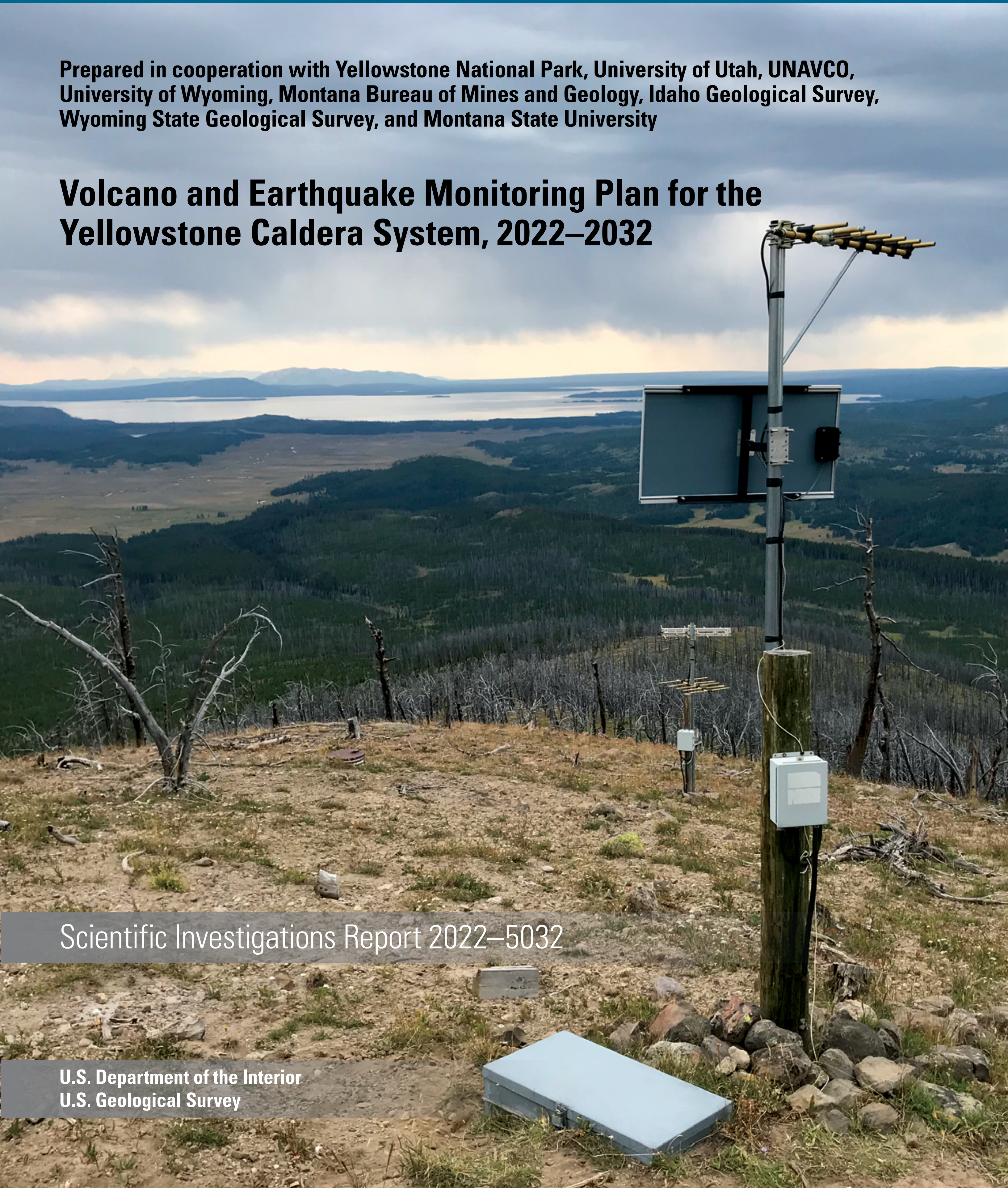

Prepared in cooperation with Yellowstone National Park, University of Utah, UNAVCO, University of Wyoming, Montana Bureau of Mines and Geology, Idaho Geological Survey, Wyoming State Geological Survey, and Montana State University

Volcano and Earthquake Monitoring Plan for the Yellowstone Caldera System, 2022–2032

Scientific Investigations Report 2022–5032

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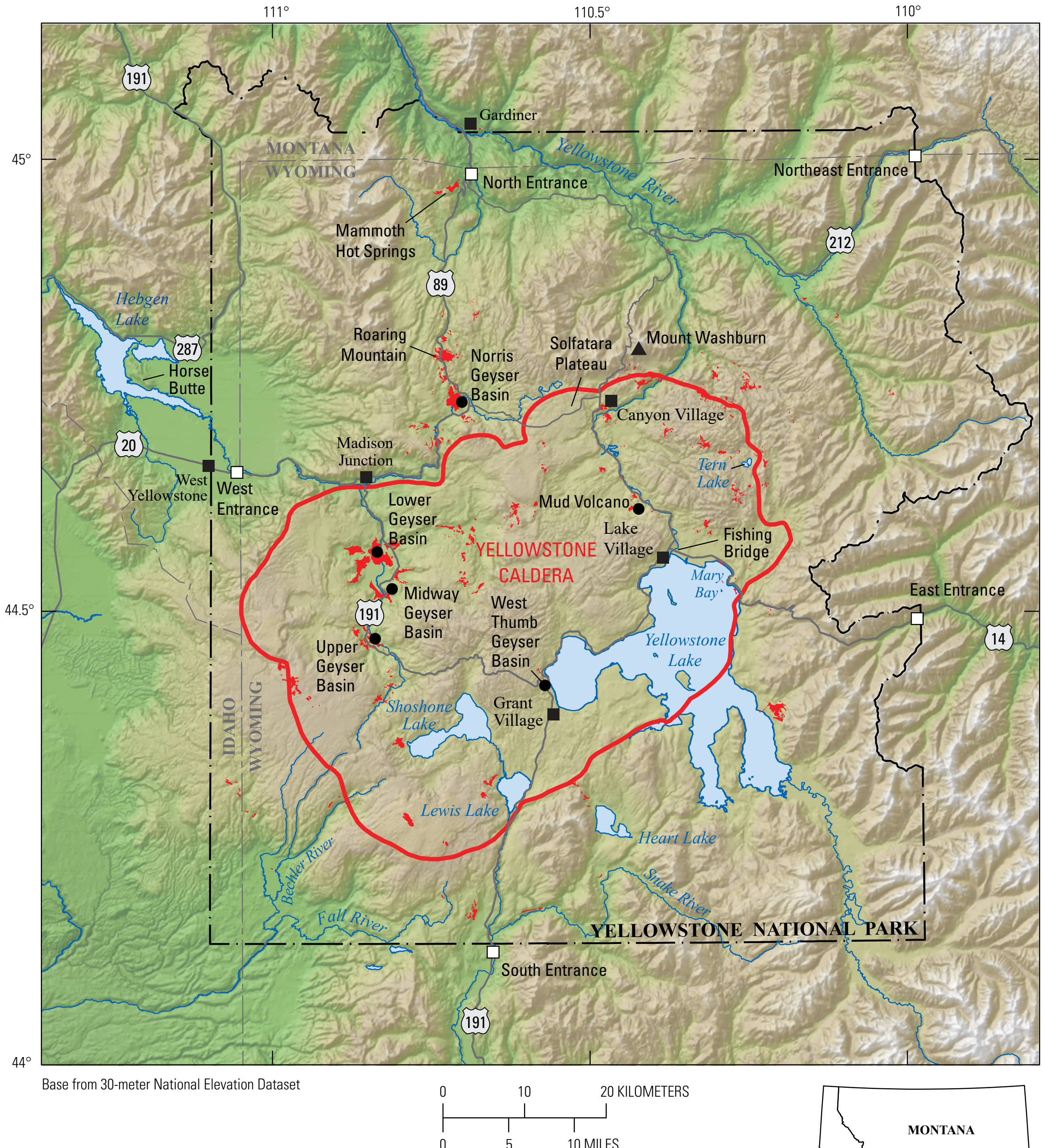

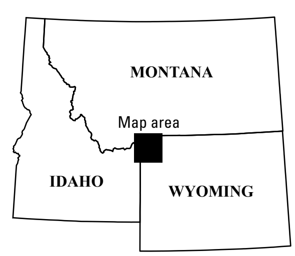

Location map showing thermal areas (in red) and noteworthy geographic features in the Yellowstone National Park region. The red line marks Yellowstone Caldera.

Cover. Photograph of seismic station YPC on Pelican Cone in Yellowstone National Park with Yellowstone Lake is in the background. Seismic monitoring is conducted under permit YELL-SCI-0114. Photograph taken by Jamie Farrell, University of Utah, August 29, 2019.

Volcano and Earthquake Monitoring Plan for the Yellowstone Caldera System, 2022–2032

By the Yellowstone Volcano Observatory

Prepared in cooperation with Yellowstone National Park, University of Utah, UNAVCO, University of Wyoming, Montana Bureau of Mines and Geology, Idaho Geological Survey, Wyoming State Geological Survey, and Montana State University

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U.S. Geological Survey, Reston, Virginia: 2022

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Volume	
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
liter (L)	0.2642	gallon (gal)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as °C = (°F – 32) / 1.8.

Abbreviations

ARRA	American Reinvestment and Recovery Act
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVRIS-NG	Airborne Visible-Infrared Imaging Spectrometer-Next Generation
DIAL	differential absorption lidar
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
HD-YLAKE	hydrothermal dynamics of Yellowstone Lake project
InSAR	interferometric synthetic aperture radar
lidar	light detection and ranging
M	magnitude
NEON	National Ecological Observatory Network
NOTA	Network of the Americas
NPS	National Park Service
NRCS	National Resources Conservation Service
NWS	National Weather Service
NVEWS	National Volcano Early Warning System
OCO-3	Orbiting Carbon Observatory
PBO	Plate Boundary Observatory
SNOTEL	snow telemetry
SPGPS	semipermanent GPS
UAS	Unoccupied Aerial Systems
USGS	U.S. Geological Survey
UUSS	University of Utah Seismograph Stations
YVO	Yellowstone Volcano Observatory

Photograph of campaign gravity measurement station in Hayden Valley, Yellowstone National Park. The gravity measurement was conducted under permit YELL-2017-SCI-7074. Photograph taken by Mike Poland, U.S. Geological Survey, October 12, 2017.

Volcano and Earthquake Monitoring Plan for the Yellowstone Caldera System, 2022–2032

By the Yellowstone Volcano Observatory[1]

Executive Summary

The Yellowstone Volcano Observatory (YVO) is a consortium of nine Federal, State, and academic agencies that: (1) provides timely monitoring and hazards assessment of volcanic, hydrothermal, and earthquake activity in and around Yellowstone National Park, and (2) conducts research to develop new approaches to volcano monitoring and better understand volcanic activity in the Yellowstone region and elsewhere. The U.S. Geological Survey (USGS) arm of YVO is also responsible for monitoring and reporting on volcanic activity in the Intermountain West of the United States.

The previous YVO monitoring plan for the Yellowstone region spanned 2006–2015 and focused on strengthening the region-wide coverage, or backbone, of monitoring systems (Yellowstone Volcano Observatory, 2006). The goals of that plan have largely been achieved thanks to significant investments in instrumentation and infrastructure, especially by the National Science Foundation EarthScope Plate Boundary Observatory (now known as the Network Of The Americas, or NOTA) and the American Reinvestment and Recovery Act. This revision of the monitoring plan, covering 2022–2032, builds upon these improvements to monitoring systems in the Yellowstone region while also accounting for new insights into the dynamics of the area's seismic, volcanic, and hydrothermal activity. These additional improvements are designed to fill gaps in the monitoring network and to better understand and track hazards associated with hydrothermal processes. These improvements include:

- Conversion of remaining analog seismic stations to digital,
- Addition of Global Positioning System (GPS)[2] stations in the vicinity of Norris Geyser Basin and other areas where changes in deformation rate and style have been observed,
- Implementation of continuous gas monitoring in several areas of Yellowstone National Park, and
- Improvements to lake, meteorological, and hydrological monitoring to better track hydrothermal activity, including that occurring on lake bottoms, and to aid in understanding of whether such activity might be influenced by external forces, like environmental conditions.

