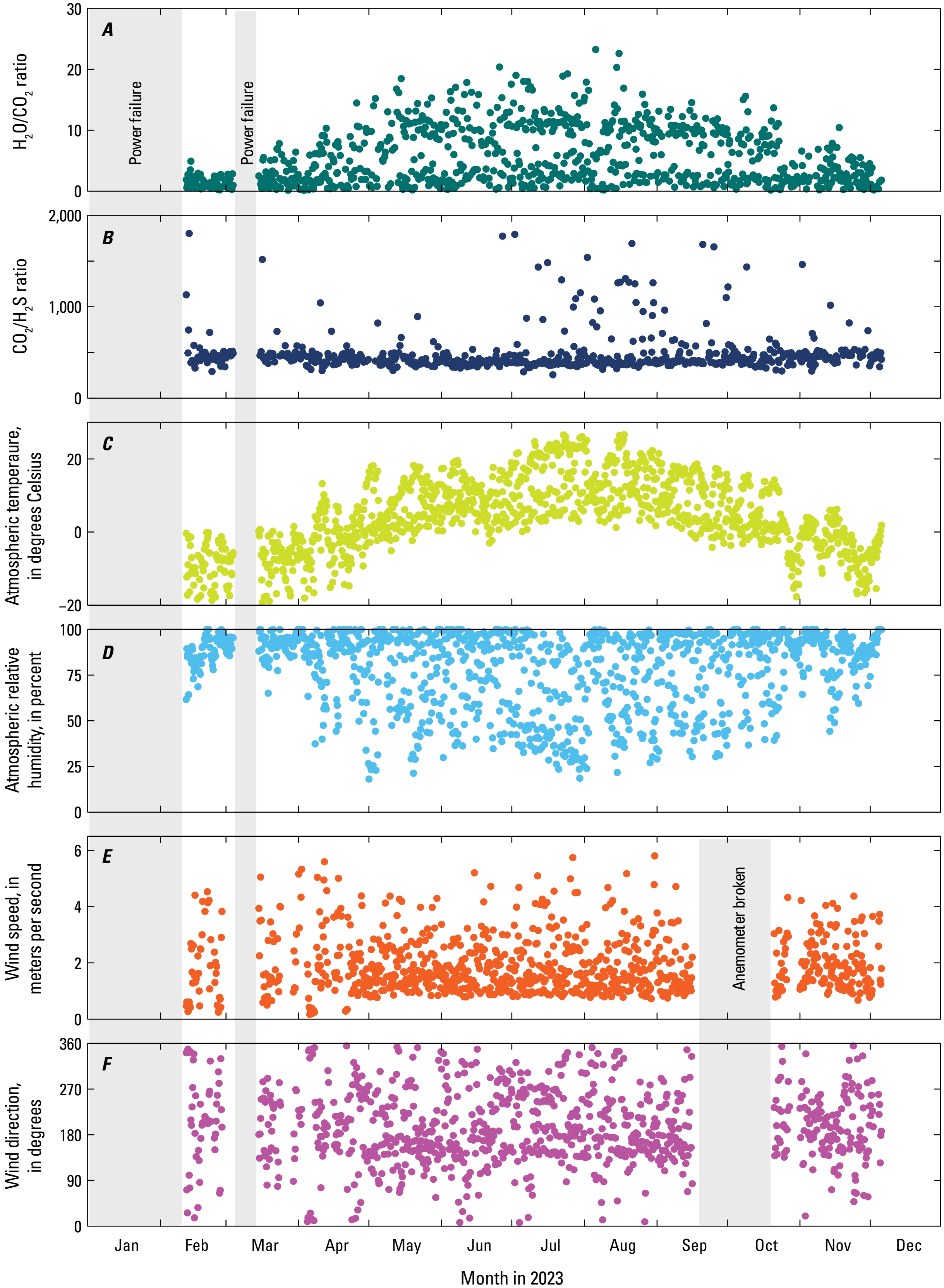


Figure 10. Times series of 30-minute average (*A*) H_2O/CO_2 ratio, (*B*) CO_2/H_2S ratio, (*C*) atmospheric temperature, (*D*) relative humidity, (*E*) wind speed, and (*F*) wind direction measured by the MUD multi-GAS station. Gray areas denote data loss due to power or equipment failure.

Linking the Chemical and Biological Characteristics of Hot Springs

An important process controlling hydrothermal activity observed at the surface in Yellowstone National Park is phase separation, which is the process by which a deep hydrothermal fluid boils as it ascends, and the gas phase becomes independent of the liquid phase. The boiled residual liquid feeds neutral-chloride thermal areas and features, like Old Faithful, and the cooled and condensed vapor phase feeds acid-sulfate thermal areas and features, like Mud Volcano. Although this model can explain the chemistry and biology of hot springs as observed at the surface, little is known about the subsurface plumbing, timescales of phase separation, and interaction between hydrothermal fluids and the rocks through which they travel. Essentially there is a two-dimensional understanding of a four-dimensional problem.

To address this gap in understanding, Sims and others (2023) conducted a detailed geophysical, geochemical, and biological study of two adjacent hot springs at Norris Geyser Basin, one an acid-sulfate spring representing the vapor phase, and the other a neutral-chloride spring representing the fluid phase. Results of the work include four new insights:

1. Geophysical imaging revealed that groundwater mixes with the vapor phase at shallow levels. This shallow groundwater carries a lot of oxygen, which starts the geobiological feedback necessary to generate the acidity in the vapor phase pools.
2. The host rock of the deep source area can be determined from the neutral-chloride hydrothermal fluids and is sedimentary, not volcanic. In contrast, acid-sulfate springs appear to have a volcanic signature, but this is acquired as the fluids ascend through volcanic rocks at shallow levels and does not reflect the geology of the source area.
3. The timescales of interactions between the fluid phase and the host rock vary for the different types of hot springs. In the acid-sulfate pool, water-rock interactions occur shallowly over tens of years, while in neutral-chloride systems, the interactions occur at deeper levels, before phase separation, over hundreds to thousands of years.
4. Phase separation in the subsurface controls spring chemistry, which in turn influences the biological diversity of the springs. While the acidification of the acid-sulfate systems begins in the shallow subsurface, microbes in the springs drive the process to make the waters acidic.

Taken together, the study emphasizes the interconnectedness between the geology and biology in Yellowstone National Park hot springs. Phase separation drives the chemical makeup of hot springs, which support, and can in turn be influenced by, microbial communities. This work was completed under research permits YELL-5840 and YELL- 6090.

Geochemical Monitoring in Yellowstone Caldera

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.

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. 24–25) 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 2023

In 2023, YVO geologists and collaborators made progress on several ongoing projects, including investigations of the compositions and ages of rhyolite lava flows, the connection between past formation of travertine within Yellowstone Caldera and climate conditions, and geologic mapping of Yellowstone National Park, including the development of methods to trace volcanic sedimentary rocks back to their source areas in the Absaroka Range. In addition, new work began on the East Gallatin-Reese Creek Fault System in the northwest part of the park, with the goal of developing a better understanding of the history of fault slip and earthquake hazards.

Understanding the Recent Volcanic History of the Yellowstone Region

During 2023, argon-argon ($^{40}Ar/^{39}Ar$) dating of the youngest episode of rhyolite volcanism from the Yellowstone Plateau volcanic field, the rhyolite of the Central Plateau Member of the Plateau Rhyolite, was completed (Stelten and others, 2023). In this technique, scientists extract the potassium-bearing mineral sanidine from the rhyolite lavas and use a variant of the conventional potassium-argon method to measure the ratio of potassium (the parent) to argon (the daughter product produced through radioactive decay) in the mineral grains, allowing the time of eruption to be precisely determined. Specifically, this work set out to test if the rhyolite from the Central Plateau Member eruptions occurred in clusters (where multiple eruptions occur over a short duration), if they erupted at separate and irregular time intervals, or if both conditions exist. This information is essential for understanding the frequency of rhyolite lava flow eruptions at Yellowstone and characterizing its volcanic hazards. Also in 2023, initial paleomagnetic work and geochemical analyses on the nine oldest units of the Central Plateau Member were completed.

Results of the $^{40}Ar/^{39}Ar$ work show that the 22 rhyolite eruptions that make up the Central Plateau Member occurred in five brief episodes at 160,000, 150,000, 111,000, 104,000, and 71,000 years ago (fig. 11). During these episodes, two to nine rhyolites erupted from volcanic vents spaced out over several kilometers to tens of kilometers (a few to several miles). These episodes are estimated to have taken a maximum of 400 years but may have occurred over much shorter durations. Between 10 and 130 cubic kilometers (2.5 and 31 cubic miles) of magma erupted during each episode (for comparison, the Mount St. Helens eruption in 1980 erupted about 0.25 cubic kilometers [0.06 cubic miles] of magma).

These results have two important implications. First, intracaldera eruptions are more dramatic events than previously appreciated. Instead of isolated events where a single lava flow erupts, it appears that intracaldera eruptions can involve multiple eruptions occurring in different parts of the caldera at approximately the same time. Second, if each of the five eruptive episodes is considered a single volcanic event (because of their short durations), then the Central Plateau Member would be represented by only five volcanic events instead of twenty-two, meaning that the long-term eruption rate at Yellowstone Caldera is even lower than currently thought.

To build on this recently published research, field work was conducted in September 2023 by USGS geologist Mark Stelten and collaborators from the University of California, Davis (Dr. Kari Cooper, Elizabeth Grant, Anjelica Guerrier, and Julia Walker). Samples of fresh volcanic glass were collected from nearly all the rhyolite of the Central Plateau Member and will be used for uranium-thorium ($^{238}U/^{230}Th$) dating—a geochronology technique that is well suited to determining ages of some rocks that are less than 500,000 years old—and geochemical analyses to further understand pre-eruptive magmatic processes associated with the Yellowstone magmatic system. These samples will be analyzed starting in 2024.

Geochronology work did not focus solely on the Central Plateau Member but also included a number of other time periods and geologic processes. Argon-argon ($^{40}Ar/^{39}Ar$) dating of deposits from caldera-forming eruptions was undertaken to better understand the distribution of deposits from these large explosions and the history of caldera formation in the Yellowstone region. In addition, $^{40}Ar/^{39}Ar$ dating of glacial erratics and cobbles in glacial deposits was completed in coordination with Dr. Shaul Hurwitz (USGS), Dr. Joseph Licciardi (University of New Hampshire), and Dr. Lauren Harrison (Colorado State University) to better understand the origin of glacial deposits found throughout Yellowstone National Park and the surrounding region. Work on both projects will continue in 2024. Finally, $^{40}Ar/^{39}Ar$ dating of basaltic rocks from the Henrys Fork caldera west of Yellowstone National Park was completed. These data indicate that basalts in that area erupted over a wide range of time, from more than one million years ago to 30,000 years ago and overlap in time with multiple caldera cycles of the Yellowstone volcanic system. These results will be interpreted in their geologic context in 2024.

Geologic Mapping of Yellowstone National Park

In 2020, a team of Montana State University researchers set out to update portions of the geologic maps of Yellowstone National Park (YVO, 2021c). Among the 22 compiled geologic maps in the park, it was clear that many of the geologic interpretations disagreed across the maps' shared boundaries (Kragh, 2023). This is neither an uncommon nor an unexpected occurrence, as compiling maps made by different authors

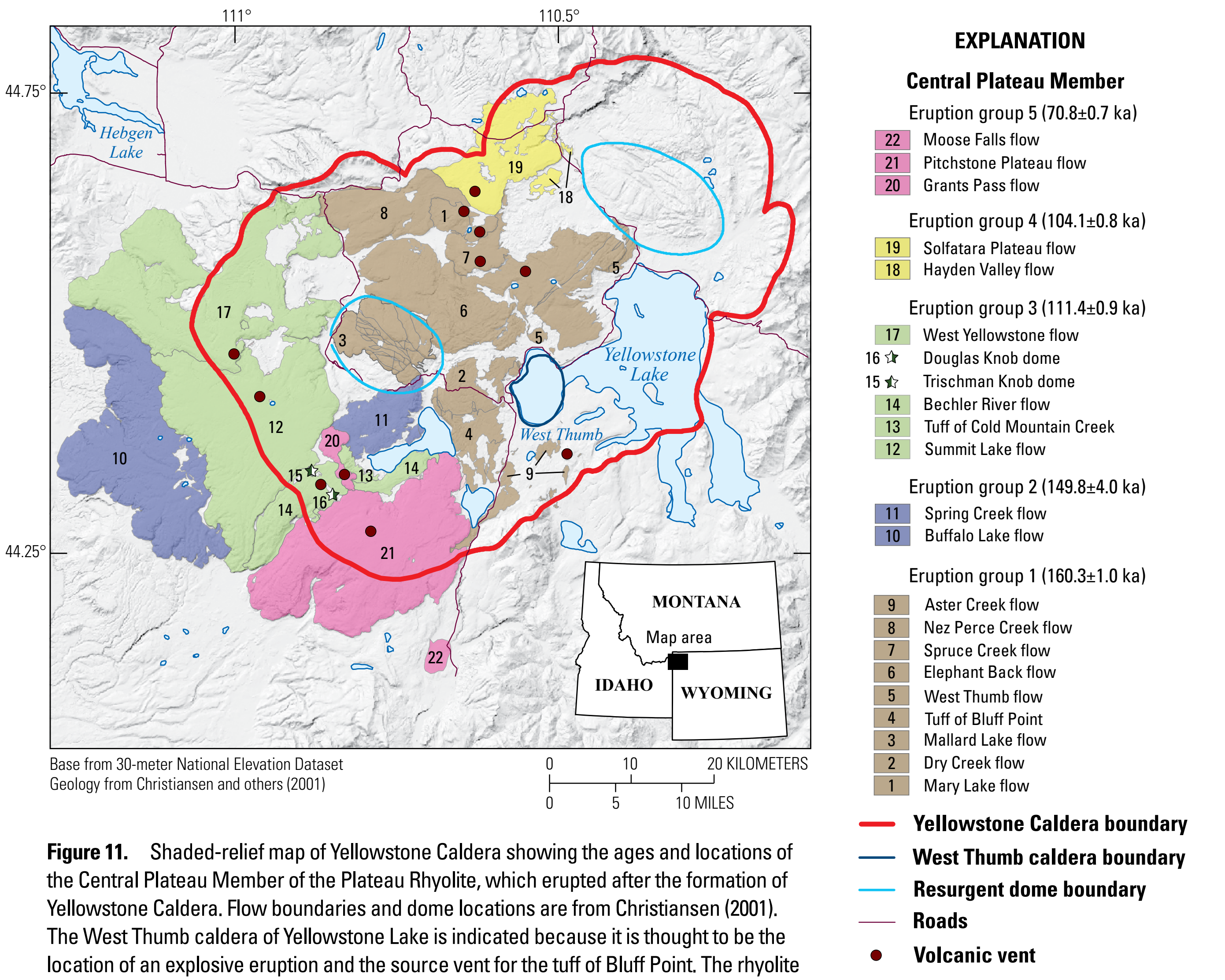


Figure 11. Shaded-relief map of Yellowstone Caldera showing the ages and locations of the Central Plateau Member of the Plateau Rhyolite, which erupted after the formation of Yellowstone Caldera. Flow boundaries and dome locations are from Christiansen (2001). The West Thumb caldera of Yellowstone Lake is indicated because it is thought to be the location of an explosive eruption and the source vent for the tuff of Bluff Point. The rhyolite of the Central Plateau Member is broken into five informal groups based on new $^{40}Ar/^{39}Ar$ eruption ages. Each informal eruption group is shown in the same color. Numbers on the map and legend are included to indicate the location of different lava flows. Group mean ages and their 95 percent confidence intervals are included next to the list of units.

with varying mapping objectives is bound to result in some discrepancies. To publish a seamless finer-scale map of the park, however, these issues need to be resolved.

From 2020 to 2022, the Montana State University team spent 66 days in the park and resolved known mapping issues in 23 individual areas (fig. 12). Some of these corrections were minor, such as connecting mismatched unit contacts, while others were significant—for example, completely redefining mapped rock units using petrology, geochronology, and geochemistry. Of the 485 edge-matching problems identified at the initiation of this project, 60 were resolved and 137 interior corrections were made to the maps (Kragh, 2023).

Even though it was not possible to address and correct all the known issues, the Montana State University work highlights that there is ample room for geological mapping projects in Yellowstone National Park. A wealth of opportunity exists for graduate students and academic scientists, USGS geologists, state geological survey scientists, and others to continue efforts to map the park at a higher resolution. Ultimately, the Montana State University team believes that the next priorities for geologic mapping in the park should occur in three phases.