The 2022–2032 monitoring plan for the Yellowstone volcanic system also proposes to improve monitoring of hydrothermal areas to better understand these dynamic systems and their associated hazards. To date, only a single seismometer has been placed within one of Yellowstone National Park's geyser basins because seismic noise associated with boiling water can hinder interpretation of overall seismic and magmatic activity, but this concern has been mitigated by improvements to backbone monitoring. Deployment of geophysical, geochemical, hydrological, and geological monitoring instruments in geyser basins will be accompanied by campaigns to measure gas and water chemistry and flux, as well as aerial and satellite surveys of gas and thermal emissions.

Close collaboration between YVO member institutions and other research agencies is needed to achieve these monitoring goals and to use the derived data to advance understanding of how Yellowstone Caldera and similar volcanic systems work. At the same time, attention must be paid to minimize the impact of monitoring efforts and infrastructure on the environment. YVO thus commits to serving as stewards of the natural, cultural, and historical resources in and around Yellowstone National Park while maximizing scientific gain for the betterment of society.

Background and Motivation

The Yellowstone Volcano Observatory (YVO), one of five observatories overseen by the USGS Volcano Science Center, was established in 2001 as a consortium between the U.S. Geological Survey (USGS), University of Utah, and Yellowstone National

[1]Attendees of the planning meeting and contributors to this publication include Michael P. Poland, Shaul Hurwitz, Jennifer Lewicki, R. Blaine McCleskey, Wendy Stovall, R. Greg Vaughan, David Susong, Carol Finn, JoAnn Holloway, and Raymond Kokaly (U.S. Geological Survey); Jefferson Hungerford, Erin White, William Keller, Behnaz Hosseini, and Annie Carlson (National Park Service); Jamie Farrell and Robert Smith (University of Utah); Madison Myers, Eric Boyd, William Inskeep, Laura Dobeck, Daniel Colman, Mark Young, Roland Hatzenpichler, Brent Peyton, and Cathy Whitlock (Montana State University); Payton Gardner (University of Montana); Jeff Johnson (Boise State University); Simon Carn (Michigan Technological University); Ken Sims and Brad Carr (University of Wyoming); and John King (Lone Pine Research). Additional input was provided by Paul Bedrosian, Deb Bergfeld, Laura Clor, David Shelly (U.S. Geological Survey); David Mencin and Glen Mattioli (UNAVCO); and Tonie Van Dam (University of Utah). The manuscript was reviewed by David Susong and Peter Cervelli.

[2]In this report, we use "GPS" as a general reference for Global Navigation Satellite Systems (GNSS). In the Yellowstone region, some GNSS stations receive only GPS signals, while others receive signals from multiple systems. GPS-only systems will gradually be upgraded by UNAVCO as resources allow.

Park. This partnership was intended to formalize and build upon decades of geologic monitoring and research by the three institutions in the Yellowstone region, and to provide monitoring data and interpretive capabilities in support of geologic hazards assessment. The consortium was expanded in 2012–2013 with the addition of UNAVCO (a non-profit university consortium funded by the National Science Foundation), University of Wyoming, Montana Bureau of Mines and Geology, Idaho Geological Survey, and Wyoming State Geological Survey, and then again in 2020 to include Montana State University. These institutions substantially broaden YVO's expertise and have cemented a partnership that is regionally, institutionally, and experientially diverse.

The aims of YVO include: (1) research into volcanic, hydrothermal, and earthquake processes in the Yellowstone region, which offers a natural laboratory for better understanding volcanic processes and improving hazards assessments, and (2) monitoring of activity associated with the Yellowstone volcanic system to provide timely warnings and interpretations for emergency managers and the public in the case of volcanic or seismic unrest. These aims require a robust monitoring network to both facilitate research into Yellowstone Caldera's magmatic, hydrothermal, and tectonic systems and detect changes that might be related to hazardous processes.

There is a broad range of volcanic and earthquake hazards that are associated with the Yellowstone Caldera system. The region has experienced three massive, caldera-forming eruptions in the past 2.1 million years, the most recent of which formed Yellowstone Caldera about 631,000 years ago. A similar-sized eruption would cause significant amounts of ash to fall on large swaths of the United States and would influence global climate for many years. More common volcanic activity is the emplacement of lava flows, which are generally non-explosive but have volumes exceeding tens of cubic kilometers. Several dozen flows have erupted both within and outside Yellowstone Caldera since its formation. Within the caldera, eruptions of rhyolite lava occurred in several phases. At least seven rhyolite lava flows erupted between the time of caldera formation and about 450,000 years ago, at least two erupted approximately 255,000 years ago, and >20 erupted between about 170,000 and 70,000 years ago. No magma has reached the surface in Yellowstone Caldera in the past 70,000 years. Outside the caldera, the youngest lava flows are about 80,000 years old (Christiansen, 2001; Christiansen and others, 2007).

The tectonic setting of the Yellowstone region makes it one of the most seismically active areas of the United States. Major earthquakes include the 1959 magnitude (*M*) 7.3 Hebgen Lake earthquake, just outside the western boundary of the park, and a *M*6.1 earthquake near the Norris Geyser Basin in 1975. An average of 1,500–2,500 earthquakes a year are located within or adjacent to Yellowstone National Park, a few of which are likely to be in the *M*3–4 range and can be felt by people nearby. Seismic swarms, which are defined as the occurrence of many earthquakes in the same small area over a relatively short period of time, are common and can include thousands of small (<*M*3) earthquakes (for example, Farrell and others, 2009). Although seismic swarms can be associated with magma migration, most seismic activity in the Yellowstone region is due to tectonic faulting and the movement of hydrothermal fluids (for example, Farrell and others, 2010; Pang and others, 2019; Shelly and Hardebeck, 2019). Distinguishing between the different sources of earthquakes is of critical importance to hazards assessment and to forecasting of volcanic activity (Christiansen and others, 2007).

Finally, the hydrothermal system associated with Yellowstone Caldera and its surroundings has produced explosions that span a range of sizes. Small explosions, commonly from existing hydrothermal features, occur almost annually. Over a dozen much larger explosions, leaving craters hundreds of meters to a few kilometers across, are evident in the post-glacial (since ~15,000 years ago) geologic record of the region. Craters like Duck Pond and Turbid Lake were produced by catastrophic boiling of shallow groundwater. Mary Bay, at 2.6 kilometers (km) in diameter, is the largest known hydrothermal explosion crater on the planet, having formed about 13,000 years ago. The most recent large hydrothermal explosion occurred about 3,000 years ago and resulted in the formation of the 500-meter (m)-diameter Indian Pond on the north side of Yellowstone Lake (Christiansen and others, 2007; Morgan and others, 2009).

All of these geologic events have the potential to recur in the Yellowstone region, and some, especially small hydrothermal explosions and strong earthquakes, are likely to take place within the coming decades. An assessment of the threat posed by all potentially active volcanoes in the United States ranked Yellowstone Caldera as 21 out of the 161 volcanoes considered (Ewert and others, 2005, 2018). The threat score is based on a combination of potential hazards, like hydrothermal explosions and the exposure to those hazards, which is heightened in the Yellowstone region owing to the millions of people who visit the national park (although the risk is seasonal, with many more people exposed during summer compared to winter months). In the event of hazardous geological activity, YVO will follow a response plan that outlines the protocols, policies, and tools that will be used, as well as the roles of the member agencies and scientific teams (Yellowstone Volcano Observatory, 2014).

In addition to monitoring geologic hazards, YVO seeks to support the National Park Service in its Congressional mandate to monitor and preserve hydrothermal resources in Yellowstone National Park. The Geothermal Steam Act of 1970, as amended in 1988, directs the U.S. Department of the Interior to preserve and monitor hydrothermal features in units of the National Park Service. This effort includes a research program directed at geothermal resources and involving both the National Park Service and the USGS. In discussing the Yellowstone region, we follow Heasler and others (2009) in defining a *geothermal* system as one that transfers heat from within the Earth to the surface and a *hydrothermal* system as a subset of geothermal systems in which the transfer of heat involves water in either its liquid or vapor state. We thus refer to the Yellowstone volcanic system's hydrothermal system, given the critical and ubiquitous role of water in the transfer of heat.

In 2006, YVO published a volcano and earthquake monitoring plan for 2006–2015 (Yellowstone Volcano Observatory, 2006). The current report builds upon the previous monitoring plan, the goals of which have largely been achieved thanks to more than 15 years of investment and effort by the agencies that make up YVO. This document presents the rationale for supporting further upgrades to monitoring systems as a means of increasing YVO's ability to track earthquake and volcanic activity in the Yellowstone region in support of hazards assessment, research, and resource preservation.

Relation to the National Volcano Early Warning System

In 2019, Congress authorized the establishment of a National Volcano Early Warning System (NVEWS) in the United States. The purpose of NVEWS is to provide a "proactive, fully integrated national-scale volcano monitoring effort to ensure that volcanoes in the United States are monitored commensurate with the threat they pose" (Cervelli and others, 2021). The initial five-year monitoring plan for establishing and operating NVEWS (Cervelli and others, 2021) calls for prioritizing additional monitoring infrastructure at 34 high- and very high-threat volcanoes in the United States. This list was developed in 2018 based on a snapshot of threat and monitoring status at that time. Yellowstone Caldera is not on this list of priority volcanoes, which reaffirms the robust nature of the existing backbone monitoring system for the volcano overall; however, improvements and upgrades are still desired to expand hazards monitoring and assessment capabilities in the Yellowstone region. Some of the improvements described in this plan reflect a renewed concern regarding hydrothermal explosion hazards, as well as new approaches to better understand and monitor hydrothermal systems in and around Yellowstone National Park.

The monitoring plan for the Yellowstone volcanic system outlined in this report identifies two important priorities for deciding future investments in monitoring infrastructure. First, existing stations will be maintained and upgraded strategically, and any gaps in monitoring networks filled. The priority will be to address gaps in core monitoring instrumentation and capability that support early warning of hazards, consistent with the USGS commitment to NVEWS. As resources allow, additional investments will be made in instrumentation to investigate underlying processes and answer basic questions about how the magmatic and hydrothermal systems in the Yellowstone region work. Second, expansion of monitoring into hydrothermal areas will not only offer scientific insights into the dynamics of hydrothermal systems, but also the potential for measuring and understanding precursory phenomena to hydrothermal explosions. Steam-driven explosions are the most common volcanic hazard in the Yellowstone region, with small explosions occurring almost annually, and larger events that form craters hundreds of meters across occurring every few centuries or millennia—far more often than magmatic eruptions (Christiansen and others, 2007; Morgan and others, 2009).

While Yellowstone Caldera is not specifically targeted as a priority for additional instrumental monitoring by the current NVEWS management plan (Cervelli and others, 2021), the volcanic system is a natural laboratory that is worthy of additional focus due to the scientific return, which will inform volcano surveillance and hazards research elsewhere, particularly on studies of large silicic caldera systems. Additional instrumentation is also consistent with evolving NVEWS priorities as the importance of monitoring the underappreciated hazards posed by even small hydrothermal explosions is recognized. This report presents a plan for enhancing volcano and earthquake monitoring capabilities in the Yellowstone region that can be conducted consistent and in parallel with NVEWS implementation.