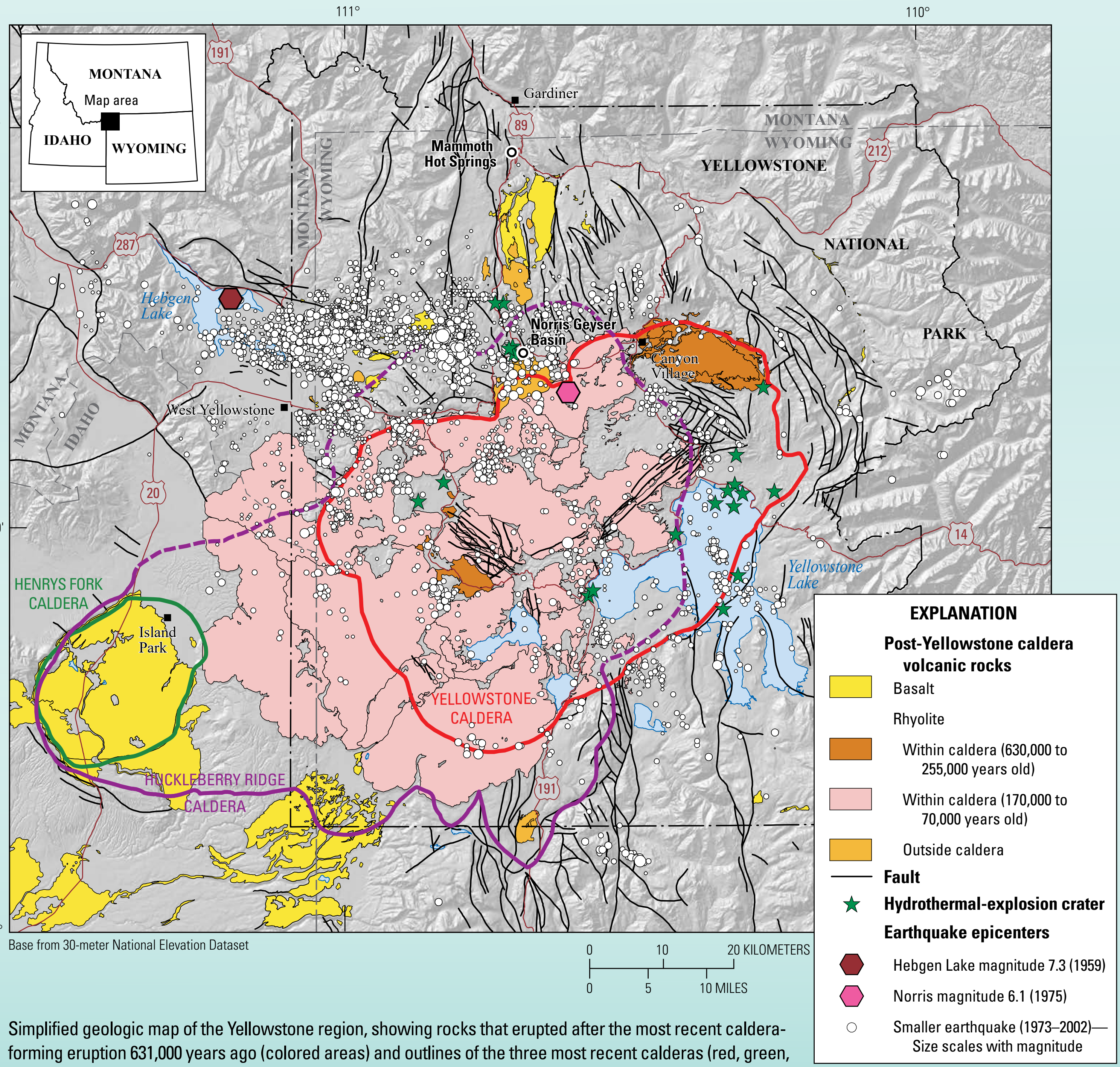
- Phase 1: Continue making boundary corrections for seamless mapping between the existing 1:62,500 scale maps. This phase would probably take about two field seasons to complete, depending on the number of workers assigned to the task.

- Phase 2: Re-map the nine smaller-scale quadrangles in the park at 1:62,500 scale. This phase is expected to take between six and ten field seasons depending on the available time and resources.

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 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, and other rock fragments welded together from their

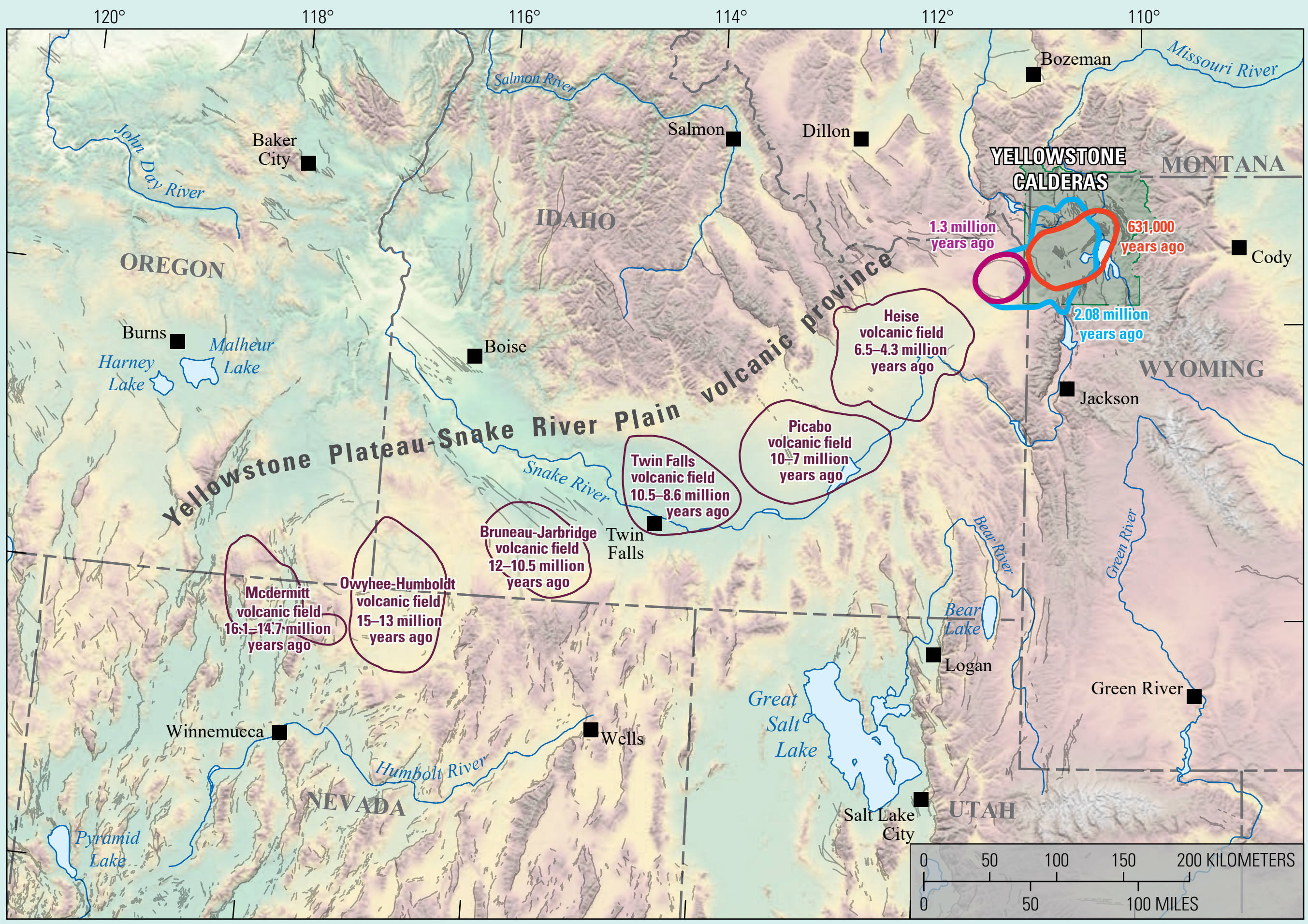


Simplified geologic map of the Yellowstone region, showing rocks that erupted after the most recent caldera-forming eruption 631,000 years ago (colored areas) and outlines of the three most recent calderas (red, green, and purple lines). Modified from U.S. Geological Survey Fact Sheet 2005–3024 (Lowenstern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

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 160,000 and 70,000 years ago. No magmatic eruptions have occurred since then, but large hydrothermal explosions have taken place since the end of the last ice age in the Yellowstone region, 16,000–14,000 years ago.

Yellowstone Caldera's volcanism is only the most recent in a 17-million-year history of volcanic activity that has occurred progressively from near the common border of southeastern Oregon, northern Nevada, and southwestern Idaho to Yellowstone National Park as the North American Plate has drifted over a hot spot—a stationary area of melting within Earth's interior. At least six other large volcanic fields 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.



Shaded relief from USGS The National Map: 3D Elevation Program. USGS Earth Resources Observation & Science (EROS) Center: GMTED2010. Data refreshed March, 2021. Color DEM from 3DEP 1 arc-second dataset from USGS's 3D Elevation Program, 2023. Vector data from Natural Earth, downloaded in 2019. USA Contiguous Albers Equal Area Conic USGS projection.

EXPLANATION

Elevation, in meters

0 4,000

Calderas and volcanic centers— Numbers are ages in millions of years of major eruptions; caldera or volcanic field boundaries inferred

1.63 2.08

1.3 Older than 4.3

Yellowstone National Park

Quaternary faults (USGS, 2020)

Map showing volcanic fields (outlined) where the Yellowstone Hot Spot produced one or more caldera eruptions—essentially "ancient Yellowstones"—during the time periods indicated. As the North American Plate drifted southwest over the hot spot, the volcanism progressed northeast, from the common border of southeastern Oregon, northern Nevada, and southwestern Idaho 16.5 million years ago and reaching Yellowstone National Park about 2 million years ago. Mountains (whites, browns, and tans) surround the low elevations (yellows and 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 Morgan and others (2017) and Smith and Siegel (2000) with permission.

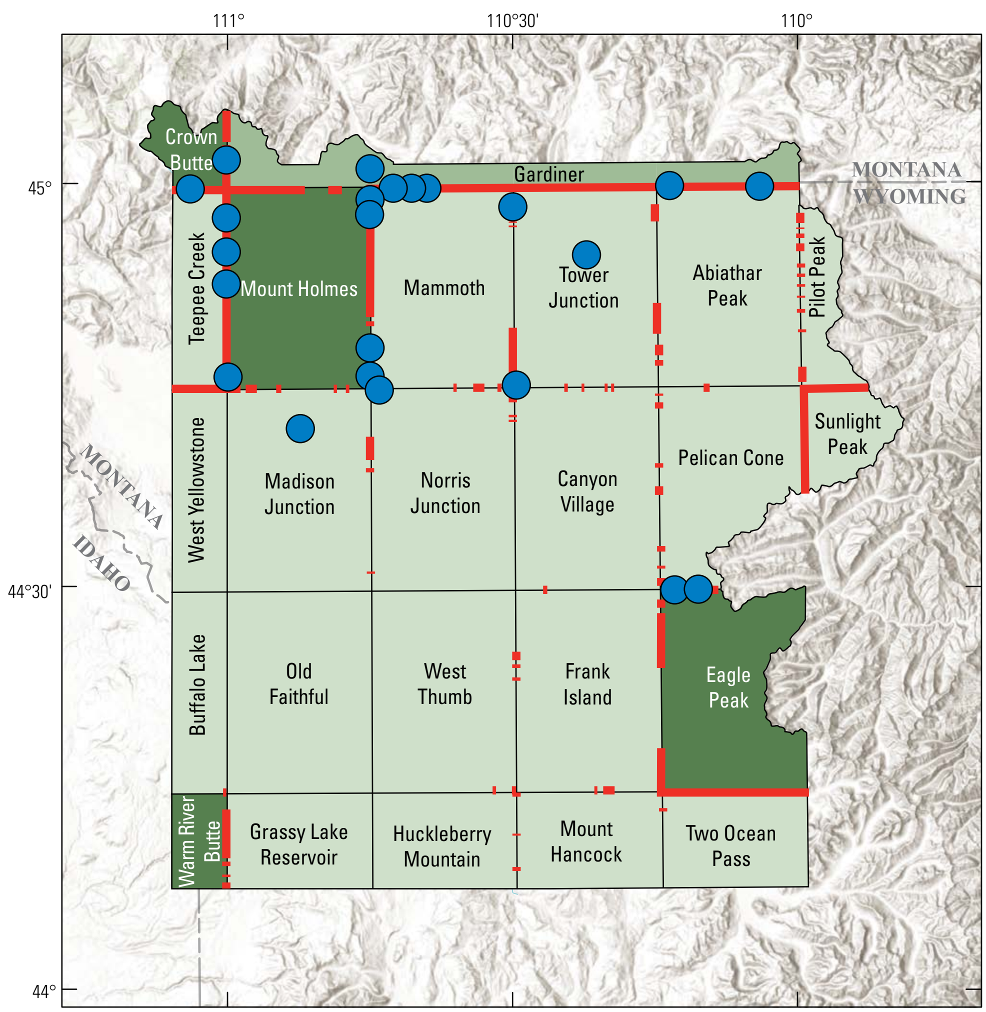
- Phase 3: Combine all the 1:62,500 scale maps and ensure the maps have seamless boundaries. With this product, geoscientists can take a holistic view of the geology of Yellowstone National Park and better identify areas for additional study.

During the project, the Montana State University team identified the need for a single whole-rock geochemical database to assist in identifying unknown map units. This recognition led to the compilation and publication of a USGS data release (Kraugh and others, 2023) that includes data from 17 publications and 494 whole-rock analyses.

Tracing the Sources of Rock Units in the Absaroka Volcanic Supergroup

As part of their geologic mapping in the Yellowstone region (see "Geologic Mapping of Yellowstone National Park" section), Montana State University geologists focused particular attention on volcanic sedimentary material, referred to as volcaniclastics. There are known mapping discrepancies in the northeast part of Yellowstone National Park between the 1:100,000 Gardiner quadrangle and the 1:62,500 Abiathar Peak and Tower Junction quadrangles (fig. 12). The southern, larger-scale maps separate the volcaniclastic units into individual formations sourced from different volcanoes, while the smaller-scale map to the north makes no such distinction. Attempting to map the northern portion at a larger scale and confirming the contact location on the southern map is essential for creating an accurate, seamless map for the area; however, when investigating these deposits, no visible distinguishing features were identified between the formations, and there was no obvious mappable contact. Each of the units consists of the same repeating sequences: mixed-composition conglomerate normally grading into sandstone, topped by another graded sequence.

Volcaniclastic units within Yellowstone National Park (fig. 13) are mainly sourced from the approximately 50-million-year-old Absaroka Volcanic Supergroup, found in large volumes throughout the eastern and northern sections of the park but extending north, east, and south of the park boundaries (Smedes and Prostka, 1972). Altogether, this volcanic chain was about 155 kilometers (96 miles) long, and more than 29,000 cubic kilometers (6,957 cubic miles) of material was produced over its approximately 16-million-year lifespan. The Absaroka Volcanic Supergroup is divided into three main volcanic groups: Washburn Group (oldest), Sunlight Group, and Thorofare Creek Group (youngest). Since its inception, the original volcanic rocks of the Absaroka Volcanic Supergroup have been continually eroded and transported away from their sources. Today, much of the Absaroka Volcanic Supergroup is made up of these eroded and redeposited rocks, referred to as secondary volcaniclastic rocks.



Base from 30-meter National Elevation Dataset

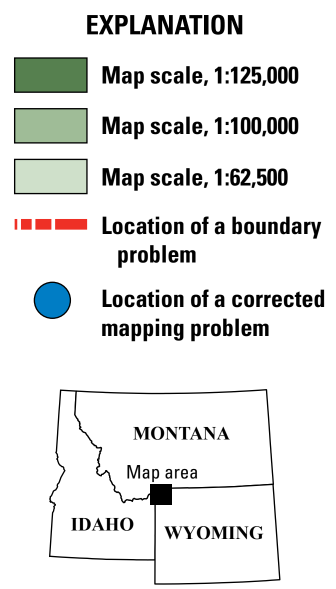


Figure 12. Map showing the most detailed geologic maps that exist for Yellowstone National Park. The red lines between maps represent known boundary mismatches. Labels are names of quadrangles. Figure adapted from the Geologic Resources Inventory 2020 Geologic Index Map of Yellowstone National Park. The Montana State University mapping team visited 23 areas (blue dots) throughout Yellowstone National Park between 2020 and 2022 and partially to fully corrected the boundary mismatches and interior geology in those areas.