Goals

To achieve the overall goal of improving knowledge and awareness of earthquake and volcanic hazards in the Yellowstone region, as well as meeting Federal mandates for monitoring Yellowstone National Park's hydrothermal features through the Geothermal Steam Act of 1970 as amended in 1988, YVO proposes to include the following upgrades and improvements to its volcano and earthquake monitoring strategy:

- Upgrade remaining analog seismic stations to digital,
- Densify the GPS network to provide additional continuous deformation monitoring in areas of persistent ground motion, like Norris Geyser Basin,
- Develop a robust network of continuous, near-real-time solute-flux monitoring stations on the major rivers draining Yellowstone to rapidly identify anomalous discharges of thermal fluids from sub-basins of the hydrothermal system,
- Establish permanent continuous gas monitoring stations and produce new maps of CO_2 emissions across the park to determine accurate background levels for the Yellowstone volcanic system,
- Conduct more monitoring of meteorological parameters, like precipitation and air pressure, and investigations of the groundwater system through the establishment of continuous monitoring wells, studies of cold spring discharge, and geophysical investigations of the shallow subsurface,
- Utilize both airborne and satellite remote sensing to detect changes in thermal and gas emissions, both via direct monitoring and through proxies like vegetation health,
- Improve lake, environmental, and hydrological monitoring to better track hydrothermal activity on lake bottoms and shorelines, and
- Expand the use of multi-parameter geophysical monitoring in Yellowstone National Park's thermal basins to better understand geyser and hot spring activity and detect changes that may be precursors to hydrothermal explosions.

Progress made since 2006–2015 Plan

The "Volcano and Earthquake Plan for the Yellowstone Volcano Observatory, 2006–2015" (Yellowstone Volcano Observatory, 2006) included recommendations for upgrading seismic, geodetic, gas, water, and thermal monitoring. The plan also recommended the development of a more robust telemetry network to support the proposed upgrades to real-time monitoring. Many of the major goals of the monitoring plan with respect to continuous observations were achieved, thanks in part to investments made possible by the 2009 American Reinvestment and Recovery Act (ARRA) and the development of the National Science Foundation EarthScope Plate Boundary Observatory (PBO)—a system designed to enhance crustal deformation monitoring in the western United States and that was federated with other GPS networks into the Network Of The Americas (NOTA) on October 1, 2018.

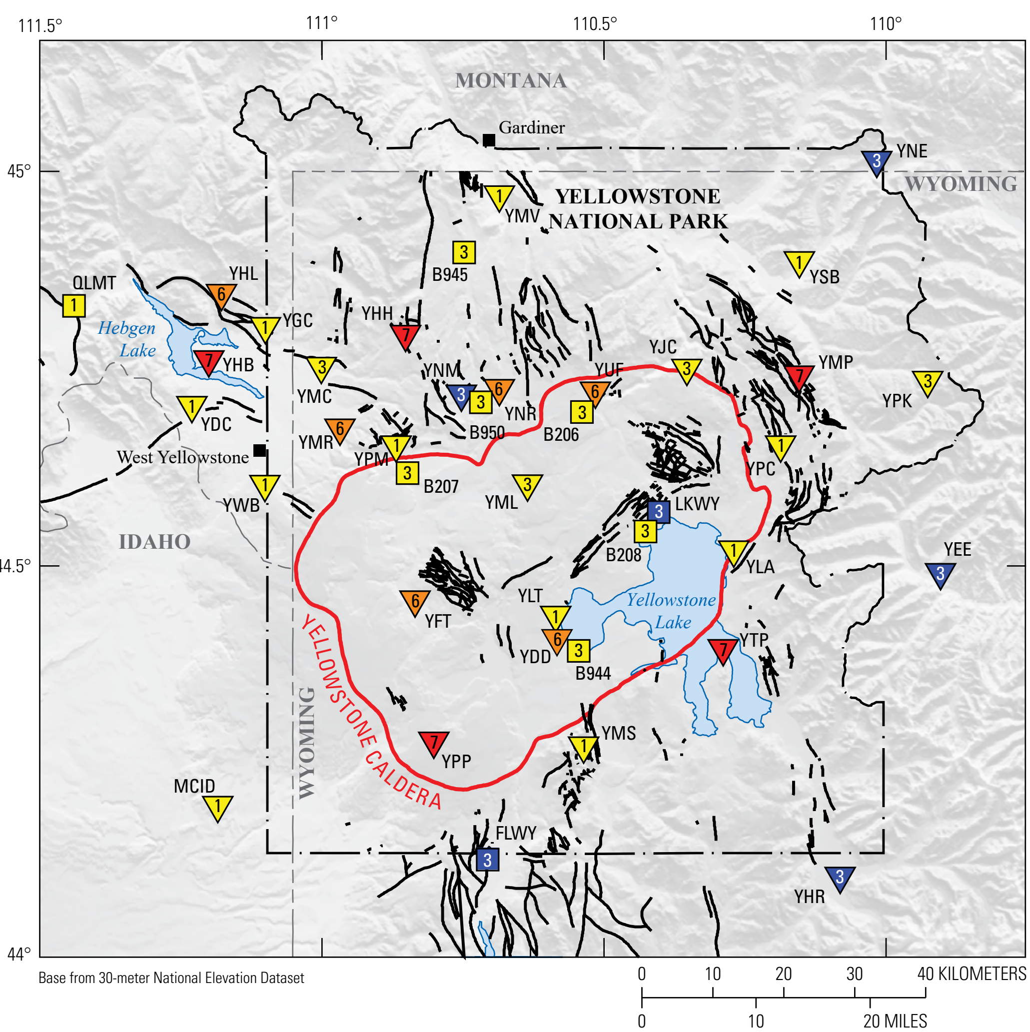
The specific elements of the 2006–2015 plan (shown in italic), and the progress made toward those goals since the plan's publication, are detailed below.

Seismology

1. *Upgrade 10 of the single-component seismometers to broadband sensors*. This goal was met with ARRA funding.
2. *Add five new seismic stations to poorly monitored areas around Yellowstone National Park*. Permits issued by Yellowstone National Park and the U.S. Department of Agriculture Forest Service allowed for installation of three new seismic stations in poorly monitored areas: stations YHR, YEE, and YNE (fig. 1).
3. *Install three-component borehole seismometers in PBO boreholes*. Borehole seismometers were installed as part of the PBO project.

Geodesy

1. *Coordinate with PBO to install continuous GPS stations at West Thumb, Roaring Mountain, and the northwestern park boundary, and install strainmeters in PBO boreholes*. Through UNAVCO, PBO installed continuous GPS stations in the northwestern corner of Yellowstone National Park (station P712) and at West Thumb (station P713) (fig. 2), but no instruments were installed near Roaring Mountain (although a semi-permanent GPS station was established nearby—see below). Strainmeters were installed in five PBO boreholes that were drilled in 2007–2008 at Lake Village, Canyon Junction, Madison Junction, Norris Junction, and Grant Village (fig. 2).
2. *Add two tiltmeter stations in existing boreholes in developed areas*. No tiltmeters were established in existing holes as had been originally intended; however, six tiltmeters were installed in PBO boreholes that were drilled in 2007–2008 at Lake Village, Canyon Junction, Madison Junction, Norris Junction, about halfway between Norris Junction and Mammoth Hot Springs, and Grant Village.
3. *Install radar reflectors above the level of winter snowpack to allow for satellite interferometric synthetic aperture radar (InSAR) measurements to be made during winter*. No radar reflectors have been installed at Yellowstone Caldera. Growth of the PBO continuous GPS network and the development of new InSAR processing techniques lessened the importance of this goal.



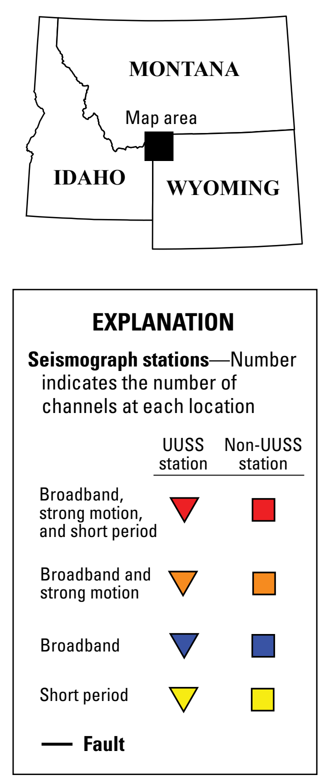


Figure 1 Map of seismic stations in the Yellowstone region, with numbers of channels indicated by number and sensor type by color. Inverted triangles indicate stations operated by University of Utah Seismograph Stations (UUSS) and squares indicate stations operated by other agencies.

Gas, Water, and Thermal Monitoring

1. *Install 3–4 gas monitoring stations to carry out continuous long-term measurements of H_2S and CO_2 concentrations near active thermal areas where degassing is prevalent.* A multi-component gas analyzer system (Multi-GAS) station was installed as a part of temporary (summer only) deployments near Norris Geyser Basin in 2016 and in the Solfatara Plateau in 2017, and as part of a year-round experiment near Mud Volcano in 2021, but no permanent gas-composition-monitoring stations have been established in Yellowstone National Park.

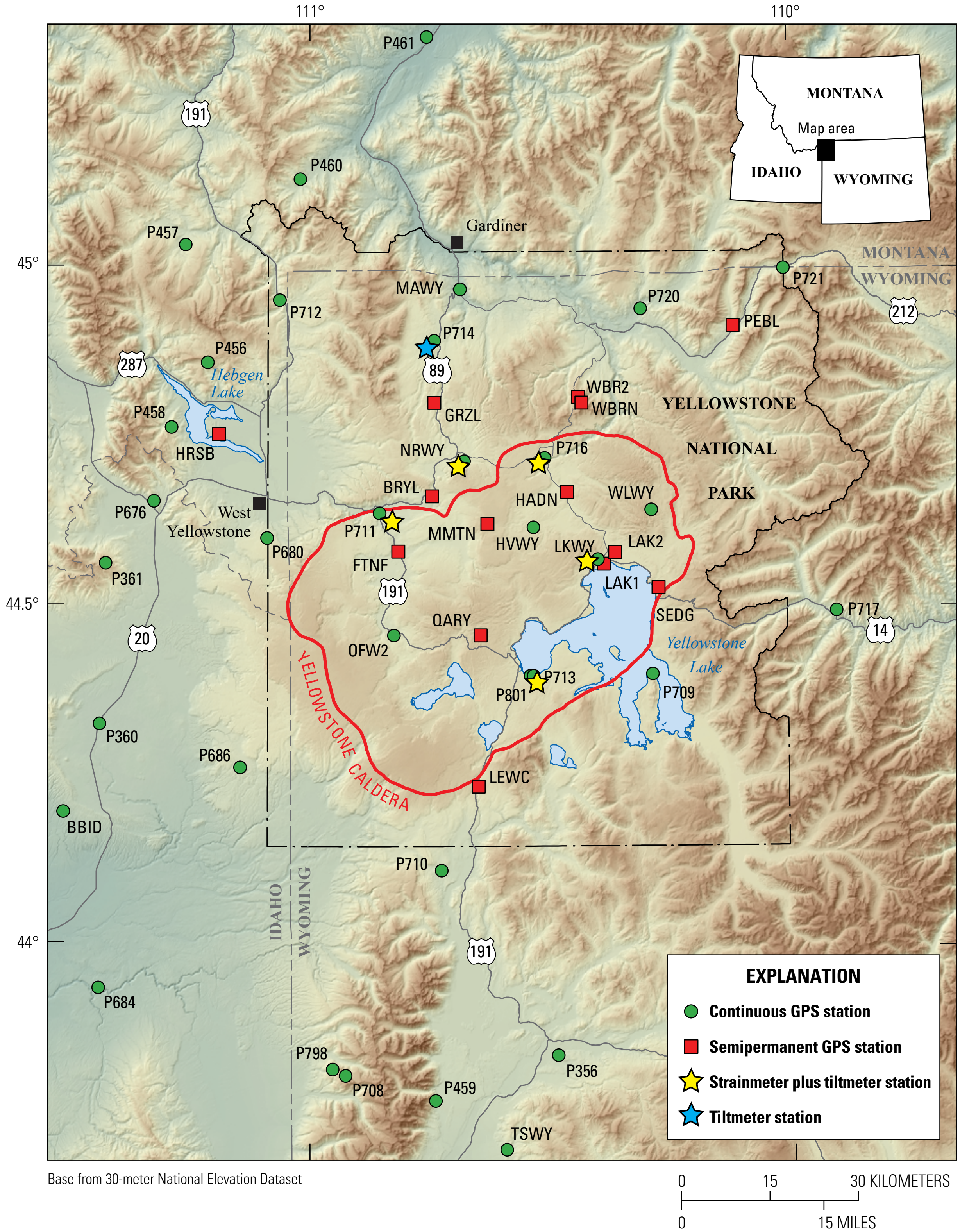


Figure 2. Map of continuous Global Positioning System (GPS), semipermanent GPS, borehole strainmeters, and borehole tiltmeters that provide surface deformation monitoring capability in and around Yellowstone National Park.