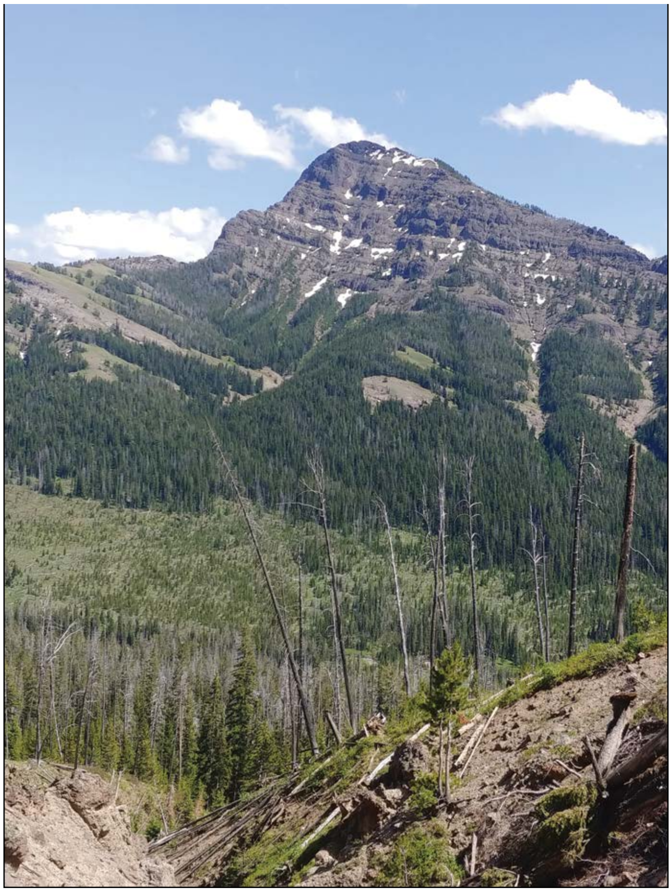


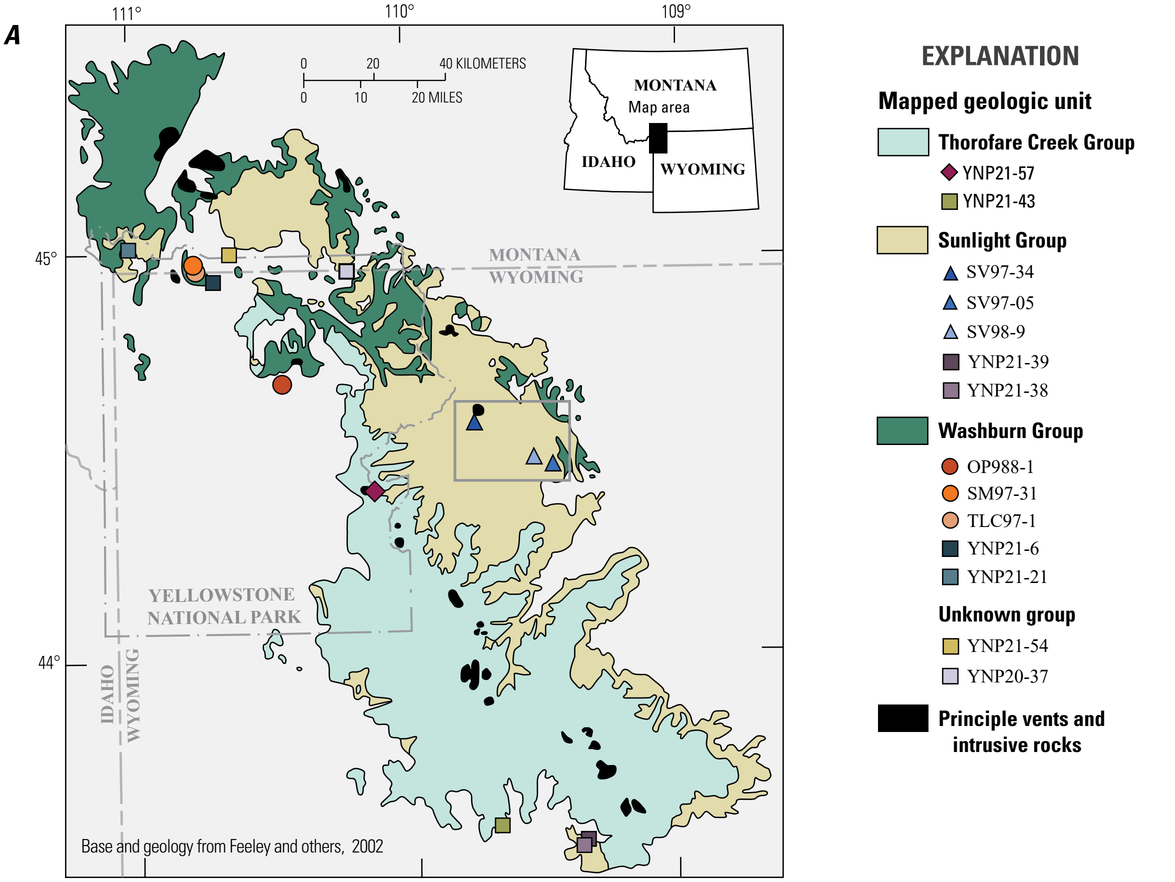
Figure 13. Volcaniclastic rocks of the Absaroka Range. Left, northern ridge of Baronette Peak showing repeating sequences of volcaniclastic rock overlying older Paleozoic rock. Right, repeating graded volcaniclastic units on the eastern side of Cutoff Mountain, near Bliss Pass. Photographs by Natali Kraugh, Montana State University, 2020.

The Absaroka Volcanic Supergroup secondary volcaniclastics dominate a good portion of the eastern and northern areas of Yellowstone National Park, with some reaching more than 80 kilometers (50 miles) from the original unit's volcanic vents (fig. 14*A*). The distance and the lack of distinct visual features between various units make it difficult to distinguish what volcaniclastic rock came from what volcanic group within the Absaroka Volcanic Supergroup, hindering the ability to update geologic maps of distal volcaniclastic units, as well as to calculate volumes for the Absaroka Volcanic Supergroup groups. Because of the lack of textural features that can be used to trace Absaroka Volcanic Supergroup volcaniclastics over great distances, a geochemical approach is needed.

Montana State University geologists attempted to "fingerprint" the volcaniclastic units using the isotopic geochemistry of the mineral plagioclase, which is found in both the primary volcanic rocks and the secondary volcaniclastic units. Isotopes are different forms of the same element that have the same number of protons in their nuclei but different numbers of neutrons and that can serve as geochemical tracers. The method, if viable, could provide insights into the formation conditions and "provenance" (source material) for distal volcaniclastic units found not just in Yellowstone National Park, but in other volcanic areas throughout the world.

Isotopic data were collected for plagioclase crystals found in seven lava flows and shallow intrusive rocks of the Absaroka Volcanic Supergroup, five volcaniclastic rocks of known origin, and one lava flow and one volcaniclastic rock of unknown origin. Lead isotope ratios on individual plagioclase crystals were measured on a single quadrupole laser ablation inductively couple plasma mass spectrometer (LA-ICP-MS) at Boise State University. The data from the primary source material—the lava flows and shallow intrusive rocks—indicated that while there is some overlap between the three volcanic groups of the Absaroka Volcanic Supergroup, the Sunlight Group plots separately from the Washburn and Thorofare Creek Groups (fig. 14*B*). The overlap between the Washburn and Thorofare Creek Groups cannot be disentangled but, fortunately, these two groups tend to be spatially distinct, with Washburn Group in the north and Thorofare Creek Group in the southeast; therefore, a combination of isotopic and location information should be sufficient in distinguishing those two groups.

Next, the volcaniclastic data of known origin and the two unknown samples were plotted over the primary isotope data to see how they compared (fig. 14*C*). The volcaniclastics of the Washburn and Thorofare Creek Groups plotted in the same areas as their corresponding primary samples, whereas the volcaniclastics of the Sunlight Group plotted well away from the general isotopic space defined for the Absaroka Volcanic Supergroup. This indicates



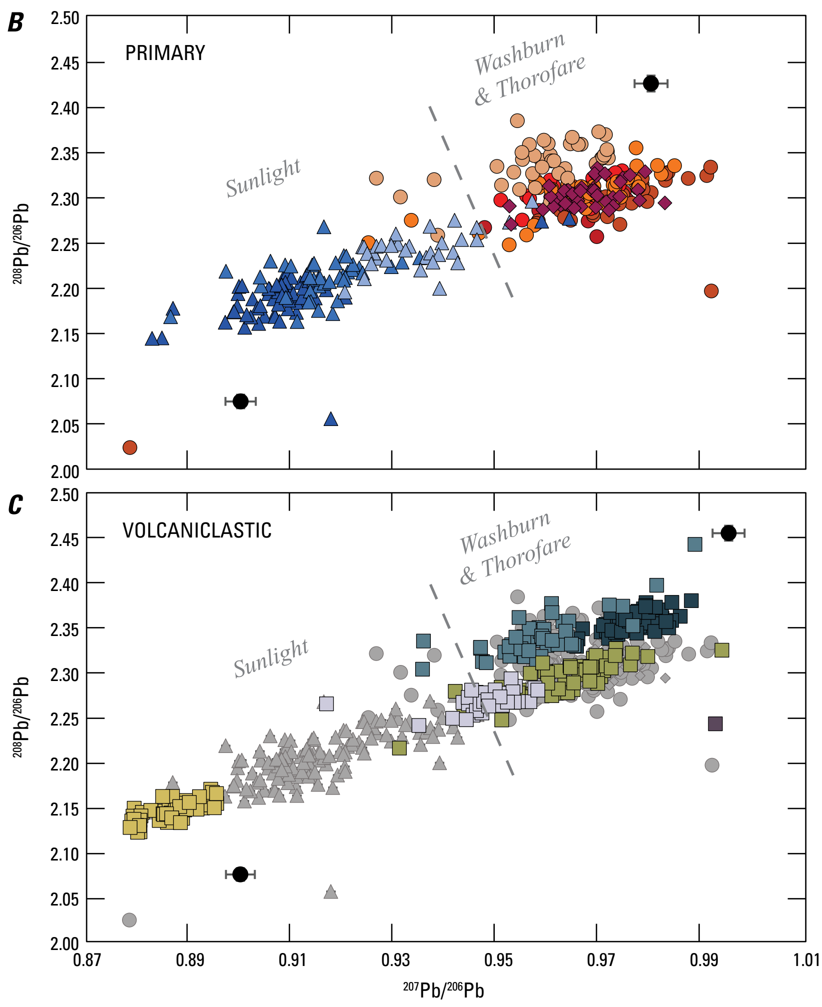


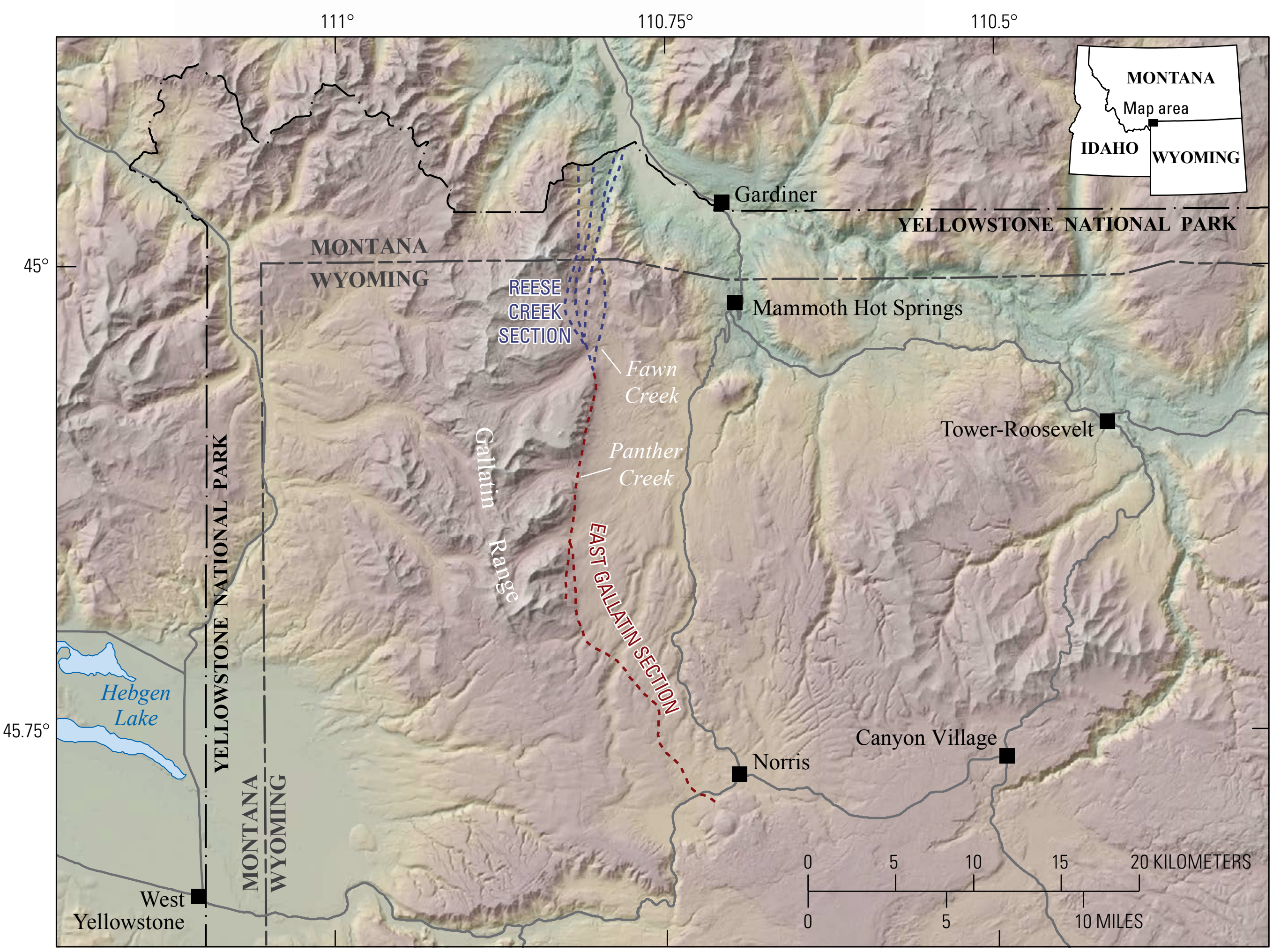
Figure 14. Generalized map and isotopic data for the Absaroka Volcanic Supergroup. *A*, Geological map showing the distribution of the Thorofare Creek, Sunlight, and Washburn Groups. Figure modified from Feeley and others (2002). Plagioclase crystals from samples displayed on the map were analyzed for radiogenic lead isotope ratios. *B*, Primary-unit lead isotope data show that the Washburn and Thorofare Creek Groups overlap while the Sunlight Group consistently plots separately. *C*, Volcaniclastic lead isotope data overlain on the primary data (same as in part *B*, but grayed out in the background). The only data that did not plot as expected were samples YNP21-38 and 39, which were expected to overlap the Sunlight Group primary data. The isotope ratios for these samples fall away from the main trend of the Absaroka Volcanic Supergroup (off plot) and may indicate that the geologic units represented by these samples are not sourced from the Absaroka Volcanic Supergroup.

that the provenance of these volcaniclastics of the Sunlight Group may not be the Absaroka Volcanic Supergroup at all, which aligns with other research suggesting that a geologic formation, the Aycross Formation, which is of similar age and characteristics as the lower Sunlight Group, is sourced from igneous rock units in Idaho (Malone and others, 2017). The volcaniclastic data also display a remarkable degree of clustering, which indicates that the volcaniclastics are not just a random mix of different sources, as would be the case for typical sedimentary rocks, but rather that they come directly from specific primary volcanic deposits.

These initial data indicate that isotopes may be used to fingerprint volcaniclastic units, aiding with geologic mapping not only in Yellowstone National Park, but also in other volcanic areas around the world. If applied to enough deposits in the Yellowstone region, it might even be possible to reconstruct the paleo-valleys and rivers of the landscape that existed 50 million years ago, providing a window into the topography of a region before the Yellowstone hotspot arrived.

Reconnaissance Study of East Gallatin-Reese Creek Fault System

Geologists from the Wyoming State Geological Survey and Montana Bureau of Mines and Geology began a project in summer 2023 studying the East Gallatin-Reese Creek Fault System in northwestern Yellowstone National Park. The East Gallatin-Reese Creek Fault System is an east-dipping normal fault system that is 40 kilometers (25 miles) long and bounds the eastern front of the Gallatin Range (fig. 15). The fault system has been active in the Quaternary (the last 2.6 million years of Earth’s history) and is modeled as a seismic source in the 2023 National Seismic Hazard Model (Hatem and others, 2023). Lidar (light detection and ranging) data, which offer high-resolution topographic information that can reveal the bare-earth surface beneath vegetative cover, were collected for Yellowstone National Park in 2020 and revealed fault scarps along the East Gallatin-Reese Creek Fault System that displace glacial deposits. Fault scarps are linear “steps” on the



Base from The National Map, 2023

Figure 15. Shaded-relief location map for the East Gallatin-Reese Creek Fault System in northwest Yellowstone National Park. The trace of the East Gallatin-Reese Creek Fault System is shown as mapped in the U.S. Geological Survey Quaternary Fault and Fold Database (Haller and Pierce, 1996a, b), subdivided into the southern East Gallatin section (dark red dashed lines) and the northern Reese Creek section (dark blue dashed lines).

landscape where past earthquakes have ruptured the ground surface and offset Quaternary deposits. Scarps along the East Gallatin-Reese Creek Fault System indicate that this fault system has experienced significant surface-rupturing earthquakes in the time since glaciers receded from the Yellowstone area at the end of the Pinedale glaciation—the most recent ice age in the Rocky Mountains that lasted until about 16,000–14,000 years ago.

Geologists began collecting samples from Pinedale glacial deposits near the fault scarps for cosmogenic radionuclide exposure dating, which measures the time that a rock has been exposed to cosmic rays at Earth's surface. The ages calculated from this exposure dating technique represent the time since these rocks were deposited and uncovered as glacial ice receded. Additionally, geologists are using lidar data to map the distribution and geometry of fault scarps along the East Gallatin-Reese Creek Fault System and calculate the vertical separation of surfaces across the fault scarps. Knowledge of the exposure age of the deposits combined with the vertical distance displaced across the fault scarp provides important constraints on the faulting history of the East Gallatin-Reese Creek Fault System, including the maximum age of the most recent surface-rupturing earthquake(s), how fast the fault is slipping, and whether the fault slip rates vary over time and along the length of the fault system. This information is fundamental to understanding the seismic hazard posed by the East Gallatin-Reese Creek Fault System, and it will provide land managers and scientists with important data that can be used in making decisions to mitigate earthquake risk in the Yellowstone region.

In partnership with Yellowstone National Park, the Wyoming State Geological Survey and Montana Bureau of Mines and Geology completed reconnaissance fieldwork in two locations with prominent fault scarps along the East Gallatin-Reese Creek Fault System in August 2023 (fig. 16).

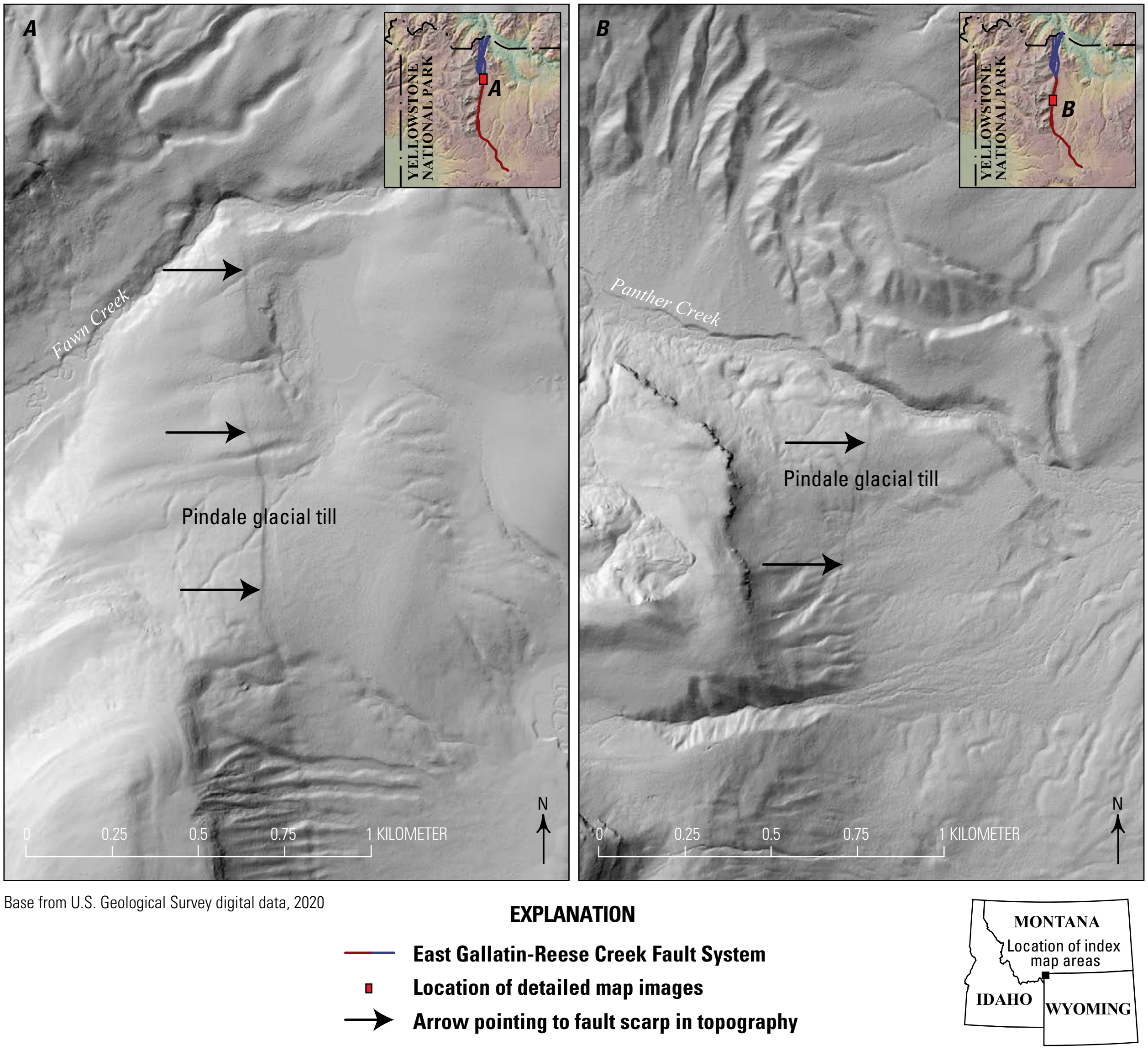


Figure 16. Lidar shaded relief maps of fault scarps along the East Gallatin-Reese Creek Fault System near Fawn Creek (*A*) and Panther Creek (*B*). Fault scarps are visible as darker lineaments in the topography and are marked by the black arrows that point to the scarp. Red rectangles on inset maps show location along the East Gallatin-Reese Creek Fault System, and locations are also shown in figure 15.

Geologists conducted preliminary mapping of the fault scarps and identified suitable samples for cosmogenic radionuclide dating that included sandstone and andesite boulders in the latest Pinedale glacial deposits. They collected four initial samples, which are currently in preparation at the Montana Bureau of Mines and Geology and will later be sent to another laboratory for cosmogenic radionuclide analysis. Wyoming State Geological Survey and Montana Bureau of Mines and Geology geologists are planning a larger field campaign to collect additional samples and complete more detailed mapping of the fault scarps along the East Gallatin-Reese Creek Fault System within Yellowstone National Park and the Wyoming-Montana border region.

Hydrothermal System Changes in Response to Climatic Variations

In the Yellowstone region, the location, volume, and deposition rate of travertine deposits provide a record of changing hydrothermal systems over century to millennial time scales. Travertine is a form of limestone that precipitates from high-temperature (25–73 °C or 77–163 °F) hot springs. The most well-known and studied travertine area in Yellowstone National Park is Mammoth Hot Springs (fig. 17). There, warm thermal waters charged with CO_2 from 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, forming travertine.

Smaller travertine deposits (less than 50 meters [164 feet] in horizontal extent and only a few meters [yards] thick) occur locally within Yellowstone Caldera in Upper and Lower Geyser Basins. These deposits are not actively growing, and 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 deposits has found that they formed during three main episodes that correspond broadly with known periods of wet climate: 13,900–13,600, 12,200–9,500, and 5,200–2,900 years ago. The oldest travertine overlaps with the timing of the most recent deglaciation that probably occurred during 16,000–14,000 years ago and resulted in about 1 kilometer (0.6 mile) of ice melting from the Yellowstone Plateau. The second period of travertine formation overlaps with a climatic oscillation that cooled global climate for a short period of time, called the Younger Dryas cold event (12,900–11,700 years ago). The third and last major travertine forming event overlaps with a short period of cool and wet climate in the Rocky Mountain region.

Travertine deposition occurred in response to the influx of large volumes of cold meteoric water from melting of glacial ice or large increases in precipitation, which increased the rate of chemical weathering of surficial sediments and recharge into the hydrothermal system. Put another way, changes in climate conditions of the Yellowstone ecosystem can change the chemistry of the hydrothermal system enough to result in variations to the minerals that are deposited at the surface. Travertine is a unique tool to study these changes because it records hydrothermal system chemistry and is a very precise chronometer (using the decay of uranium to thorium, which can be measured to solve for the age with an accuracy of within 50 years on average), all in the same material.

Figure 17. Photograph of rapidly forming travertine at Narrow Gauge Spring, located in Mammoth Hot Springs. Photograph by Lauren Harrison, U.S. Geological Survey, in May 2022 under permit YELL-2022-SCI-8192.

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. 34–35).

Summary of Heat Flow Studies in 2023

The total geothermal radiative heat output from Yellowstone National Park's thermal areas in 2023, 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 also similar to past years, although measurements were not possible on the Gardner River because of damage to the monitoring site, probably as a result of debris and sediment from the June 10–13, 2022, flooding that was remobilized by spring snowmelt. Together, the thermal infrared remote sensing and chloride-flux measurements indicate that the total thermal discharge remained relatively steady.

Thermal Infrared Remote Sensing

Most of Yellowstone National Park's thousands of thermal features are clustered together into about 120 distinct regions. These thermal areas are defined as having multiple thermal features, characterized by 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. There are also numerous bodies of water—typically lakes, ponds, or wetland areas that are thermally emissive because they receive heated water from a nearby thermal area, a nearshore thermal spring, or from underwater vents.

Analysis and interpretation of thermal infrared remote sensing data for characterizing Yellowstone National Park's thermal areas and thermal water bodies 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 of Yellowstone National Park's thermal areas and thermal water bodies 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 orbital thermal infrared data. Higher-resolution thermal infrared data have been useful in the past for characterizing these areas; however, such data from airborne surveys are not regularly acquired over the Yellowstone region due to their high cost. Fortunately, thermal areas and thermal water bodies 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 and high-resolution visible data are used together to characterize Yellowstone National Park's thermal areas and thermal water bodies.

The primary satellite-based thermal infrared data used for thermal area characterization in the Yellowstone region are from 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 area at night every 8 days. In 2023, a total of 41 nighttime scenes from Landsat 8 and Landsat 9 were acquired. Of these, 33 were too cloudy to be of use; however, there were clear nighttime thermal infrared scenes acquired in the winter, on January 31 and February 16, 2023; the data from January 31, 2023, were processed and analyzed for this report (fig. 18).

The results of the January 31, 2023, 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 46 °C (54 to 83 °F) above background, were Sulphur Hills and Midway Geyser Basin. These two thermal areas also had the highest geothermal radiant emittance values, ranging from 112 to 159 watts per square meter. The thermal area with the highest total geothermal radiative power output (in megawatts) was Norris Geyser Basin, emitting about 189 megawatts, with Lower Geyser Basin a close second at 178 megawatts. Other large areas with notably high geothermal radiative power output include Astringent Creek and Roaring Mountain, with outputs greater than 100 megawatts. The total geothermal radiative power output summed for all of Yellowstone National Park's thermal areas was 2.0 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). Because 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 2023. Specific conductance measurements were made at monitoring sites along Tantalus Creek and the Madison, Firehole, Gibbon, Snake, Gardner, Yellowstone, and Fall Rivers (see sidebar on monitoring thermal changes on p. 34–35). The current network provides information at several scales (park-wide, watersheds, and individual geyser basins). The Madison, Yellowstone, Snake, and Fall River monitoring sites capture the hydrothermal discharge within their watersheds, and the sum of these four rivers captures the entire hydrothermal discharge from Yellowstone National Park. Additional monitoring sites along their tributaries provide higher resolution and can be used to identify changes at geyser-basin or hot-spring scales.

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 2023 field trips to assess the solute-specific conductance correlations.

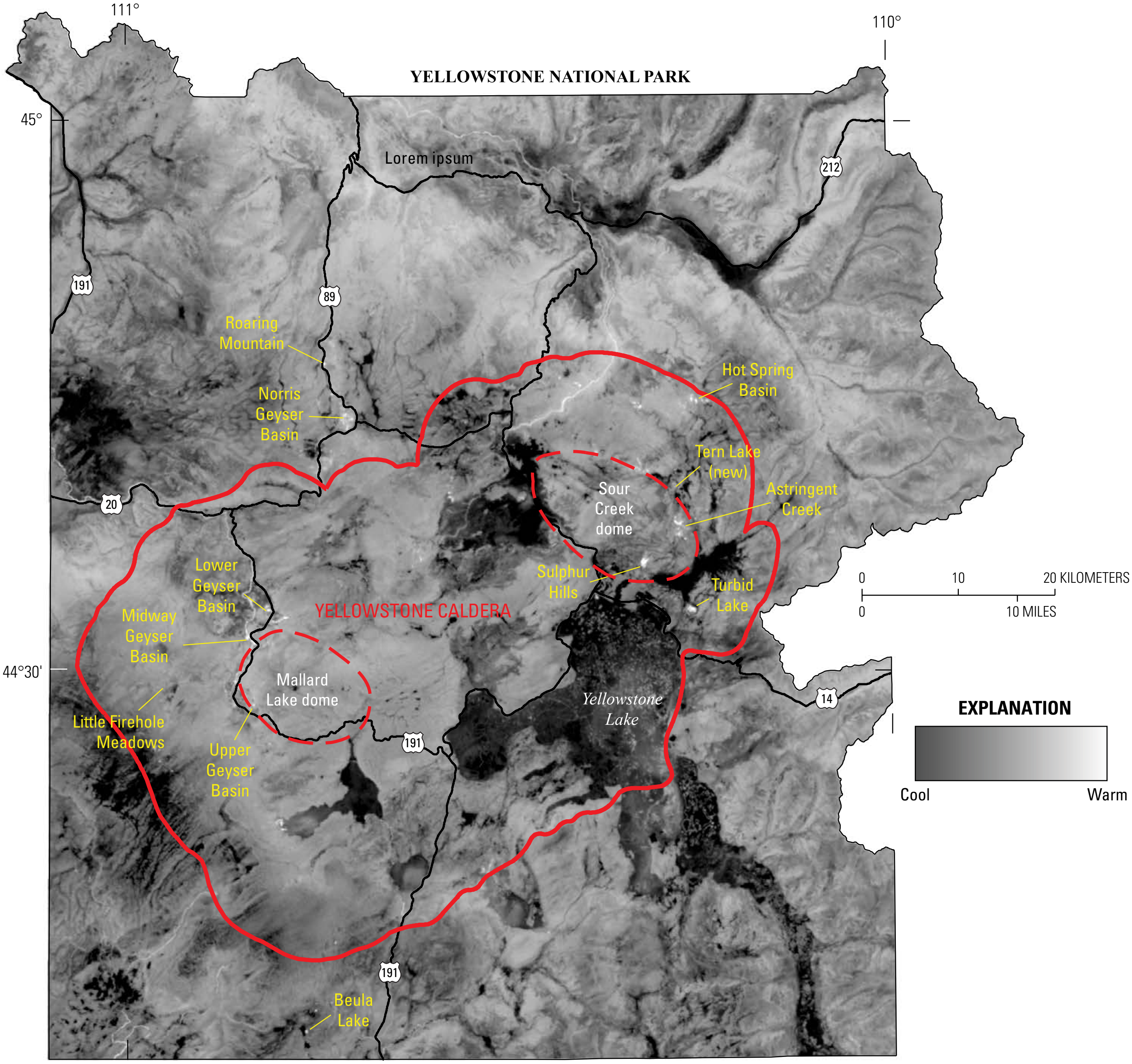


Figure 18. Landsat 8 nighttime thermal infrared image of Yellowstone National Park from January 31, 2023. Satellite-based thermal infrared data show areas on the surface that are warmer versus cooler, and they can be used to estimate surface temperature and the geothermal radiative heat output from the Yellowstone magmatic and hydrothermal system. The warmest areas (lightest in shade) in this image are as much as 46 °C (83 °F) above background. Geologic structures are indicated in red (solid line is caldera boundary, and dashed lines mark resurgent domes); thermal areas are labeled in yellow.