2. *Install 3–4 CO_2 gas-flux monitoring stations*. After successful test deployments in 2016 and 2017, a continuous and telemetered eddy covariance CO_2 and heat flux monitoring station was installed near Norris Geyser Basin in 2018. The station was removed in 2020 for repair after several components failed, but it operated continuously for over 2 years. Lessons learned from its performance will be used to guide future installations.

3. *Add new streamgaging stations at locations including Firehole River above Midway Geyser Basin, Gibbon River near Norris Geyser Basin, Yellowstone River near Mud Volcano, Yellowstone River south of Yellowstone Lake, Boundary Creek, and Bechler River*. No new streamgages were installed in Yellowstone National Park, although capabilities to existing stations were increased to allow for continuous measurements of specific conductance (a proxy for chloride flux and several additional solutes). The Boundary Creek streamgaging station was decommissioned in 2004, and a recent study (McCleskey and others, 2020) did not support future addition to the network because the hydrothermal discharge from southwest Yellowstone Caldera is captured at the existing Fall River monitoring site.

4. *Install a network of telemetered temperature sensors at Norris Geyser Basin*. Using ARRA funding, a system of 10 temperature monitoring stations was installed in 2010 to track changes at various features in Norris Geyser Basin. As of 2021, 9 of the stations are still maintained.

5. Continue geochemical and thermal monitoring campaigns, including:

   a. *Annual gas flights to calculate CO_2 discharge.* Gas flights with fixed-wing aircraft have not continued owing to funding limitations.

   b. *Ground-based gas-flux measurements.* CO_2 fluxes were measured by eddy covariance and portable soil CO_2 fluxmeter techniques. Volumetric mixing ratios of H_2O, CO_2, and H_2S were measured by a Multi-GAS instrument near Norris Geyser Basin in 2016 (Lewicki and others, 2017a,b), and at Solfatara Plateau in 2017 (Lewicki and others, 2019; Yellowstone Volcano Observatory, 2019) before year-round deployment of the eddy covariance system near Norris Geyser Basin in 2018 (Yellowstone Volcano Observatory, 2021a, b, c).

   c. *Sampling of gas and water from selected features for geochemical analysis.* Gas and water sampling of selected hydrothermal features have occurred annually throughout Yellowstone National Park; data are available from Bergfeld and others (2019), McCleskey and others (2012, 2016, 2019), and McCleskey and Stevens (2019).

   d. *Annual thermal infrared monitoring flights over thermal areas.* Thermal flights have not continued owing to funding challenges, but overall thermal monitoring has occurred via satellite (Vaughan and others, 2012, 2013, 2020).

   e. *Reconnaissance of lake-floor vent systems.* A major effort funded by the National Science Foundation and supported by USGS and YVO during 2016–2018 focused on better understanding the hydrothermal dynamics of Yellowstone Lake (HD-YLAKE). The work resulted in numerous new insights into lake-bottom thermal systems and their activity over time (Sohn and others, 2017).

In addition to the above specific efforts, the 2006–2015 monitoring plan proposed continuing to support temporary deployments of dense, portable instrument networks, and to focus additional monitoring in thermal areas, like Norris Geyser Basin and Upper Geyser Basin (Yellowstone Volcano Observatory, 2006). Additional power and radio hardware was added at Sawtell Peak, Mount Washburn, and Horse Butte to make the telemetry more robust. Data storage units were added to those locations to maintain data integrity in case of a transmission dropout, backfilling data once telemetry is back online. Monitoring of hydrothermal areas has advanced, for example, with the installation of the YNM seismometer station at Norris Geyser Basin (fig. 1)—the instrument can detect eruptions of Steamboat Geyser—and the establishment of the Norris Geyser Basin temperature monitoring network, but comprehensive monitoring of hydrothermal activity continues to be a goal.

Status of Volcano and Earthquake Monitoring in 2022

The Yellowstone Volcano Observatory employs a variety of methods to assess volcanic and earthquake activity in the Yellowstone region. A network of seismometers is used to locate earthquakes that may be caused by fault movement or subsurface fluid migration and can also be used to track seismic wave speeds, providing constraints on the structure of the subsurface. Deformation-monitoring equipment, including GPS stations, tiltmeters, and strainmeters, detect subtle displacement of the ground, which can help to identify regions of magma, water, or gas accumulation or withdrawal. Water and gas chemistry measurements provide insights into hydrothermal and magmatic conditions occurring beneath the ground, and thermal monitoring, both from direct measurements and via satellite, can pinpoint changes in surface temperatures associated with variations in the characteristics of Yellowstone National Park's thermal basins. Data from ground-based networks are telemetered, often in real-time, to data centers and research institutes—for example, operated by University of Utah Seismograph Stations, UNAVCO, and USGS—so that changes in deformation, earthquake activity, and thermal and gas emissions can be immediately identified and interpreted in terms of potential hazards. Satellite data are also available at low latency, and campaigns to collect samples of water and gas, as well as geophysical data from specific areas, provide a context in which to interpret both long- and short-term changes detected by satellite and continuous monitoring. Used together, these data can:

- Track earthquake activity, including seismicity that is associated with major tectonic events, like the 1959 *M*7.3 Hegben Lake earthquake just west of Yellowstone National Park (for example, Farrell and others 2009),
- Identify differences between tectonic, hydrothermal, and magmatic activity, which is critical to forecasting potential future volcanic eruptions (for example, Farrell and others, 2010; Pang and others, 2019; Shelly and Hardebeck, 2019; Wicks and others, 2020), and
- Assess changes in thermal activity that may provide an indication of the potential for hazardous hydrothermal explosions (for example, Vaughan and others, 2020).

Below, we describe the status of earthquake and volcano monitoring in and around Yellowstone National Park as of 2022. For additional background on monitoring caldera systems, and on the specific monitoring networks employed in the Yellowstone region, see Lowenstern and others (2006) and the 2006–2015 YVO monitoring plan (Yellowstone Volcano Observatory, 2006).

Seismology

Seismicity in the Yellowstone Plateau is monitored by the University of Utah Seismograph Stations, which has the responsibility for operating and maintaining the Yellowstone Seismic Network (https://www.usgs.gov/volcanoes/yellowstone). The network consists of 46 separate stations, many of which have multiple channels (fig. 1). A total of 150 channels are used to detect and locate seismicity in the Yellowstone region, providing a magnitude of completeness of *M*1.5 (Farrell and others, 2009), meaning that all earthquakes *M*1.5 and greater can be located regardless of where they occur in the Yellowstone region. The network also regularly records earthquakes in the *M*0–1 range, and even *M*<0, in areas of Yellowstone National Park and surroundings where seismic coverage is densest.

Ground Deformation and Gravity Change

Ground deformation monitoring stations in the Yellowstone region include a mix of continuous and semipermanent GPS, borehole strainmeters, and borehole tiltmeters (fig. 2). Continuous ground deformation monitoring stations in the Yellowstone region are maintained by UNAVCO as part of NOTA (Murray and others, 2020). There are 15 continuous NOTA GPS stations within Yellowstone National Park and a similar number just outside the park that provide real-time information on surface deformation across the Yellowstone Plateau (https://www.usgs.gov/volcanoes/yellowstone). In addition, as part of the PBO project, UNAVCO installed five borehole strainmeters, six borehole seismometers, and six borehole tiltmeters within Yellowstone National Park (Jaworowski and others, 2016). Since 2008, USGS scientists have also deployed more than a dozen semipermanent GPS (SPGPS) stations during summer months (Dzurisin and others, 2017). SPGPS stations fill gaps in the continuous GPS network, which is important for better understanding subsurface processes (for example, Wicks and others, 2020) and for studying seasonal changes, like deformation associated with the level of Yellowstone Lake—work that was aided by the installation of a lake level gage near Grant Village by UNAVCO in 2017 (Yellowstone Volcano Observatory, 2019).

Campaign gravity measurements can be combined with deformation monitoring to map changes in mass beneath the surface that may be caused by magma and (or) groundwater accumulation and withdrawal. Gravity surveys conducted in the 1970s–1990s indicate that past episodes of uplift and subsidence are related to intrusions of magmatic or hydrothermal fluids and subsequent degassing (Arnet and others, 1997). Surveys conducted in 2017 have documented that gravity variations are not substantially influenced by seasonal fluctuations in groundwater and surface water levels, indicating that the technique is well suited to track changes in hydrothermal and magmatic processes in the Yellowstone region (Poland and de Zeeuw-van Dalfsen, 2019).

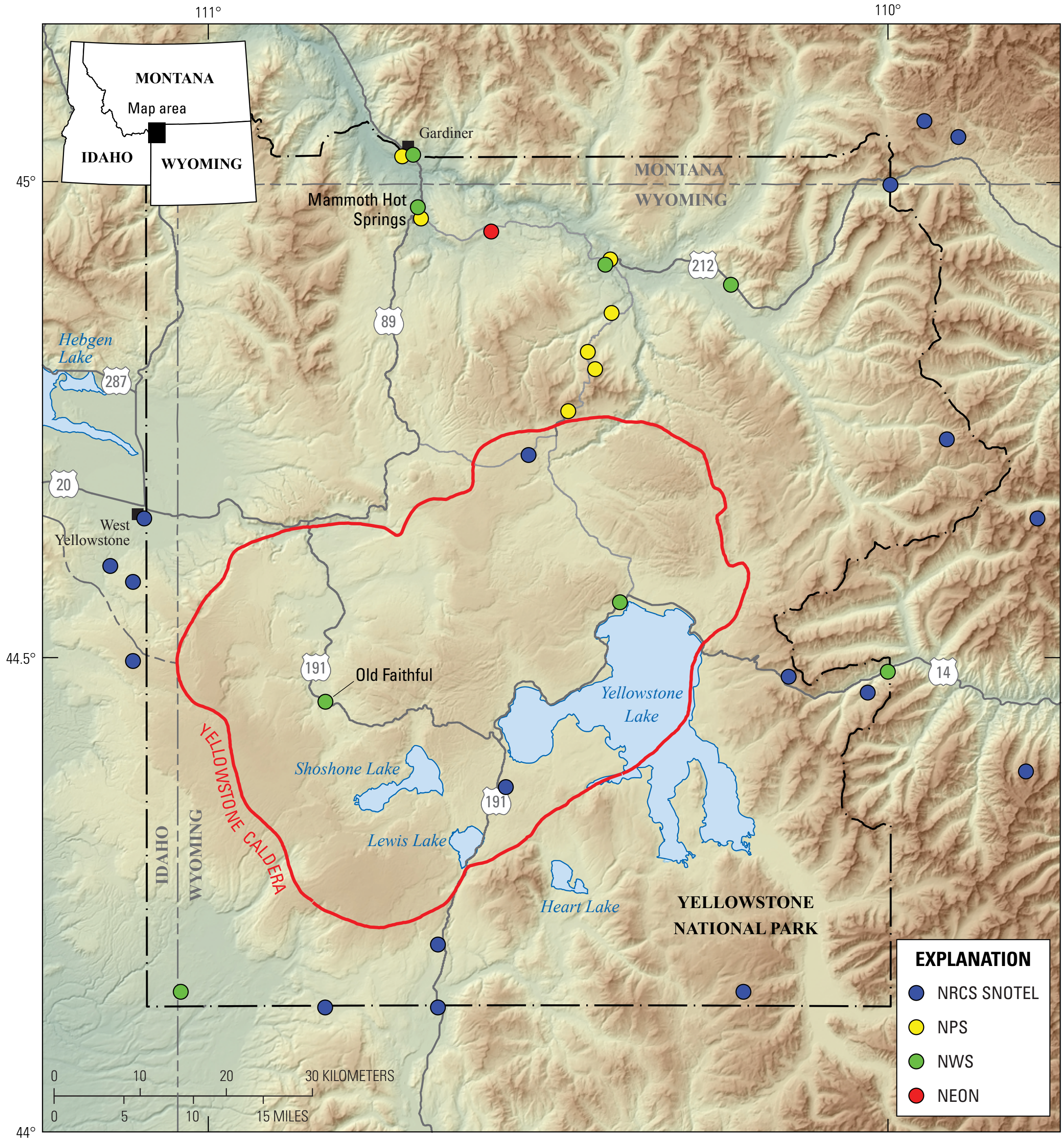
In addition to ground-based instruments, deformation in the Yellowstone region is tracked by satellite-based InSAR. These data are typically not useful during winter months, when snow cover obscures the ground, but they provide excellent spatial resolution of ground motion from summer to summer across one or more years, or over the course of a single summer.