SIDEBAR

Monitoring Thermal Changes at Yellowstone Caldera

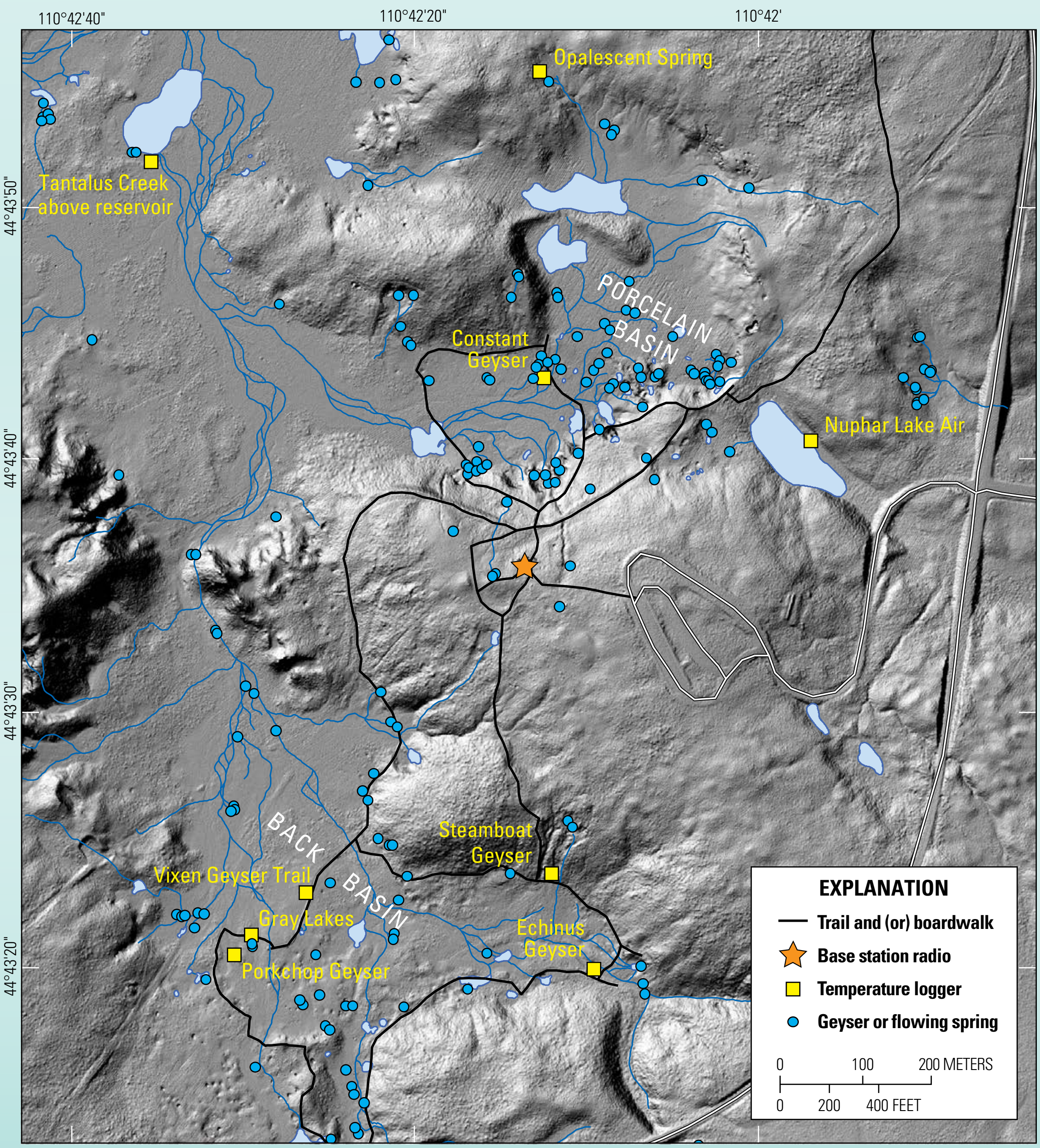
A lot of heat is released in the Yellowstone region from thermal features like hot springs, geysers, mud pots, and fumaroles. Tracking the temperatures and sizes of thermal areas is critical for monitoring Yellowstone Caldera's hydrothermal activity and for understanding and preserving these spectacular 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).

Temperature probes, however, 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 the 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. Chloride monitoring is now done continuously by automated 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 low 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.

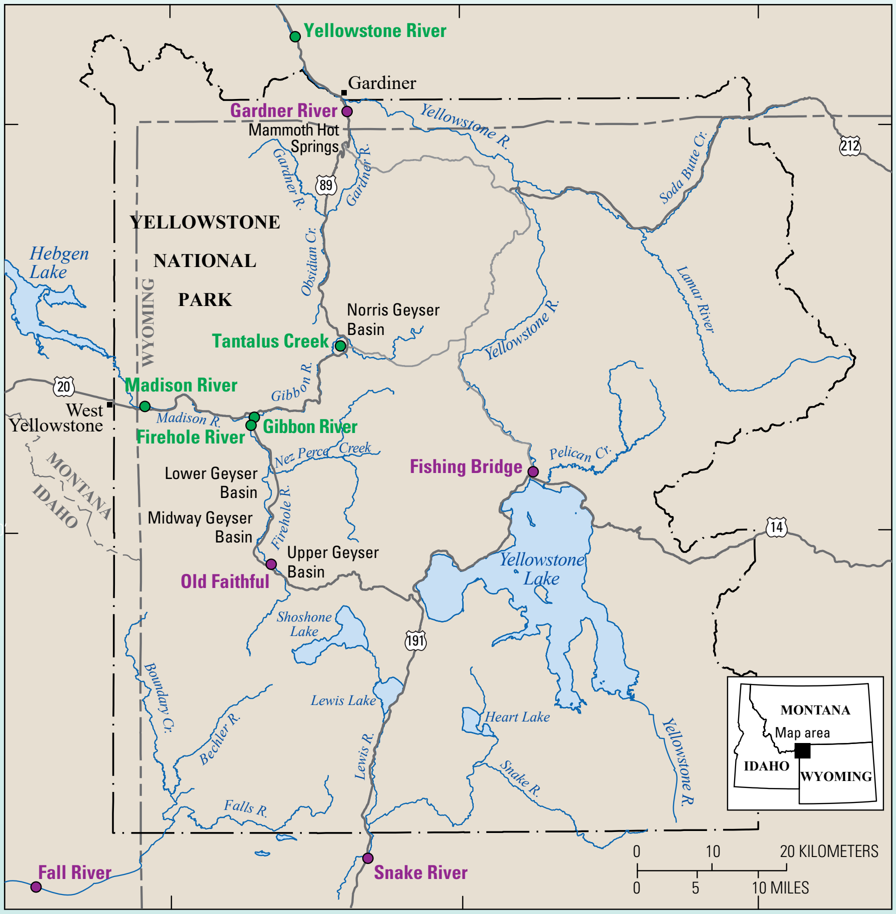
One of the challenges of thermal-infrared remote sensing is that temperature contrasts can be low, and thus challenging to discern. Hot springs and fumarole fields are relatively subtle thermal features compared to extremely hot features like active lavas or fires because the thermal features exhibit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



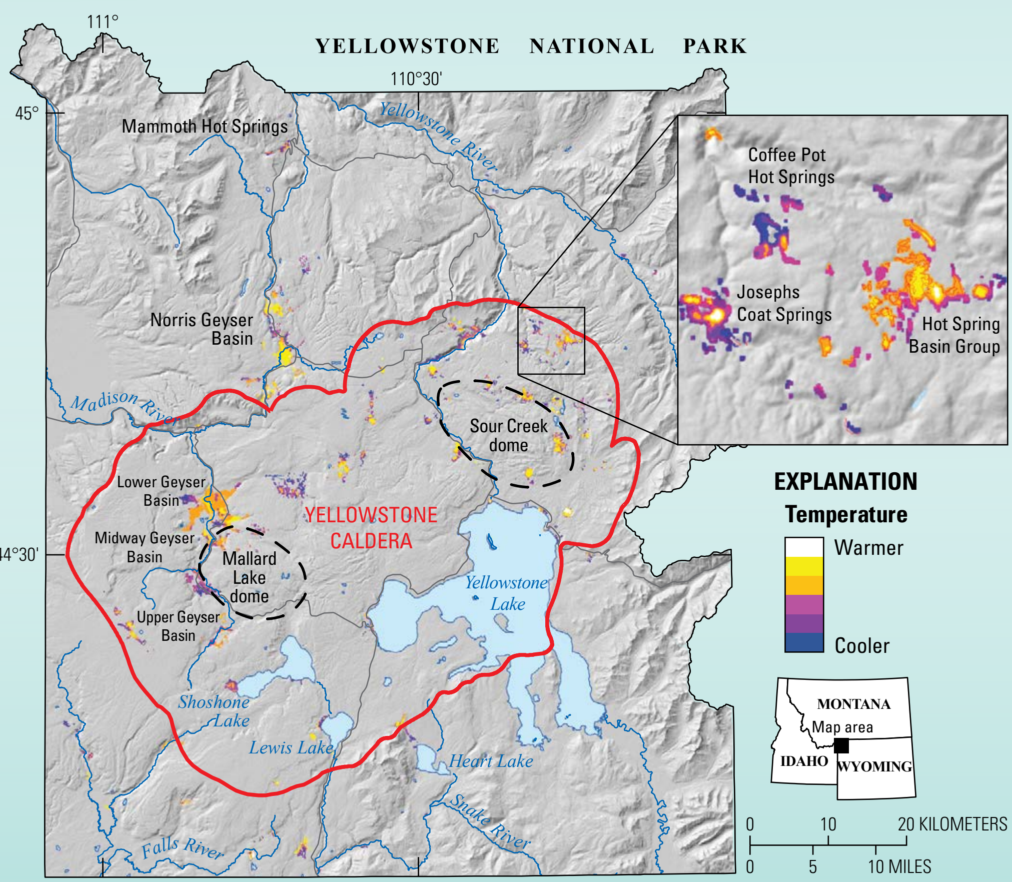
Base from 2009 EarthScope 0.5-meter lidar data

Map of temperature measurement sites in Norris Geyser Basin.

radiance and maximizes thermal 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 into the thermal vent inventory database.



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



Base from 30-meter National Elevation Dataset

Satellite thermal-infrared temperature anomaly map of Yellowstone National Park's thermal areas based on a Landsat 8 image from 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.

Quantifying the chloride flux was challenging in 2023 because of the flooding that occurred in the northern areas of Yellowstone from June 10–13, 2022. During the storm, a specific conductance probe was buried under about 1.2 meters (4 feet) of debris at the Gardner River monitoring site. The monitoring site was relocated downstream along the Gardner River; however, during the 2023 spring snowmelt the monitoring equipment was damaged again, likely as a result of remobilized debris and sediment. Consequently, most of the data from this site for water year 2023 were not recovered, and the chloride flux was not determined for the Gardner River. Similarly, monitoring equipment at the Yellowstone River at Corwin Springs monitoring site was washed away during the 2022 storm. New equipment was installed, but during the 2023 spring high-flow runoff, a large sand and gravel bar migrated downstream and was deposited on top of the newly installed equipment at the Corwin gage. Consequently, the error in the annual chloride flux is expected to be close to ±15 percent.

In 2023, the total chloride flux leaving Yellowstone National Park was 49±7 kilotons, which was determined by summing the flux from the Madison, Yellowstone, Snake, and Fall Rivers. This is similar to historical measurements of 51±5 kilotons (based on data collected during 1983–2003 and 2013–2022). The percentages of the total flux from the Madison (41 percent), Yellowstone (36 percent), Snake (11.5 percent), and Falls (11.5 percent) Rivers for 2023 are shown in figure 19*A*. The 2023 chloride fluxes measured at every monitoring site were similar to historical (beginning in 1983) fluxes (fig. 19*B*).

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 that exist in comparative isolation, follow patterns that allow their activity to be forecast. However, the eruption times for most geysers in Yellowstone National Park are unpredictable. Thermal features mostly occur in clusters, forming about 120 distinct regions called thermal areas that are found throughout Yellowstone National Park (see sidebar on p. 34–35).

Summary of Geyser Activity and Research in 2023

As has been the case since 2018, the most noteworthy geyser activity in Yellowstone National Park during 2023 continued to be the eruptions of Steamboat Geyser, the tallest active geyser in the world. Fewer eruptions occurred in 2023 compared to the previous five years, indicating that the geyser's current period of activity might be waning. In addition, Giant Geyser, in Upper Geyser Basin, erupted for the first time since early 2019, the level of Nuphar Lake, in Norris Geyser Basin, continued to rise in response to runoff from nearby thermal features, and a short segment of boardwalk on Geyser Hill, in Upper Geyser Basin, was closed from late May until August in response to the formation of

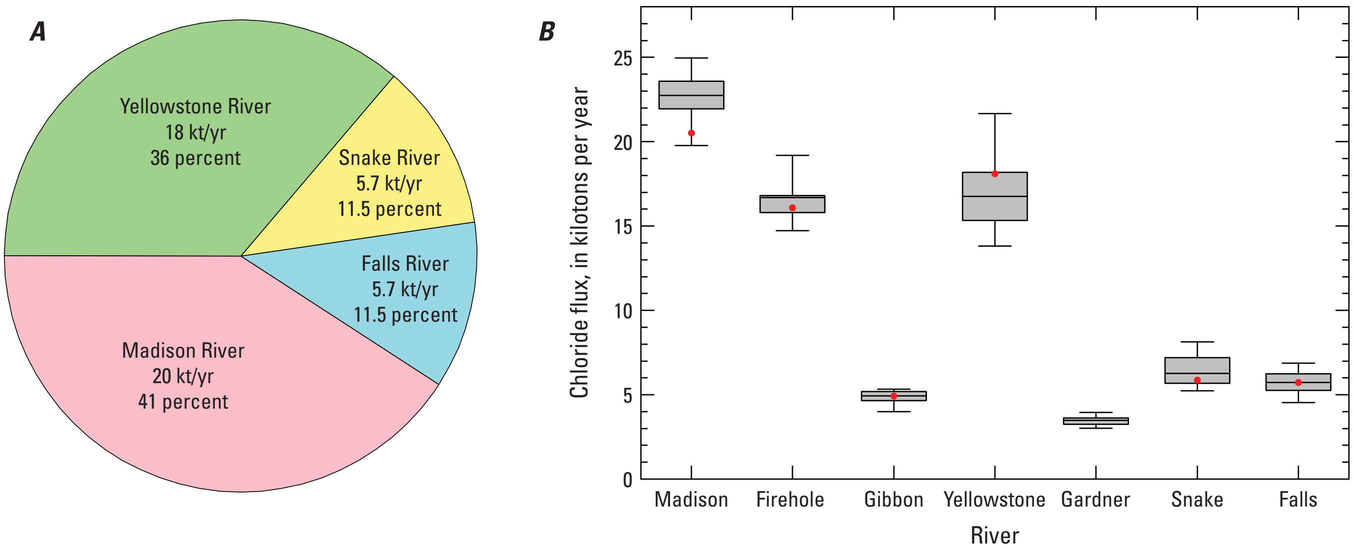
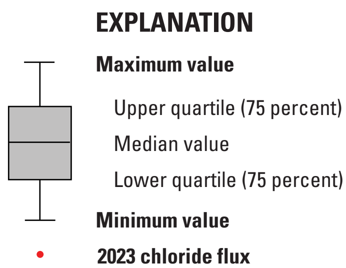


Figure 19. *A*, Pie diagram showing the 2023 chloride flux, in kilotons per year (kt/yr), and the percentage of the total flux (49 kt/yr) for the four major rivers (Madison, Yellowstone, Snake, and Fall Rivers) that drain the Yellowstone National Park region. Fluxes were measured at gaging locations where the rivers leave the park (see sidebar on p. 34–35). *B*, Boxplots showing the distribution of chloride flux measurements collected from 1983 to 2022. The 2023 chloride flux for each monitoring site is shown in red (no measurement was possible for the Gardner River).



new, and reactivation of existing, small thermal features that threw debris and hot water into the pathway for a short period of time.