Gas Chemistry, Water Chemistry, and Meteorology

Measurements of water and gas chemistry are most often completed by direct sampling of hydrothermal features. By 2018, water sampling had been conducted at nearly all major thermal areas of Yellowstone National Park, providing a baseline for comparison in the event of any future unrest. Limited continuous gas monitoring was implemented in the mid-2010s. Joint deployment of an eddy covariance system—a meteorological technique that measures the turbulent flux of CO_2, H_2O, and heat emitted upwind of the sensors—and a Multi-GAS station (for measuring concentrations of H_2O, CO_2, H_2S, and SO_2) was completed during the summer months near Norris Geyser Basin in 2016 (Lewicki and others, 2017b) and at Solfatara Plateau in 2017 (Lewicki and others, 2019; Yellowstone Volcano Observatory, 2019). The eddy covariance monitoring station was reinstalled for a two-year deployment near Norris Geyser Basin during 2018–2020 (Yellowstone Volcano Observatory, 2021a, b, c).

Monitoring of meteorological parameters, like precipitation, wind, and barometric pressure, which are critical factors for interpreting seismic, deformation, thermal, and chemical changes in the Yellowstone region, occurs at several land-based weather stations across the park and the greater Yellowstone region (fig. 3). Meteorological stations are distributed in and around the park and managed by multiple agencies and programs, including the National Resources Conservation Service (NRCS) snow telemetry (SNOTEL) sites, National Weather Service (NWS) sites, National Park Service

(NPS) sites, and a National Ecological Observatory Network (NEON) station. Instrumentation, data quality, and the number of years in service vary widely between stations. The NWS stations are the primary source of long-term observational records for weather and climate in the park, and several of these stations have records of more than 100 years. NPS stations record air temperature, precipitation, relative humidity, soil moisture, soil temperature, and solar radiation for climate studies. Operations began in 2018 in the northern part of the park at the NEON Blacktail Deer Creek monitoring station, which is among the most technologically advanced long-term environmental monitoring stations in the Yellowstone region and includes an eddy covariance tower, meteorological station, and broad array of aquatic and terrestrial instrumentation.



Base from 30-meter National Elevation Dataset

Figure 3. Map showing meteorological monitoring stations in and around Yellowstone National Park, including National Resources Conservation Service (NRCS) snow telemetry (SNOTEL) sites, National Park Service (NPS) sites, National Weather Service (NWS) sites, and a National Ecological Observatory Network (NEON) station.

Thermal Monitoring

Direct measurements of thermal output across the Yellowstone region are made via satellites with instrumentation capable of detecting thermal anomalies. Especially valuable are thermal infrared sensors with moderate spatial resolution (9–100 m), like the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and the Thermal Infrared Sensor (TIRS) on Landsat 8. During nighttime in winter months, there is a maximum thermal contrast between warm and ambient features, allowing for easy recognition of changes in thermal patterns and calculations of radiative geothermal heat flux (fig. 4). Notably, thermal infrared remote sensing data acquired via satellite were used to identify a newly formed thermal area near Tern Lake, in the east-central part of Yellowstone National Park in 2018 (Vaughan and others, 2020; Yellowstone Volcano Observatory, 2021a).

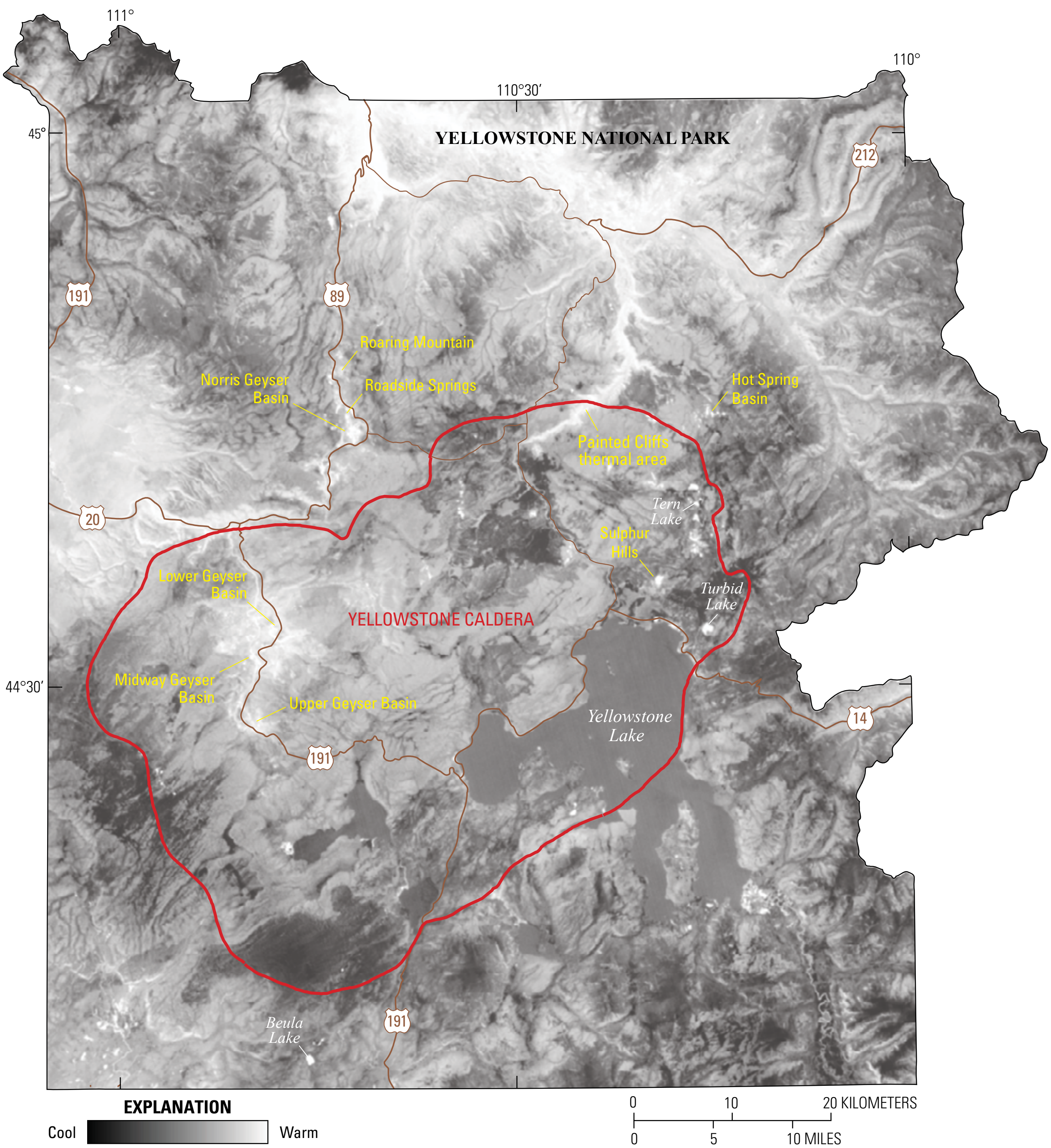
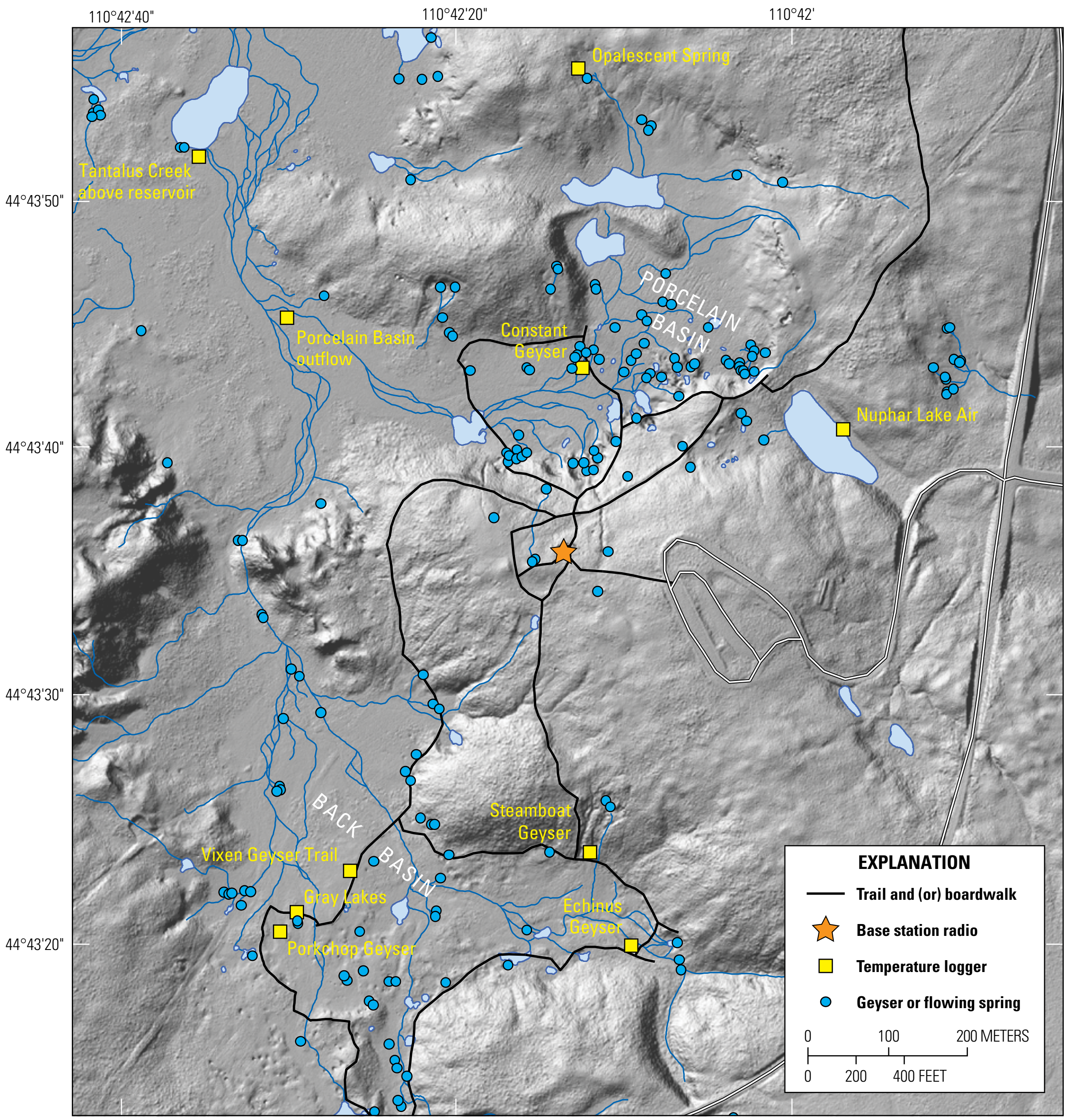


Figure 4. Satellite thermal infrared temperature image of Yellowstone National Park based on a nighttime Landsat 8 scene from May 9, 2018. The warmest areas (lightest in shade) in this image are 20–30 degrees Celsius (°C) (36–54 degrees Fahrenheit [°F]) above background. Red line designates the boundary of Yellowstone Caldera.

Monitoring the temperature of individual hydrothermal features is accomplished via ground-based systems, including the Norris Geyser Basin temperature network (fig. 5). Although Yellowstone National Park maintains numerous thermal monitoring stations, data from these stations must be manually downloaded. The YVO-operated Norris Geyser Basin network, however, consists of nine stations that are connected via radio and that download their data daily or as needed. It is possible to detect geyser eruptions from these records even when no one is present, like the late fall 2017 activity of Echinus Geyser (Yellowstone Volcano Observatory, 2019).

Temporal variations in discharge and thermal output from the numerous hydrothermal features in Yellowstone National Park have been studied by measuring chloride flux in the major rivers. The total heat output is estimated using the chloride inventory method, which assumes that all chloride discharged by rivers draining Yellowstone National Park is derived from a single deep fluid with a chloride concentration of 400 milligrams per liter and a temperature of 340 degrees Celsius (°C; Fournier, 1979, 1989).

Monitoring chloride flux overcomes the difficulty of continuously tracking changes over a broad area by using the rivers as a delivery system, and the method can be used to detect anomalous hydrothermal activity (although small events might be missed given the dilution from the overall volume of river water). Specific conductance is a proxy for chloride concentration and is measured continuously by 10 automated monitoring stations (five of which are telemetered) along Yellowstone National Park's major rivers, where water discharge and temperature are measured simultaneously (fig. 6).



Base from 2009 EarthScope 0.5-meter lidar data

Figure 5. Map of telemetered temperature measurement sites in Norris Geyser Basin.

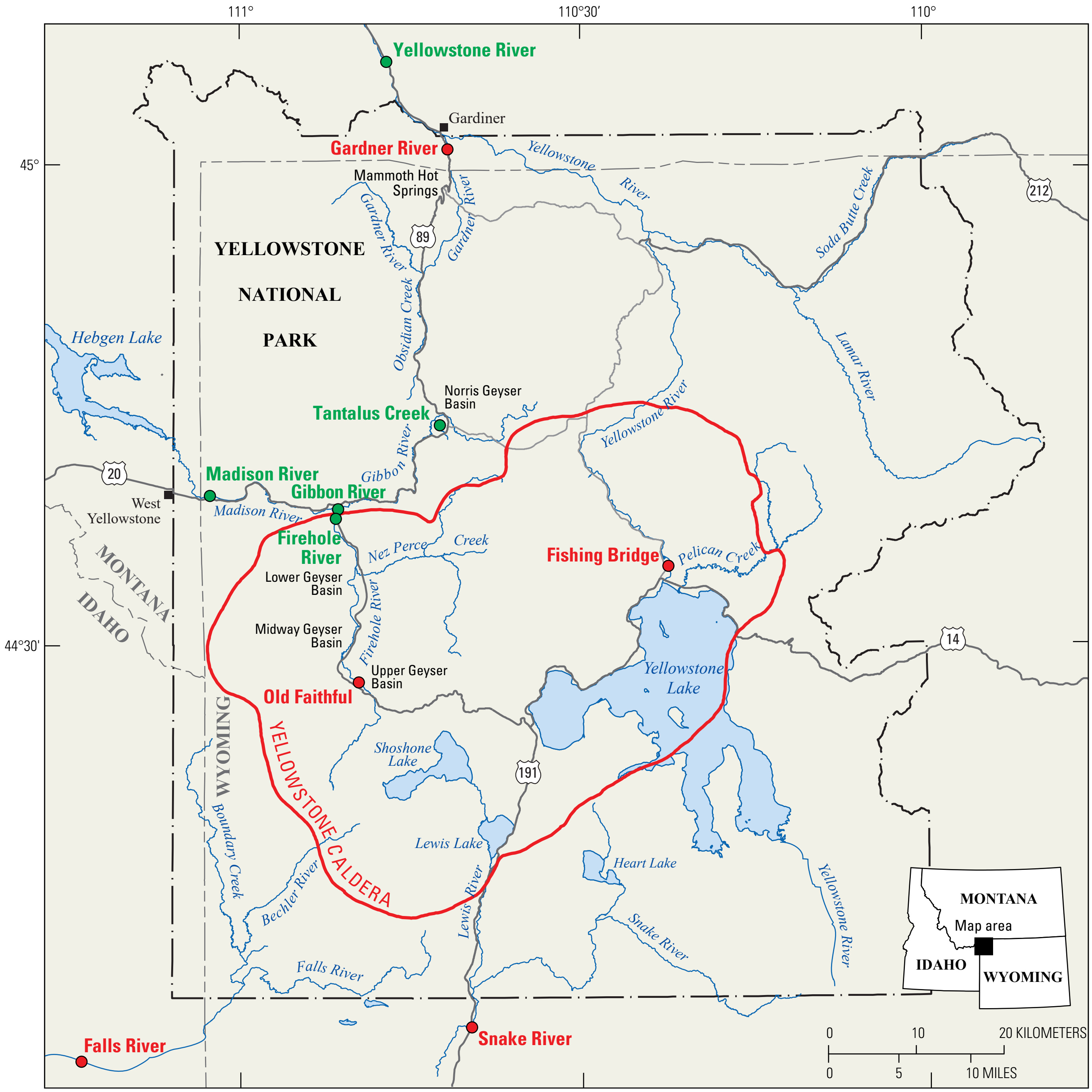


Figure 6. Map showing specific-conductance monitoring sites for determining chloride flux in rivers that drain thermal areas in Yellowstone National Park. Green stations are telemetered and red stations do not have telemetry.

Future Volcano and Earthquake Monitoring Needs

Even though exceptional progress has been made toward the goals of the 2006–2015 monitoring plan for the Yellowstone volcanic system, the rapid pace of technological advancement and growing knowledge of tectonic and magmatic activity in the Yellowstone region require that monitoring plans be adaptable and responsive to changing situations. In addition to incorporating new techniques/instruments and densifying overall monitoring, YVO proposes to conduct a more detailed exploration of hydrothermal areas. These areas have largely been avoided by geophysical monitoring because thermal areas tend to be characterized by high levels of background seismicity and ground motion that obscure regional earthquake activity and deformation. Hydrothermal features change over a variety of spatial and temporal scales in response to a range of mechanisms, including local and distant earthquakes and environmental conditions (Hurwitz and others, 2008; Heasler and others, 2009; Hurwitz and Manga, 2017). Understanding the nature of these changes is critical for better interpreting how hydrothermal activity may reflect potential hazards. Given that regional monitoring networks are now well established and the Yellowstone volcanic system is adequately monitored to detect early signs of volcanic unrest, future expansion of monitoring will include a focus on characterizing the dynamic nature of Yellowstone National Park's hydrothermal features.

Below, we separate proposed monitoring activities into "backbone" and "hydrothermal" categories. Backbone monitoring is meant to enhance the recognition and understanding of broad tectonic and magmatic activity across the Yellowstone region, whereas hydrothermal monitoring is geared toward recognizing small-scale changes in thermal areas and interpreting their causes, which may lead to better understanding of such hazards as hydrothermal explosions. We note that there is some overlap between these categories—for example, gas emissions come from hydrothermal areas. We also emphasize the importance of balancing scientific and monitoring objectives with YVO's commitment to stewardship of natural, cultural, and historical resources in Yellowstone National Park. Prior to deployment of any monitoring equipment, YVO scientists will submit full research proposals to Yellowstone National Park for compliance review and permitting requirements. For this reason, we do not highlight specific locations for instrument deployment in this report; rather, we emphasize general areas where additional monitoring would improve understanding and the nature of that monitoring. Investigators will collaborate with park staff to determine the site locations that will best fulfill monitoring, science, and resource preservation goals.

Backbone Monitoring

Backbone monitoring to track volcanic and earthquake activity is mostly accomplished via permanent geophysical networks, especially seismic and ground deformation instrumentation. Monitoring of river chemistry, as well as gas and thermal emission rates, are also important for understanding changes in overall activity of the Yellowstone volcanic system.

Seismology

The Yellowstone Seismic Network (fig. 1) is robust and well established. The major upgrade needed is to add digital broadband sensors to the 15 stations that currently have only short-period analog sensors—namely stations MCID, YMS, YLT, YLA, YPC, YSB, YMV, YPM, YGC, YWB, YDC, YMC, YML, YJC, and YPK (fig. 1). Broadband instruments have greater range and sensitivity and can record a wider variety of seismic signals, which is why broadband sensors are replacing short-period instruments at other volcanoes monitored by the USGS and partner institutions. The short-period sensors would be retained as a backup in case the broadband sensors fail.

We also anticipate future advancements in seismic data processing that will enable YVO to leverage data from an upgraded Yellowstone Seismic Network to further enhance seismic monitoring capabilities. For example, over the next several years, machine learning algorithms will become routinely incorporated into seismic processing software. This will enable several potential improvements, including the abilities to (1) detect and locate more small-magnitude earthquakes (effectively improving the magnitude of completeness for the region), (2) rapidly and accurately locate earthquakes and determine their magnitudes, and (3) seamlessly scale the ability to process large volumes of data when seismic activity rates increase. Because seismicity provides real-time and direct information on subsurface processes, next-generation seismic processing software could substantially enhance YVO's ability to monitor the Yellowstone volcanic system and issue public information in a timely manner. Upgrades to seismic data processing may be particularly apparent during earthquake swarms, when seismic activity rates in the Yellowstone region can temporarily increase by orders of magnitude, with new algorithms providing the basis to interpret the hazards implications of evolving swarms in real time.

Geodesy

Like the seismic network, the continuous NOTA GPS network (fig. 2) is also well positioned for monitoring ground deformation in the Yellowstone region. A significant gap in the network is in the vicinity of Norris Geyser Basin, which has emerged as an important center of deformation over the past 20 years (Wicks and others, 2020). In that area, only station NRWY reliably captures the dynamic nature of deformation in the Norris Geyser Basin region, although changes are weakly visible in data from nearby stations P711 and P716. Semipermanent GPS stations fill some of the gaps but are typically only deployed for 5–6 months of the year. We therefore recommend the installation of two additional continuous GPS stations in the general vicinity of Norris Geyser Basin, with the instrument sites to be determined in collaboration with Yellowstone National Park to ensure adherence to permitting and compliance requirements. Other gaps also exist, particularly in the southwest part of Yellowstone National Park, where there are no GPS stations and only one seismic station.

Borehole strainmeters and tiltmeters also provide continuous monitoring data but are difficult to maintain. For example, the instruments installed in the NOTA borehole near Canyon Village in 2008 failed in 2016 owing to the high temperature and corrosive environment of the hole. The borehole instruments have been of limited value in tracking changes in ground deformation in and around Yellowstone National Park, the noteworthy exception being the research that used strain associated with seiche waves (standing waves that cause short-term variations of a few to ~15 centimeters [1–6 inches] in water level) on Yellowstone Lake to characterize magma storage beneath the surface (Luttrell and others, 2013). The load caused by these waves resulted in a much larger strain signal than expected, which provided constraints on the melt fraction and viscosity of the upper part of the magma reservoir beneath Yellowstone Caldera. YVO intends to maintain these instruments while operable, but reinstallation following future instrument failures will depend on a review of costs and benefits at that time.