Research efforts during the year focused on the eruptive history and characteristics of Steamboat Geyser, the subsurface structure and eruption mechanism of Spouter Geyser in the Black Sand Basin of Upper Geyser Basin, and field- and remote-sensing-based documentation of small thermal areas on the north side of Mallard Lake Dome, just southeast of Lower Geyser Basin.

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 to decades. 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, with some eruptions separated by only days to weeks.

Steamboat Geyser Eruption Statistics

In 2018, Steamboat Geyser (fig. 20) entered a new phase of increased activity, with 32 major water eruptions—a new record for a single calendar year (see 2018 YVO 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 2019 and 2020 YVO annual report [YVO, 2021b, c]). In 2021, however, there were only 20 major water eruptions (see 2021 YVO annual report [YVO, 2022a]), and 11 eruptions occurred in 2022 (YVO, 2023). Even fewer occurred in 2023—just 9 eruptions. It is unclear if fewer eruptions during 2021–2023 is an indication that the current episode of frequent eruptive activity is coming to an end.

Each eruption of Steamboat Geyser followed the same general pattern: gradually increasing minor activity over hours to days, culminating in a major eruption that lasts tens of minutes. A steam phase, lasting for about a day, follows the liquid 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 has been the case since 2021, the intervals between geyser eruptions in 2023 were longer and more variable than in the years of more frequent eruptions during 2018–2020. The shortest interval between eruptions was just over 23 days, which occurred in January, and the longest interval was more than 77 days during June–August. In previous years, the shortest intervals between eruptions were in early 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]) and continued in 2022 and 2023, when the longest intervals were in late summer. How the current episode of frequent eruptions may end is unknown, but the trend of the past three years suggests that the number of eruptions will continue to diminish in 2024.

YVO uses 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 flows. All these data are freely available on the YVO website, accessible at https://www.usgs.gov/volcanoes/yellowstone. In addition, a new monitoring station installed in September 2023 (see "New Monitoring Station at Norris Geyser Basin" section) added infrasound to the techniques that can be used to identify Steamboat Geyser eruptions. Infrasound refers to low-frequency sound waves, inaudible to human ears, that are generated by geologic processes, including geyser eruptions. The three-microphone infrasound array that was installed in the center of Norris Geyser Basin provides the ability to detect the direction of any strong infrasound sources, and this array has proven remarkably effective at detecting eruptions of Steamboat Geyser (fig. 3). In addition to detection, infrasound monitoring may provide information on geyser dynamics—for instance, how the strength of a Steamboat Geyser eruption varies over its course, transitioning between liquid water and steam phases.

Figure 20. Photograph of Steamboat Geyser at sunrise on September 6, 2023. In 2023, 9 major water eruptions occurred—fewer than the annual numbers of the preceding 5 years and with more variable intervals between eruptions. Photograph by Michael Poland, U.S. Geological Survey.

Research Into Steamboat Geyser Activity

In 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. Several partially mineralized wood samples were found on the sinter shelf immediately southeast of Steamboat Geyser's vents (all samples were collected under the National Park Service Geology Programs Milestones Research Permit 2016-9). The wood samples, which are tree remnants, were dated using radiocarbon methods to determine when the trees grew, which can indicate times of geyser inactivity. Trees do not grow on the sinter deposits close to the geyser vent during periods of frequent, or even occasional, eruptions. Dating these fossilized wood samples revealed that they most likely came from trees that grew for periods of less than 20 years during the late 15th century, mid-17th century, and the late 18th century (Hurwitz and others, 2023). Philetus Norris, second superintendent of Yellowstone National Park and namesake of Norris Geyser Basin, believed that he witnessed Steamboat Geyser's formation in August 1878. The wood sample ages provide evidence that Steamboat Geyser was active in the centuries prior, and that Norris may have just seen a particularly violent major eruption. The three age clusters line up with periods of regional drought, suggesting that Steamboat Geyser, like Old Faithful Geyser, may be susceptible to variations in climate—when there is less rainfall, geyser activity diminishes and trees can grow closer to the geyser vents.

Research also focused on live trees surrounding Steamboat Geyser. Most trees 14–24 meters (46–79 feet) from the vent show significant signs of stress, including dead branches and canopy tops. Aerial and ground-based photos taken since 1954 indicate that all three of Steamboat Geyser's recorded more active phases (1961–1969, 1982–1984, and 2018–present) adversely affected nearby trees, primarily in the dominant downwind direction. Only the phase occurring since 2018, however, was associated with distant tree death up to 250 meters (820 feet) away. There is evidence for increased ground temperatures in the 2018–present distal tree kill area, so other factors appear to be contributing to vegetation health during the current eruptive phase beyond the localized area over which silica-rich spray from the geyser exerts a significant control.

Additional research delved into a mystery surrounding Steamboat Geyser's seismic signature. The geyser is one of just two that are powerful enough to produce repeated eruption signals at a station in the Yellowstone Seismic Network (the other is Giantess Geyser in the Upper Geyser Basin). This is due to both eruptive intensity and distance from seismometers—the network was designed to detect small earthquakes, so seismometers were typically placed far away from geyser basins to avoid unwanted noise related to hydrothermal activity.

When analyzing data from seismic station YNM, located in the Norris Museum building just 340 meters (about 1,000 feet) north of Steamboat Geyser, researchers noticed that wintertime eruption signals were generally much weaker than summer signals (Reed and Manga, 2023). The straightforward explanation would be that eruption intensity is weaker in the winter, but visual observations did not support this possibility. The next most likely explanation is that some environmental factor affects how the seismometer records the geyser's eruptions. In this case, snow turned out to be the culprit—the strength of shaking recorded at YNM decreased as snow depth increased (fig. 21). Snow is a good absorber of sound because acoustic waves don't travel well through porous materials. The shaking recorded at YNM during Steamboat eruptions originates as noise produced by liquid water and steam jetting. These acoustic waves then transmit some energy into the ground; if snow is present, less energy is transferred. The findings highlight the benefits of long-term monitoring and also have implications for interpretation of the sounds produced at active snow-covered volcanoes.

Subsurface Structure and Eruption Mechanism of Spouter Geyser

Yellowstone National Park is home to roughly 500 geysers, making it the most concentrated geyser field in the world. Over a century of research has revealed many insights into geyser systems and characteristics, but many aspects of geyser eruption dynamics remain uncertain.

Ciraula and others (2023a, b) used geophysical measurements to investigate the near-surface structure and eruption mechanisms of Spouter Geyser, in the Black Sand Basin of Upper Geyser Basin. The specific goal of the work was to use electrical and electromagnetic properties to track hydrothermal fluid as it moved through the subsurface beneath Spouter Geyser through several cycles of eruption and subsequent recharge. The results support what is known as a "bubble trap" model where, almost like a teapot, water boils in a cavity—a bubble trap—beneath the ground that is laterally offset from the location of the geyser. Steam bubbles accumulate above the liquid water, and the gradually increasing pressure from the liquid and steam eventually exceed the pressure that the system can sustain. At that point, water flows out of the bubble trap through the conduit and up to the surface, resulting in an eruption. Even though these results are specific to Spouter Geyser, they point to a subsurface structure beneath geysers and a dynamic mechanism that is probably applicable to all geysers, as was proposed at Old Faithful and Lone Star Geysers. The research was conducted under Yellowstone Permit Yell-6090.

Rise in Level and Change in Color of Nuphar Lake, Norris Geyser Basin

Just west of the short road into Norris Geyser Basin is a small body of water called Nuphar Lake, which is about 175 meters (575 feet) long by 60 meters (200 feet) wide and fills the space between the current Norris Geyser Basin access road and an old roadbed that was abandoned decades ago and that now serves as a trail along the east margin of the Porcelain Basin area of Norris Geyser Basin. The cold lake, named for a genus of aquatic plants that include the water lily, is not directly related to changes in Yellowstone Caldera's hydrothermal system but over the last few years has experienced some interesting changes in color and water level.

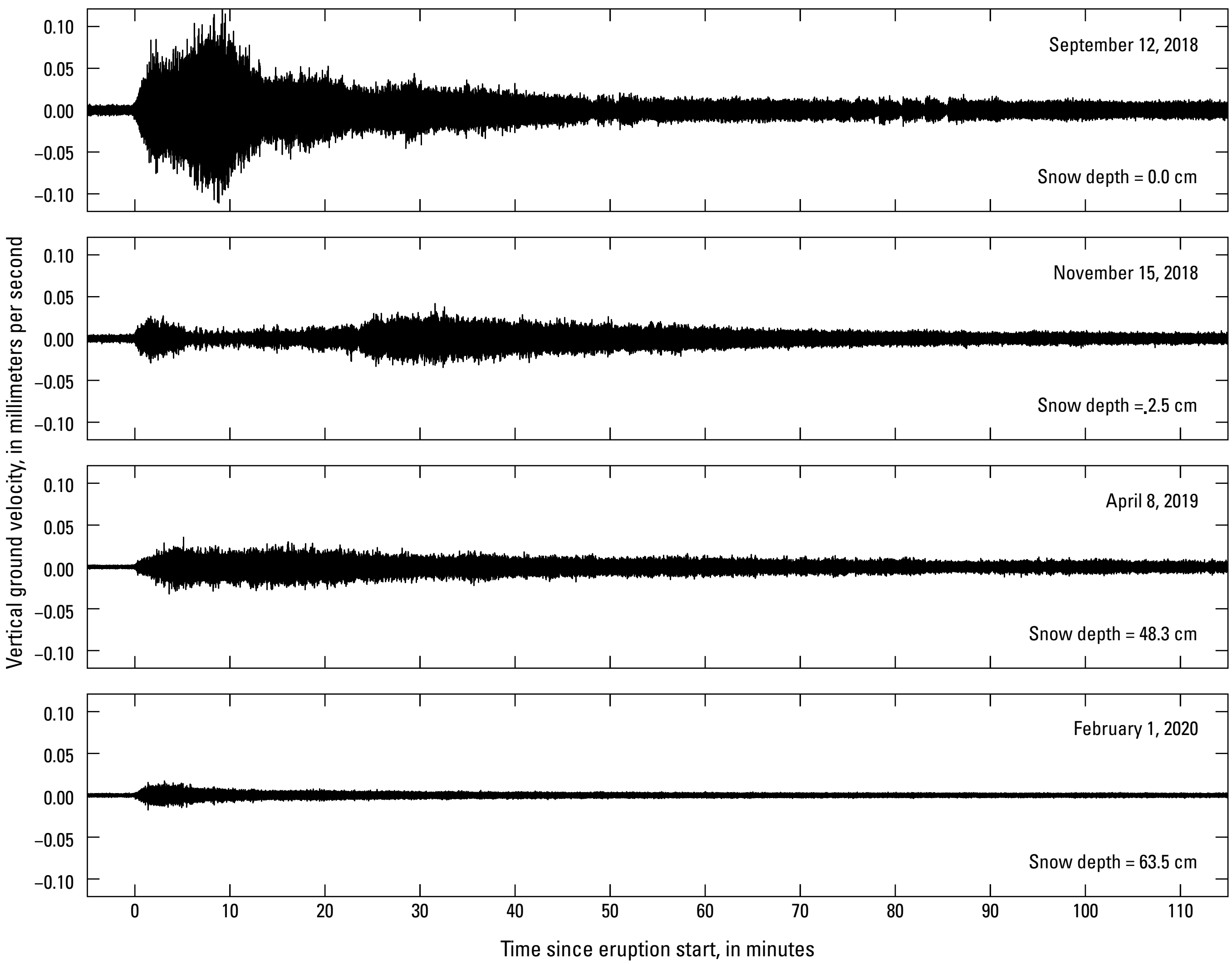


Figure 21. Four examples of vertical ground shaking during Steamboat Geyser eruptions as recorded by seismic station YNM. The vertical scale is the same for each seismogram. At deeper snow depths, the shaking appears weaker. This is because snow suppresses the amount of energy that is transmitted into the ground by the geyser's eruption. Figure modified from Reed and Manga (2023).

The level of the lake fluctuates, rising and falling by a few tens of centimeters (1–2 feet) with the seasons and according to rain and snowfall amounts. Between 2021 and 2022, however, the lake level rose significantly and caused the trail between Norris Campground and the geyser basin to be closed because of flooding. The color of the lake also began to change, from the typical dark green, to a milky blue-green, reminiscent of many of Yellowstone National Park's hot springs. By 2023, the lake level had risen by several feet (more than a meter) relative to its 2021 level (fig. 22). One of the Norris Geyser Basin temperature-monitoring stations along the lakeshore had to be repositioned as a consequence of the rising water levels.

The changes are caused by water flowing into Nuphar Lake from hot springs located to the north on a ridge above Porcelain Basin. These springs normally flow southwest into Porcelain Basin, but on occasion subtle changes the shapes and activity of the springs causes flow to the south, into Nuphar Lake. For example, Yellowstone National Park geologist Rick Hutchinson noted in 1971 that hot spring waters flowed into the lake, but only for a 2-day period in September of that year[4]. Thermal water also sometimes flows into the lake from features just to the east, occasionally impacting the color of the lake for short periods.

The recent change in thermal water runoff has killed many of the trees between Nuphar Lake and Porcelain Basin and altered the lake's color—changes that are easily seen in satellite imagery (fig. 22). In the winter months of 2022 and 2023, the northern part of the lake remained ice free, which is clear evidence of thermal input from nearby hot springs.

In addition to the rising lake level, water also seeps under the old roadbed, flowing underground from Nuphar Lake into Porcelain Basin. The seepage is indicated by green moss-like vegetation that is

[4]Thanks to M.A. Bellingham for her help in researching previous changes at Nuphar Lake noted in Yellowstone National Park and Geyser Observation and Study Association logs and notes, and for sharing her own observations of changes in the area over the past decade.

growing in the water, which also appears cooler than the surroundings in thermal imagery (fig. 23). Similar seeps have been documented repeatedly in this area. For example, in the 1990s there was so much water flowing into Porcelain Basin that it drowned many of the adjacent thermal features. Incline Geyser, a powerful geyser on the floor of Porcelain Basin that was last active in the early 1990s, has occasionally served as a drain for some of this water. The seeps are most vigorous in the spring and early summer, when groundwater and lake levels are high, and less active in the late summer and fall.

The potential consequences of this input of thermal water into Nuphar Lake are unclear. It is possible that the lake will overflow its banks, adding cooler water to Porcelain Basin and quenching, at least temporarily, some of the thermal features in that area. Such changes are most likely to occur in spring or early summer months of future years when the lake and groundwater levels are highest owing to seasonal snowmelt. It is also possible that the outflow from the hot springs feeding Nuphar Lake will change course once more, sending thermal water back into Porcelain Basin and returning the lake to lower levels and its usual deep green hue.

Thermal Unrest on Geyser Hill

On May 24, 2023, observers on Geyser Hill in Yellowstone's Upper Geyser Basin, near Old Faithful, witnessed something that hadn't been seen for two years: an eruption of Aurum Geyser. According to citizen scientist observations[5], Aurum Geyser erupted nearly 30 times over the subsequent 14 days, sending water to a height of about 6 meters (20 feet). The same day Aurum Geyser erupted, Beehive Geyser erupted twice and began a series of eruptions with an interval of 15–16 hours (normally that geyser erupts about every 18–22 hours, although with substantial variation). Minor features became more active as well. By May 30, a small geyser known as UNNG-GHG-17 (a designation based on a system for "naming" small or otherwise unnamed features according to geographic location), in the runoff channel of Doublet Pool, began erupting for the first time since 2018, with eruption columns of about 1 meter (3 feet) approximately once every 90 minutes for the first few days of its reawakening.

[5]Tracking hydrothermal activity is a time-consuming effort that has benefitted greatly from community involvement. The observations from Geyser Hill during summer 2023 include input from Graham Meech, Lori and Steve Walker, Shannan Marack, AJ Ferrara, and several other members of Yellowstone National Park staff and the public.