Ground-based geodetic surveys will continue in the Yellowstone region. These include the annual deployment of the semipermanent GPS network from May to October, as well as gravity measurements at selected sites in the Norris Geyser Basin area and across the Sour Creek and Mallard Lake resurgent domes (fig. 7). Establishing a multi-year time series of annual gravity measurements might shed more light on subsurface processes, especially during changes in the sense and rate of deformation in the Norris Geyser Basin area or across Yellowstone Caldera and could even contribute to a better understanding of groundwater conditions. Likewise, expanding absolute gravity measurements, which have been completed on a near-annual basis at four sites in the park since 2009, to include a site in the area of Canyon Village (between the Norris and Lake stations) would aid in efforts to better understand subsurface mass changes caused by accumulation and withdrawal of magma and groundwater (fig. 7).

Finally, we intend to continue regular InSAR observations of the Yellowstone region. These data have been critical for understanding broad-scale changes in surface deformation patterns, and they are available at a range of spatial resolutions capable of detecting changes from the scale of individual geyser basins (hundreds of meters) to across Yellowstone Caldera (tens of kilometers). The pending launch of additional satellites with InSAR capabilities—most notably the National Aeronautics and Space Administration (NASA)-Indian Space Research Organization (ISRO) Synthetic Aperture Radar mission, called NISAR, which will employ a wavelength that can penetrate vegetative cover—will provide important new datasets that will aid studies of magmatic, hydrothermal, and tectonic deformation across the Yellowstone Plateau and augment monitoring of the Yellowstone volcanic system for any changes in the state of the volcanic system.

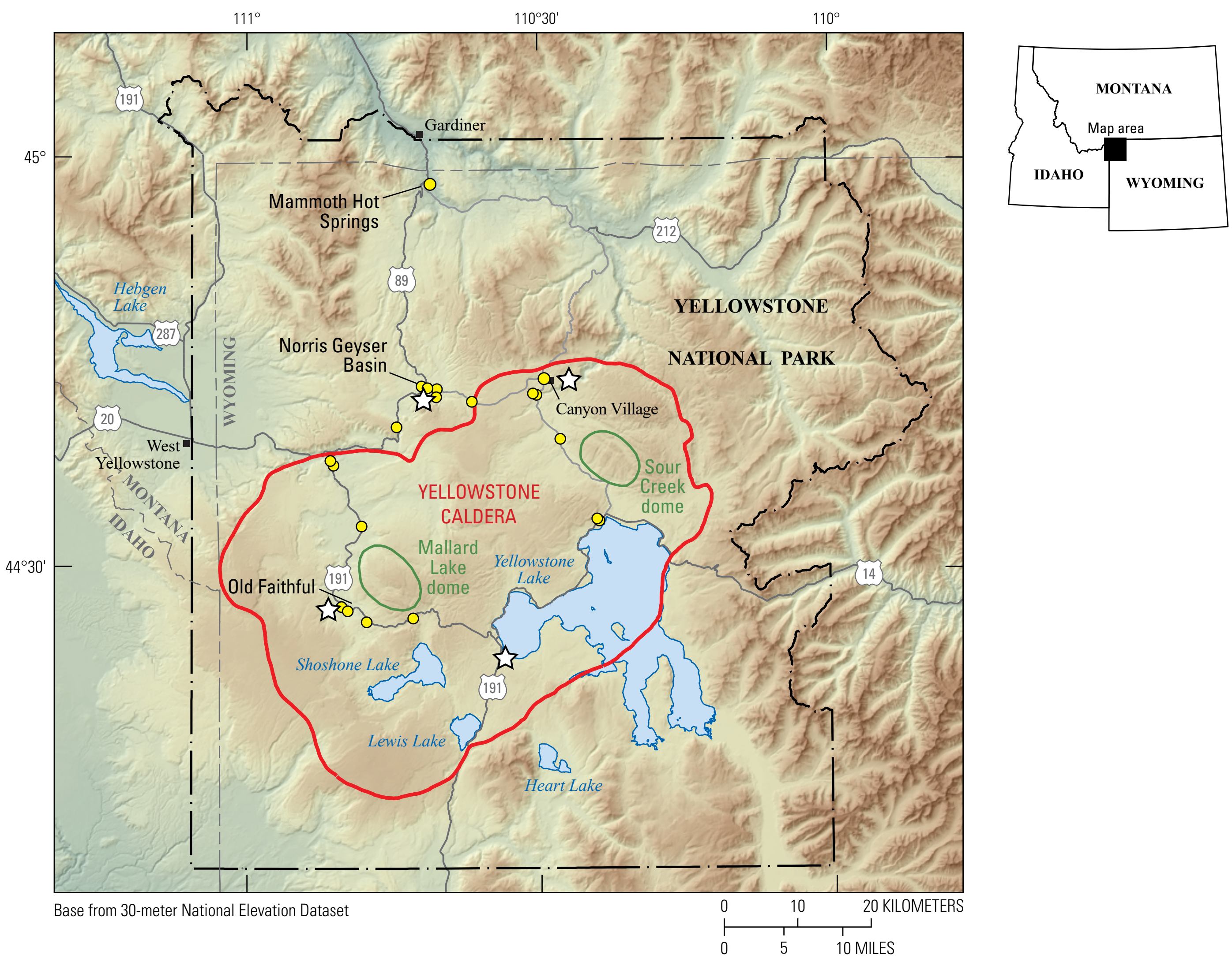


Figure 7. Map of campaign gravity stations (yellow circles) that show long-term stability (based on analysis by Poland and de Zeeuw-van Dalfsen, 2019) and provide good coverage of the Norris Geyser Basin area as well as the Sour Creek and Mallard Lake resurgent domes (green outlines) within Yellowstone Caldera. Absolute gravity stations, established in 2009, are shown as white stars with station names.

Gas and Water Geochemistry

Continuous monitoring of gas emissions to track variations in composition and emission rate across the entire Yellowstone volcanic system is not yet feasible, given the numerous sources of gas discharge in the Yellowstone region; however, continuous gas monitoring is appropriate for individual hydrothermal areas to detect changes in output that may reflect volcanic unrest (see below). Similarly, comprehensive water chemistry monitoring of the many springs is not possible. To monitor regional gas and water chemistry variations, we will use two approaches. First, continuing the practice of survey-style sampling of gases and waters for geochemical analysis from thermal areas throughout the Yellowstone region will allow for comparisons to previous measurements and might reveal changes over time. These surveys would ideally occur every 2 to 5 years at the most important thermal areas (based on patterns of past activity and public visitation) and as needed at other locations. At the locations of any continuous gas monitoring stations (for example, Lewicki and others, 2017b, 2019), annual measurements are needed. Second, aerial surveys would provide the most reliable estimate of total gas emissions from the Yellowstone volcanic system. In the past, these surveys have been done using fixed-wing aircraft, but technological advances have made use of Unoccupied Aerial Systems (UAS) more cost-effective, and UAS flights can be lower and thus capture a greater CO_2 signal (since CO_2 is denser than air). Survey flights of gas emissions, particularly via UAS, are considered vital during 2022–2032 to quantify overall gas flux from the Yellowstone volcanic system.

Thermal Emissions

Thermal monitoring of the Yellowstone volcanic system will be accomplished by a combination of moderate-resolution satellite thermal infrared remote sensing, using instruments such as ASTER or the Thermal Infrared Sensor on Landsat 8 (fig. 4), and high-resolution airborne thermal infrared images acquired from either helicopter, fixed-wing aircraft, or UAS. Such imagery is vital for mapping changes over time and understanding the evolution of thermal features, which might provide information about the state of the hydrothermal and magmatic systems. For example, helicopter-acquired thermal imagery of a new thermal area near Tern Lake documented the pattern of surface temperature (fig. 8; Vaughan and others, 2020), which can be used as a baseline for assessing changes based on future thermal survey overflights. Airborne thermal imagery has also been used to great effect in the Old Faithful area (Jaworowski and others, 2020) and Norris Geyser Basin (Heasler and Jaworowski, 2018) to map pathways for the flow of hydrothermal fluids. High-resolution visible imagery, acquired by airborne and commercial satellite instruments, is also valuable, offering additional means of mapping the extents of thermal areas and detecting changes over time.

Monitoring of specific conductance in the rivers draining Yellowstone National Park provides chloride-flux data for assessing changes in thermal output. The current network can be used to quantify the chloride flux from major drainage basins thanks to numerous telemetered streamgages (fig. 6), but two additional stations are needed on the Yellowstone River near Canyon Village and at the Yellowstone Lake outlet near Fishing Bridge to capture the contributions of specific thermal basins to overall chloride flux. A new site near Canyon Village would require both a specific conductance instrument and a streamgage. A specific conductance instrument was deployed next to an existing streamgage at Fishing Bridge in summer 2020, but data are not telemetered. Currently, only five of the ten existing conductance-monitoring stations are telemetered and providing data in real time. Adding telemetry to the existing five sites and to any new stations that are installed would improve monitoring changes in thermal output via Yellowstone National Park's river system.

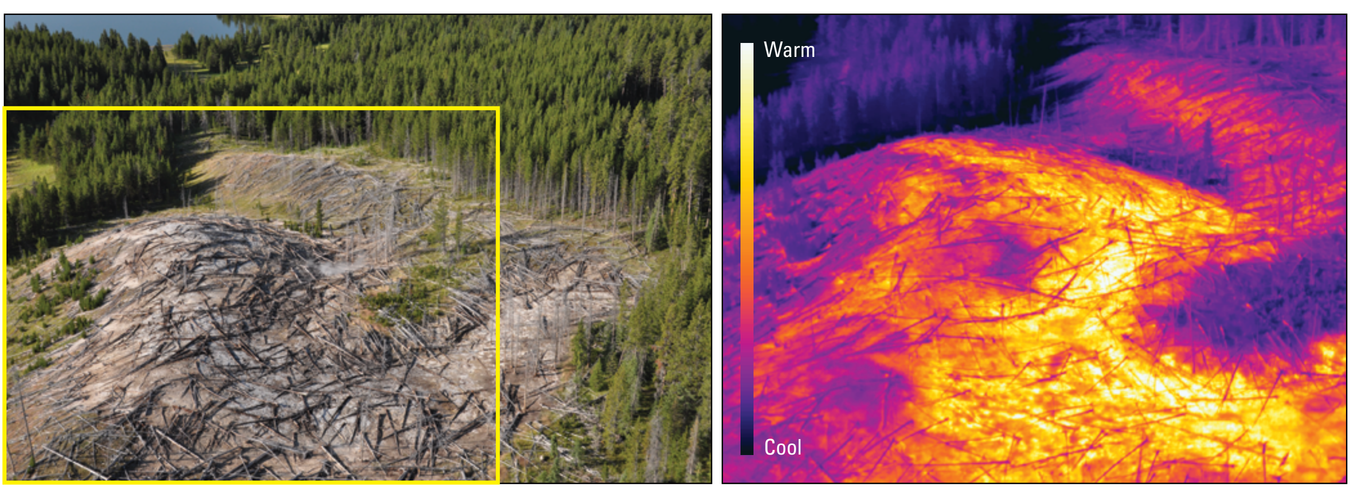


Figure 8. Aerial visible (*left*) and corresponding thermal (*right*) images of the new thermal area near Tern Lake (see fig.4 for location). Yellow box in visible image outlines area covered by thermal image. U.S. Geological Survey photographs by Mike Poland (visible) and R. Greg Vaughan (thermal) on August 19, 2019.

Hydrology

Fournier and others (2002) noted that widespread quasi-annual changes in thermal features in Norris Geyser Basin—the so-called “annual disturbance”—may be caused by interactions between the geothermal system and cold groundwater. The influence of changes in groundwater level on thermal activity, including discharge of thermal waters, however, is largely unknown. It has also been observed that hydrothermal areas sometimes respond to earthquakes, with small hydrothermal explosions and changes in geyser eruption frequency common consequences after both local and distant earthquakes (for example, Marler and White, 1975; Hurwitz and Manga, 2017). These responses of thermal features may reflect changes in subsurface permeability that could be better explored with groundwater monitoring through assessment of the response to processes like solid Earth tides and barometric pressure variations (Ingebritsen and Manga, 2019). A better understanding of the mechanisms controlling the dynamic nature of Yellowstone National Park’s thermal areas can aid with assessing and forecasting hazards associated with hydrothermal processes.