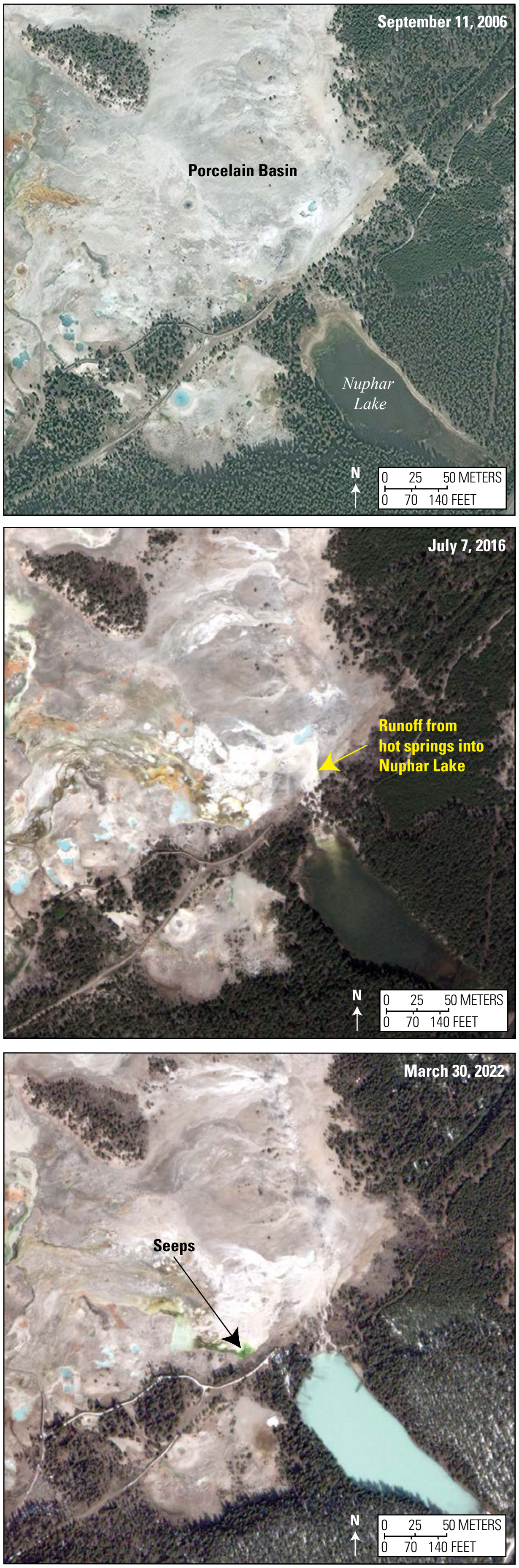


Figure 22. High-resolution satellite images of the Porcelain Basin and Nuphar Lake areas of Norris Geyser Basin on September 11, 2006 (left), WorldView-3 on July 7, 2016 (middle), and WorldView-3 on March 30, 2022 (right). Note the change in color of Nuphar Lake, from deep green to light blue, over time, as well as the increased evidence of flow from thermal features on the east side of Porcelain Basin into the lake, as indicated by the death of trees and appearance of white sinter deposits. Cool-water seeps are also apparent into Porcelain Basin in the 2022 image. Data processed by Greg Vaughan, U.S. Geological Survey, and provided by Maxar Technologies under the NextView license.

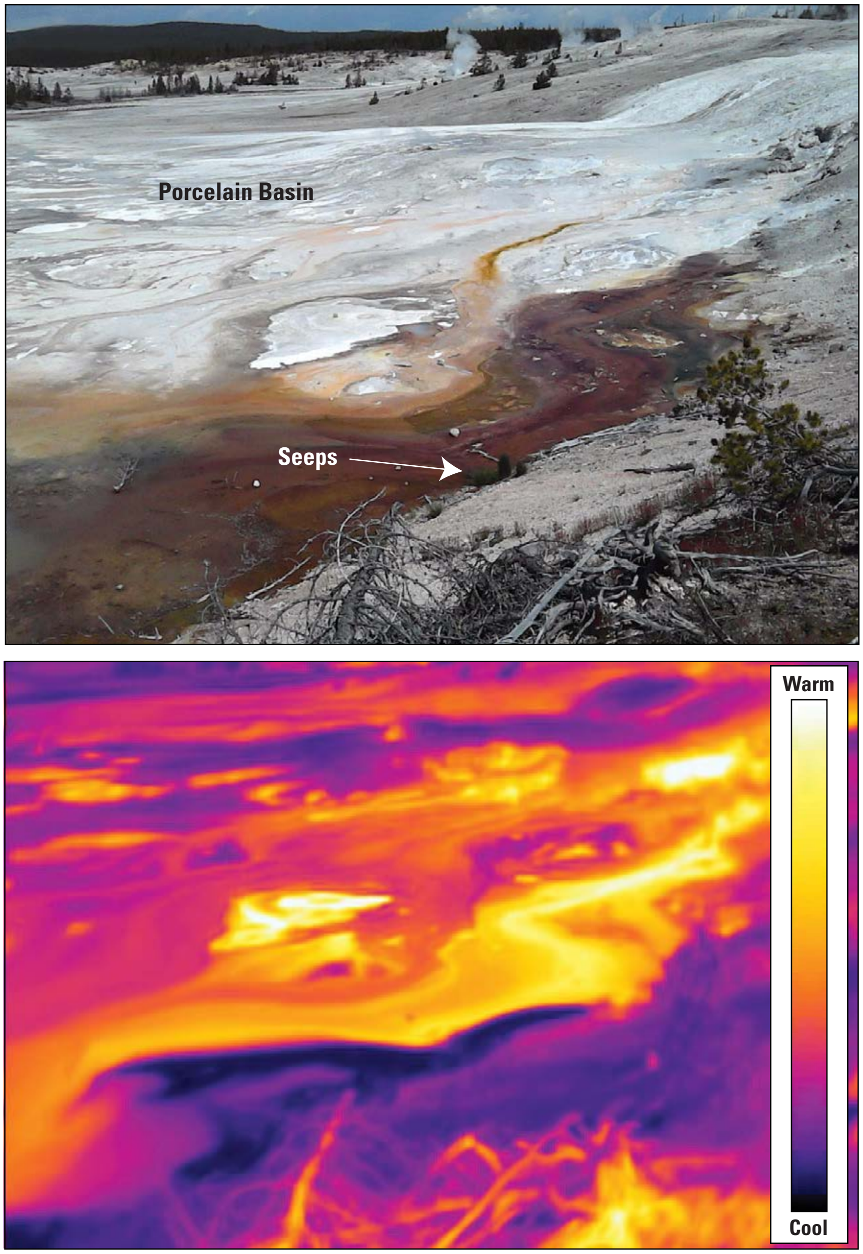


Figure 23. Visible (top) and thermal (bottom) images of Porcelain Basin looking to the north from the old roadbed. Nuphar Lake is off the photograph to the right. Seeps into Porcelain Basin are clearly evident in the thermal image as having cooler temperatures relative to the surroundings and appear to flow underground from Nuphar Lake. Photographs by Michael Poland, U.S. Geological Survey, July 1, 2023.

When UNNG-GHG-17 began to erupt again, a new feature, dubbed “UNNG-GHG-17a,” broke through the surface about 3 meters (10 feet) to the southeast of and next to a boardwalk. As the new feature erupted, it churned up broken bits of sinter (rock made of silica minerals precipitated from geyser water) and tossed out debris, some of which landed on the boardwalk (fig. 24*A*). By June 5, the hole from UNNG-GHG-17a had grown to a diameter of 0.75 m (2.4 feet). The activity of UNNG-GHG-17 and UNNG-GHG-17a was closely linked, with the latter consistently erupting about 8 minutes after the former, but the patterns changed over the course of a few days. Whereas initially, UNNG-GHG-17a would drain between eruptions, park geology staff visiting the site on June 5 found a mostly stagnant pool filled to its rim with water, and soon the two features began erupting independently of one another, with the interval between eruptions growing longer.

As activity at UNNG-GHG-17 and UNNG-GHG-17a waned, a previously existing feature near Doublet Pool, partially beneath the boardwalk, sprang to life. Informally named “Snow Globe” for the way it churns up small flakes of sinter, this feature, with water temperatures of 88 °C (191 °F), began erupting at least tens of centimeters (1–2 feet), with some droplets landing on the boardwalk. Activity at this feature was nearly constant on June 4, with eruptions reported about every 90 seconds. Then, on June 7, a new vent a few inches (several centimeters) west of “Snow Globe” opened, splashing water in frequent eruptions, and draining with a small whirlpool (fig. 24*B*).

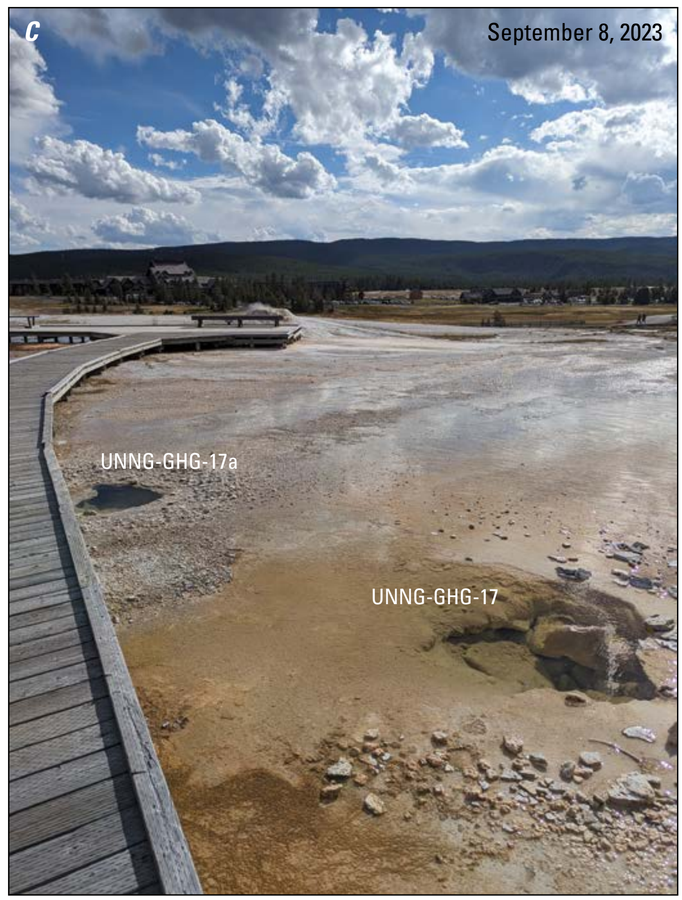


Figure 24. Photos of features that were new or reactivated during thermal unrest on Geyser Hill in May–June 2023. *A*, Looking north from near Sponge Geyser on June 28, 2023, at reactivated feature UNNG-GHG-17 and new feature UNNG-GHG-17a, which threw hot water and debris onto the boardwalk, prompting the path to be temporarily closed. *B*, Looking south from near Doublet Pool on June 28, 2023, at "Snow Globe" features adjacent to and partially beneath the boardwalk. *C*, Looking south from the middle of the formerly closed boardwalk on September 8, 2023, at features UNNG-GHG-17 and UNNG-GHG-17a, which were both dormant by this time. Sponge Geyser is in the background, behind the bench on the boardwalk. Photographs by Michael Poland, U.S. Geological Survey.

As a result of this activity, a boardwalk closure was put into effect between Sponge Geyser and Doublet Pool to protect visitors and staff from tossed debris and boiling water (fig. 25). Activity at all features, old and new, waned through June, and most features were dormant or had returned to patterns of normal activity by July (fig. 24*C*), although some remained active, like Aurum Geyser, which continued to erupt sporadically every few days for the remainder of the summer. The boardwalk closure was lifted in early August 2023.

The activity that occurred on Geyser Hill during May–June 2023 bears a remarkable similarity to that which occurred in the same area during September 2018 (YVO, 2021a). That period included a rare eruption of Ear Spring that brought decades worth of human trash to the surface, including coins, hats, cans, a cinder block, and a baby's pacifier. It was during this period that the feature known as UNNG-GHG-17 first formed. Changes like those of 2018 and 2023 occur frequently and are an excellent example of the dynamic nature of Yellowstone National Park's geyser basins.

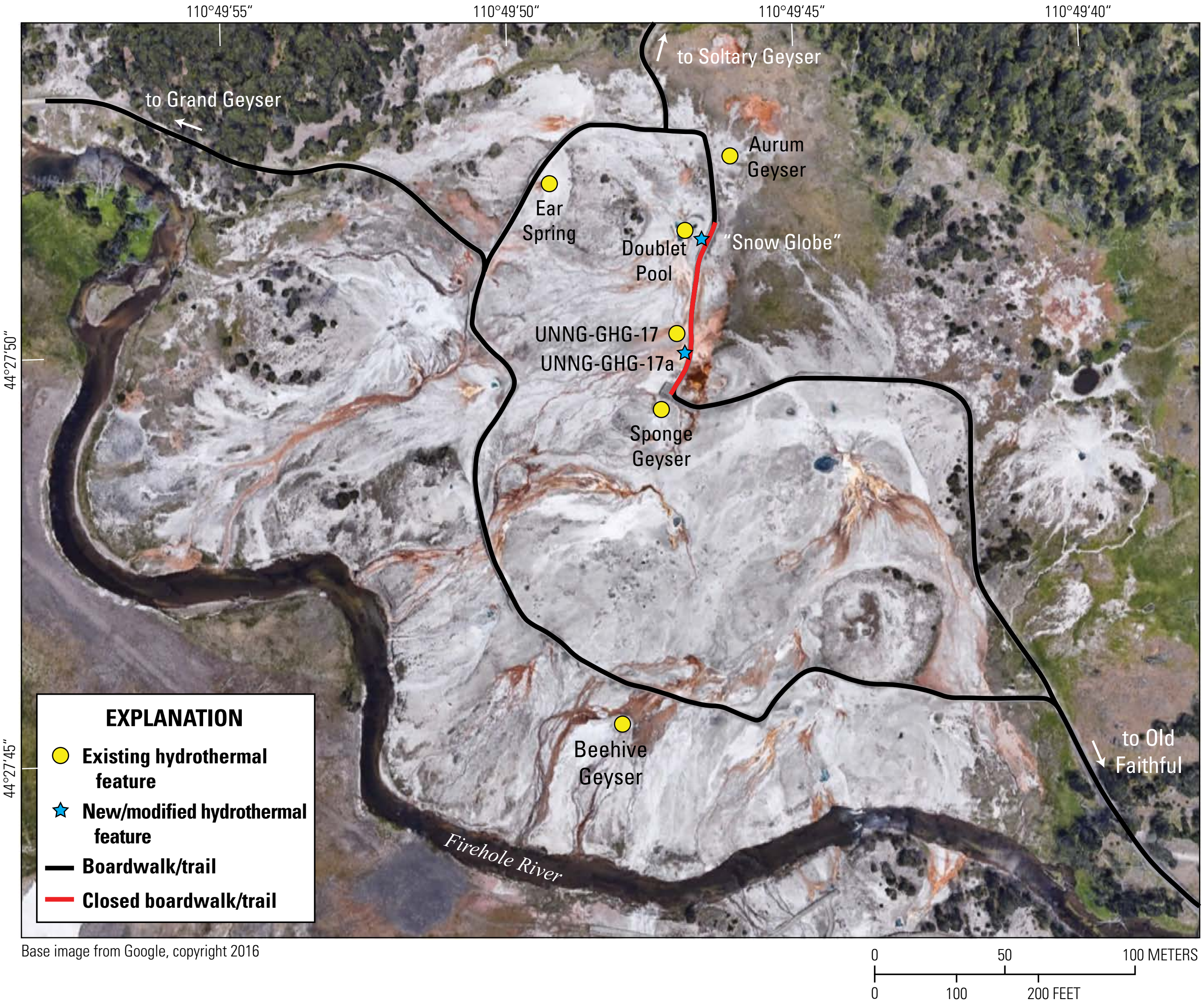


Figure 25. Map of Geyser Hill, Upper Geyser Basin, Yellowstone National Park, showing selected thermal features, including new and reactivated features that were active during the May–June 2023 thermal unrest, and area of boardwalk that was closed during late May to early August.

Recognition of Previously Unmapped Thermal Areas North of Mallard Lake Dome

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 and are not easily recognizable from the ground. 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 pixels [about 300 feet]) 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 pixels in those datasets enable detection and accurate characterization of the visible signs of thermal areas, including vegetation stress and mortality, mineral deposits and 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 2–3 kilometers (1.2–1.9 miles) southeast of Firehole Lake in Lower Geyser Basin, along the north-northeast edge of Mallard Lake Dome (fig. 18), there is a hilly area, much of which still bears scars from the 1988 wildfires, with patchy stands of trees, scattered isolated smaller trees, and large meadows with low grasses, mosses, and fallen trees (fig. 26*A*). There are numerous thermal features present as well—probably more than 100 individual features—but they were only recently recognized and have yet to be systematically mapped, sampled, and studied. The thermal features are clustered into a few dozen discontinuous areas, collectively called the Mallard Lake Dome thermal area. Surface temperatures in these areas are not high enough to be clearly detected with moderate-resolution thermal satellite infrared data. Only through analysis of high-resolution visible data that were acquired in the winter, when snow was on the ground, were the thermal areas detected as conspicuous snow-free zones, warm enough to prevent snow accumulation (fig. 26*B*). Archived data going back to the 1980s show that these thermal areas are not new, like the one near Tern Lake (Vaughan and others, 2020; YVO, 2021a), but they had not been previously mapped nor characterized in the field.

During September 2023, USGS and Yellowstone National Park scientists were able to visit some of these thermal

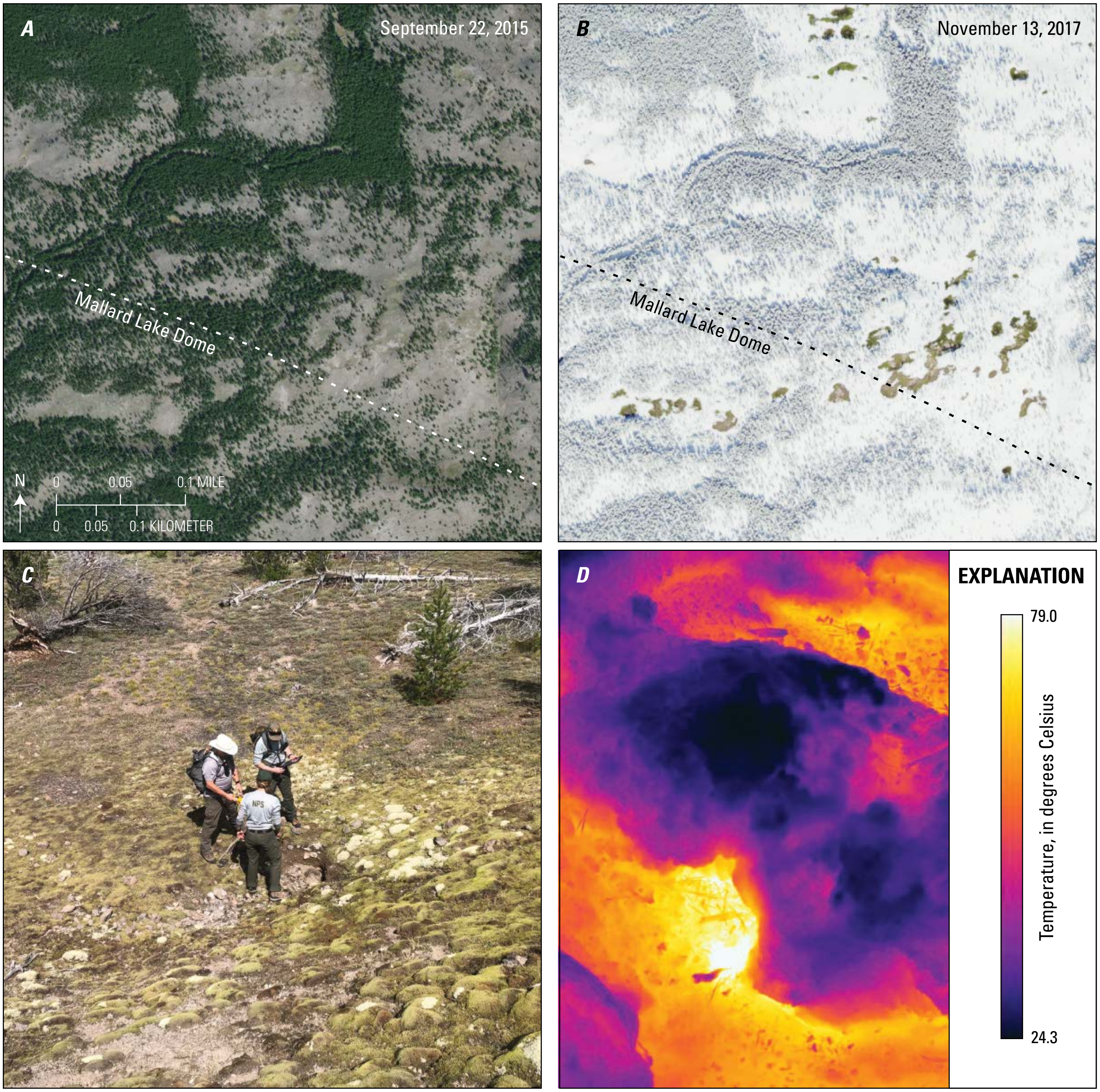


Figure 26. *A*, National Agriculture Imagery Program natural color image from September 22, 2015, of the Mallard Lake Dome thermal area as it appears during summer months. *B*, National Agriculture Imagery Program natural color image from November 13, 2017, of the Mallard Lake Dome thermal area as it appears when snow is on the ground. Small brown areas are heated ground indicated by the lack of snow. *C*, Field photo of characteristic thermal feature in the Mallard Lake Dome thermal area. Photograph by Greg Vaughan, U.S. Geological Survey, September 7, 2023. *D*, Thermal image of characteristic thermal feature in the Mallard Lake Dome thermal area. Field of view is approximately 1 meter (3 feet). Photograph by Greg Vaughan, U.S. Geological Survey, September 7, 2023.

features in the field. The features are mostly isolated fumaroles surrounded by small zones of barren rocks and patches of moist soil with mosses and grasses. The fumarole vents tend to be slight topographic depressions with some emission of barely visible steam and a sulfurous odor, and the areas have hydrothermally altered rocks coated with sulfur crystals. Surface temperatures at these fumarole vents measured with a hand-held thermal camera ranged from 60 to 79 °C (140 to 174 °F); thermocouple-based temperature measurements were up to 95.6 °C (204 °F) at a depth of 10–20 centimeters (4–8 inches) (fig. 26*C* and 26D).

Field-based confirmation of previously unmapped thermal areas that were detected using remote sensing data is an exciting result, but more work needs to be done to thoroughly map the individual vents, sample effusing gases, and determine if there are larger areas of diffusely venting warm ground. There may be more thermal areas like this in Yellowstone that have yet to be discovered.

Exploration of Little Firehole Meadows Thermal Area

Using airborne electromagnetic surveys conducted in 2016, a low-resistivity area in the Madison Plateau, approximately 7 kilometers (4.3 miles) west of the Upper Geyser Basin, was recognized (Finn and others, 2022). The area, called Little Firehole Meadows, is covered with glacial deposits and has large areas without tree coverage. High-resolution visible wintertime satellite images going back to 2008 show that parts of this meadow are consistently warm enough to prevent snow accumulation in winter (YVO, 2023). Among the thermal features on the north side of Little Firehole Meadows is a small hillside, barren of vegetation, with bright, hydrothermal mineral deposits or hydrothermally altered rocks, about 1,000 square meters (0.25 acre) in area.

In September 2023, USGS scientists visited the eastern and northern part of Little Firehole Meadows and established that some of the thermal areas detected by satellite are indeed localized features with altered ground and thermal water that are surrounded by grasses. A small pool in the north part of the meadow, just below an area with altered ground (Figure 27*A*) previously detected from space, was sampled and taken to the laboratory for chemical analysis. The temperature of the pool was 49.6 °C (121.3 °F) and the pH was 4, indicating it is an acid-sulfate spring. The water has very low concentrations of chloride (0.5 milligrams per liter) and relatively high concentration of sulfate (122 milligrams per liter). Another feature that was visited had a water temperature of 52.3 °C (126.1 °F) and a pH of 5. This feature (Figure 27*B*) was not sampled because it could not be approached safely.

The thermal activity in the Madison Plateau differs from that in the geyser basins. The plateau is at relatively high elevation, and boiling of deep groundwater releases steam and acid gases that ascend to the surface. Condensation of the steam and gas at the ground surface causes the water to be acidic. This configuration is similar to the setting in thermal areas in the eastern parts of Yellowstone National Park that are also at higher elevations. In contrast, in the geyser basins at lower elevations, water boils at, or just below, hot springs resulting in neutral to alkaline-chloride chemical compositions, like those found at Old Faithful Geyser and Grand Prismatic Spring.

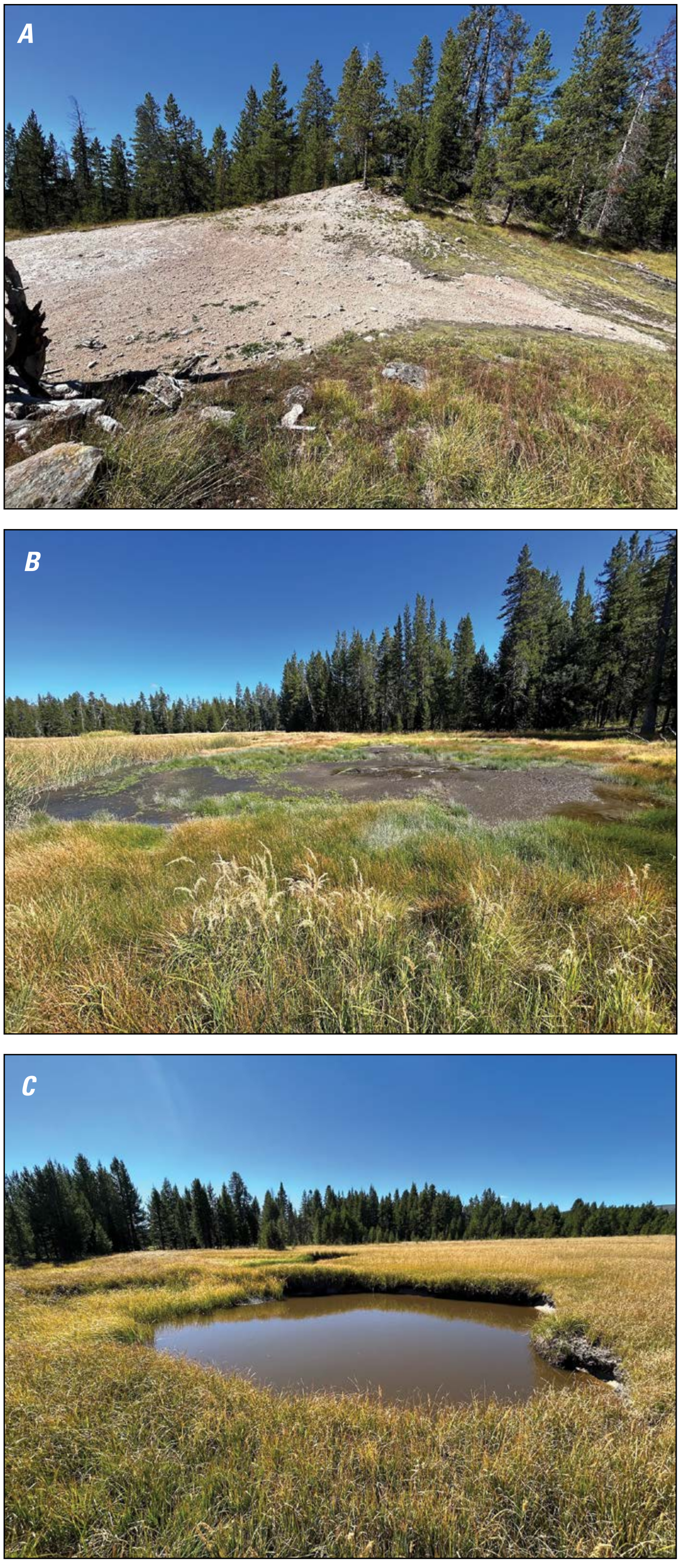


Figure 27. Photos of thermal features in Little Firehole Meadows on the Madison Plateau, in western Yellowstone National Park. *A*, Looking north at an area in the northern part of the meadow with thermally altered ground. *B*, Thermal feature in the northern part of the meadow with very small amounts of water at a temperature of 52.3 °C (126.1 °F). *C*, Warm pool in the eastern part of the meadow. Photographs by Shaul Hurwitz, U.S. Geological Survey, in September 2023.

Communications and Outreach

The newly remodeled Fishing Bridge Visitor Center reopened in 2023 and includes new interpretive displays on Yellowstone Lake that highlight geologic, biologic, cultural features, and resources. YVO scientists contributed to these displays, and also helped to update the three-dimensional bathymetric map of Yellowstone Lake that forms a centerpiece of the visitor center's west wing. In addition, YVO scientists traveled to Gardiner, Montana, in June and presented a summary of recent research and monitoring results from geological, geochemical, and geophysical studies the Yellowstone region, and met with community members and visitors to answer questions.

YVO also continued to produce products that have now become traditional, including monthly video updates of activity (posted on "USGSVolcanoes" Facebook and X [Twitter] pages, the USGS YouTube channel "Yellowstone" playlist, the USGS Multimedia Gallery [downloadable], 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. YVO scientists from USGS also participated in over 20 media interviews throughout the year, including for podcasts, radio, print and online outlets, documentaries, and local and national television and cable news.

Scan here to view the Caldera Chronicles online

https://www.usgs.gov/volcanoes/yellowstone/caldera-chronicles?utm_source=yvo-annual-report-2024&utm_medium=qr-code&utm_campaign=nh-volcanoes-fy24

Scan here to view the 2022 YVO monitoring plan

https://pubs.usgs.gov/publication/sir20225032?utm_source=yvo-annual-report-2024&utm_medium=qr-code&utm_campaign=nh-volcanoes-fy24

Summary

In 2023, measurements from monitoring stations in and around Yellowstone National Park indicated background levels of seismicity, deformation, and thermal emissions. The number of located earthquakes (1,623) was within the typical range of annual seismicity 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 continued impacts from the June 2022 flood caused a failure of the monitoring station on the Gardner River and complicated measurements on the Yellowstone River north of the park. Geyser activity was mostly normal, and 9 major water eruptions occurred at Steamboat Geyser, the third straight year of a decrease in the number of eruptions from the world's tallest geyser. In late May, an episode of thermal unrest occurred on Geyser Hill, near Old Faithful in Upper Geyser Basin, with new thermal features forming and dormant features reactivating. The proximity of some of these features to a boardwalk resulted in the closure of a short section of a pathway from late May until early August, by which time all thermal and geyser activity in the area had returned to normal.

The year was noteworthy for the installation of the first dedicated multi-parameter hydrothermal monitoring station, in Norris Geyser Basin. The station immediately paid dividends, providing indications of geyser activity in the area while also tracking earthquake activity, ground deformation, and changes in weather conditions. In addition, power systems were upgraded on the continuous gas monitoring station located near Mud Volcano, and two seismic sites were converted from analog to digital. These improvements address goals given in the 2022–2032 monitoring plan for the Yellowstone Caldera system (YVO, 2022b).

Geologic investigations focused on defining the timing and style of lava eruptions of the Central Plateau Member of the Plateau Rhyolite, with 22 eruptions taking place during 5 brief episodes between 160,000 and 71,000 years ago. Field and laboratory work addressed the sources and characteristics of the approximately 50-million-year-old Absaroka Range volcaniclastic rocks, which are abundant in the northern and eastern areas of Yellowstone National Park. In addition, a pilot study identified materials on the East Gallatin-Reese Creek fault system, in northwest Yellowstone National Park, that may be suitable for dating, and thus better constraining the earthquake history and seismic hazard of this important regional fault. New research results will be highlighted in future editions of YVO's weekly series of online articles, Yellowstone Caldera Chronicles, which can be accessed at https://www.usgs.gov/volcanoes/yellowstone/caldera-chronicles, as well as in annual reports, monthly updates and videos, and public presentations.

YVO was saddened by the passing of Robert Fournier in early 2023. Bob was a pioneer in understanding hot spring and hydrothermal activity in Yellowstone National Park, considering the region his "cornerstone of reality." In reality, his comprehensive studies established the scientific cornerstones for a new understanding of geyser and hydrothermal activity, benefiting generations of researchers who work not only in Yellowstone National Park, but also at similar systems around the world. We are grateful for his contributions and shall miss his wisdom and friendship.

2023 Publications

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Steaming thermal features of Porcelain Terrace and Porcelain Basin in Norris Geyser Basin, Yellowstone National Park. Runoff into Nuphar lake, to the right from features on the terrace have killed several trees in the area. Photograph by Michael Poland, U.S. Geological Survey , June 30, 2023.

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