Presently there are no groundwater wells with continuous monitoring within Yellowstone National Park, although there are several monitoring wells providing continuous water-level measurements and access to groundwater for sampling collection outside the park in Montana. These are operated as a collaborative effort between Yellowstone National Park and the Montana Bureau of Mines and Geology as the Yellowstone Controlled Groundwater Area project—a statutory requirement of the Montana Water Compact (Montana Water Law: MCA 85-20-401; https://leg.mt.gov/bills/mca/title_0850/chapter_0200/part_0040/section_0010/0850-0200-0040-0010.html). Adding new groundwater monitoring wells within Yellowstone National Park could potentially improve knowledge of groundwater flow patterns and conditions. These sites would ideally include continuous monitoring of temperature, water level, and specific conductance, and be capable of supporting water chemistry sampling and microbial investigations. Monitoring wells could take advantage of still-accessible existing wells, like the ones located in Biscuit Basin area of the Upper Geyser Basin (well Y-7) and Mammoth Hot Springs (well Y-10) that were drilled as part of a research program that occurred between 1967 and 1968 (White and others, 1975). The quality of the boreholes and suitability for continuous monitoring, however, are unknown.

As an alternative, cold-water spring discharge might be considered as a window into the groundwater system. The goal of such research is to gain a better understanding of fundamental aspects of groundwater in the Yellowstone region, including water budget and flow patterns and the subsurface extent of the hydrothermal system. Thermal waters clearly extend beneath much of Yellowstone National Park even if they are not expressed at the surface, as indicated by near-boiling temperatures encountered at a depth of only ~200 feet (~60 m) in a PBO borehole near Grant Village in an area devoid of surface thermal features (Jaworowski and others, 2016). If boreholes are not feasible, airborne geophysical surveys can provide important constraints on the groundwater flow system within 1–2 km of the surface, as demonstrated by Finn and others (2022).

Lake Monitoring

The installation of a water-level monitoring system on Yellowstone Lake in Grant Village in 2017 allows for detailed observations of seiche waves (Luttrell and others, 2013) and other lake-level variations across a variety of temporal scales. As shown by past lake-level observations (Hamilton, 1987), these data are helpful for understanding sources of seismic noise and causes of surface deformation (for example, Yellowstone Volcano Observatory, 2019). Establishing additional lake-level monitoring stations on the main part of Yellowstone Lake, for example, near Lake Village, Fishing Bridge, or on a southern shore, would provide important additional constraints on lake level changes that can be used to support studies of Yellowstone National Park’s magmatic and hydrothermal systems, and to better interpret changes in geophysical monitoring data that may relate to geologic hazards.

Many studies, including ones carried out under the HD-YLAKE project, have documented substantial hydrothermal activity in Yellowstone Lake, but knowledge of hydrothermal activity in Shoshone, Lewis, and Heart Lakes, which have thermal areas along their shores, is lacking. In addition, many smaller lakes also have hydrothermal activity and contain either underwater vents or near-shore springs that may not yet be included in Yellowstone National Park’s inventory of thermal features. There are several hazards that are unique to lakes. For example, if magma erupts underwater or lava flows into a lake (both very unlikely events, but not impossible), the interaction between molten material and cold lake water could be explosive. Such interactions could substantially expand the size of the areas that are affected by the eruption. Earthquakes underneath the lakes or landslides into the lakes or below the water surface can be another source of hazard because, under some circumstances, displacement of large volumes of water can cause local tsunamis.

To better monitor the lakes with thermal areas near their shores, several studies are needed, including bathymetric surveys and mapping of thermal features. Characterization of the three-dimensional, time-varying properties of lake waters—primarily temperature and salinity used to determine the density of lake water, and the seasonality of freezing and thawing, which may reflect the heat output of nearby or lake-bottom thermal features—is also important for lake monitoring. A pilot project might include adding a specific conductance sensor and pressure transducer at the outlet of Lewis Lake, which is the most accessible of the three smaller lakes and presents the most hazard to visitors given its proximity to the highway. These data would provide important information on the thermal input to, and water level in, Lewis Lake and how those vary over time.

In continuation of studies at Yellowstone Lake that characterized post-glacial (since ~15,000 years ago) changes in hydrothermal activity, studies in the other lakes (Shoshone, Lewis, and Heart Lakes) could provide records of the hydrothermal activity preserved in lake-bottom sediments. If practical, continuous monitoring systems at lakes with active hydrothermal features would offer valuable insights into the magnitude of near-shore and lake-bottom hydrothermal activity. In addition to lake level measurements, these systems could include lake-floor deformation stations (sensitive pressure transducers) and chemical sensors that can track changes in the composition of thermal water flowing into the lakes.

Meteorology

Finally, YVO will work to densify the network of meteorological stations in and around Yellowstone National Park to provide continuous data related to parameters such as air temperature and pressure, precipitation, relative humidity, shortwave radiation, and wind speed and direction. These aid interpretations of surface deformation and gravity change, hydrological processes, heat flow and gas emissions, and other monitoring data. Although there is generally a station present every 20–30 km, they are largely absent in hydrothermal areas, the northeast quadrant of the park, along the southeast shore of Yellowstone Lake, the mountain ranges occupying the eastern portions of the park, and much of the southwestern part of the park (Davey and others 2006), and only a few monitoring stations are co-located with other YVO instrumentation. Instead, environmental monitoring stations are commonly concentrated along road corridors and developed areas. Establishing additional monitoring sites, possibly co-located with existing geophysical sensors to take advantage of power and telemetry and established in collaboration with other institutions that are interested in meteorological data, would substantially improve measurements of meteorological parameters.

Hydrothermal Monitoring

Hydrothermal areas are host to one of the most common volcanic hazards in Yellowstone National Park: discrete, powerful hydrothermal explosions (Christiansen and others, 2007). Comprehensive instrumental records before, during, and after hydrothermal explosions in Yellowstone National Park do not exist, although the conditions preceding a few small hydrothermal explosions have been well documented. The best example might be the September 5, 1989, explosion of Porkchop Geyser in Norris Geyser Basin, which produced a crater more than 10 m across. The years prior to that explosion were characterized by water chemistry variations, and abnormally high geyser eruptions were documented immediately before the event (Fournier and others, 1991). Other sudden changes in geyser activity appear to take place with little to no warning, like the 2018 eruption of Ear Spring in the Upper Geyser Basin, and the 2018 reactivation of Steamboat Geyser (Reed and others, 2021; Yellowstone Volcano Observatory, 2021a). Without monitoring systems in place before such activity, however, it is impossible to know if there were any precursory signals that might have given an indication of the impending changes.

The lack of monitoring within hydrothermal basins limits the ability to better understand, and potentially forecast, hydrothermal explosions, and by extension to protect park visitors, staff, infrastructure, and natural resources (Heasler and others, 2009). For example, there is only a single permanent seismometer located in a thermal area—station YNM, at Norris Geyser Basin (fig. 1). That instrument has proven crucial for detecting and characterizing eruptions of Steamboat Geyser (Reed and others, 2021; Yellowstone Volcano Observatory, 2021a). When seismometers have been deployed in large numbers around geysers, the results have been highly informative. For example, a temporary array of seismometers installed around Old Faithful Geyser was able to image the ascent of boiling water through the geyser's plumbing system, providing a map of water conduits and storage areas (Wu and others, 2017). A similar experiment at Steamboat Geyser documented a vertical conduit extending to a depth of at least 120 meters (about 400 feet), several times deeper than the conduit that feeds Old Faithful Geyser (Wu and others, 2021). Multi-parameter monitoring of geyser activity has also yielded outstanding insights into geyser behavior thanks to Yellowstone National Park's status as a premiere natural laboratory for hydrothermal research. A 4-day experiment at Lone Star Geyser in September 2010, which included observations from seismic, deformation, gravity, and acoustic measurements, and thermal and visible video, provided constraints on numerous facets of the geyser's activity, from subsurface boiling to the dynamics of eruptive jets (Karlstrom and others, 2013; Vandemeulebrouck and others, 2014). Without this type of monitoring, however, there is little sense of the temporal evolution of hydrothermal areas, or even individual features like geysers and hot springs, that might allow for the recognition of an impending change in activity (Heasler and others, 2009). Anticipated future enhancements in real-time detection and location of small magnitude earthquakes (see "Seismology" portion of "Backbone Monitoring" section) might also facilitate the challenging task of detecting potential short-term precursors of hydrothermal explosions. Capabilities in this regard could be enhanced further by a real-time combination of seismic outputs with complimentary data streams, such as thermal or geochemical data, which could be explored using machine learning and similar artificial intelligence approaches.

The Yellowstone region's hydrothermal system represents the interface between the deep Earth and the biosphere. The heat that powers the thermal areas found across Yellowstone National Park originates from an upper crustal magma reservoir that is a result of a deep mantle plume, which also transports magmatic volatiles from depth toward the surface and contributes to the conditions necessary to support life (Hurwitz and Lowenstern, 2014), such as the high-temperature bacteria *Thermus aquaticus* (Brock, 1967). This bacterium is the source of the heat-resistant enzyme Taq DNA polymerase, one of the most important enzymes in molecular biology because of its use in the polymerase chain reaction DNA amplification technique, from which the field of biotechnology grew. There is a feedback between geology and biology in hydrothermal areas, with microorganisms both responding to and controlling aspects of the geologic system (for instance, Fouke, 2011; Lindsay and others, 2018). Research and monitoring related to Yellowstone Caldera's deeper magmatic system can aid with understanding of critical biological systems, and changes in these biological systems can likewise provide indications of changing hydrothermal activity.

Monitoring of hydrothermal activity in Yellowstone National Park will not only aid hazards assessment, but also fulfill the federal mandate established by the Geothermal Steam Act of 1970, as amended in 1988, and support preservation of park resources and infrastructure. The most obvious site for a preliminary monitoring network is Norris Geyser Basin, where there is a history of broad thermal disturbances, fluctuating geyser activity, and small hydrothermal explosions (Heasler and others, 2009), and where there is already a telemetered temperature-monitoring network and permanent broadband seismometer in place. Initially, campaign-style monitoring experiments can be deployed to test the utility and feasibility of specific techniques, including the requirements for year-round power and communications infrastructure. Insights from these experiments can be used to develop a permanent, telemetered, real-time monitoring network with a low environmental impact that provides monitoring of geophysical and geochemical changes, as well as variations in physical properties like water levels and temperature. Lessons learned at Norris Geyser Basin can then be used to expand hydrothermal monitoring to other thermal areas in the Yellowstone National Park, like the geyser basins of the Firehole River.

Geophysical Monitoring

The core of any geophysical monitoring network is seismic and deformation instrumentation. We suggest the installation of multiple stations within Norris Geyser Basin with co-located broadband seismic and GPS sensors. These stations would target both the broad area as well as specific features, like Steamboat Geyser. Collocating multiple instruments reduces the environmental footprint and impact of the network and facilitates power and telemetry. In addition, high-resolution (~1 m pixel size or smaller) InSAR can provide maps of localized deformation within individual geyser basins. A pilot study using such data may help to identify areas where permanent GPS and seismic stations might be positioned to best characterize transient processes.

Another valuable monitoring tool is passive infrasound—acoustic waves that are low frequency and therefore generally below the threshold of human hearing. Infrasound produced by volcanic eruptions can be used to detect explosions, track eruption intensity, and potentially identify eruption precursors (for example, Johnson and Watson, 2019). Infrasound can also be used to characterize geyser eruptions (Johnson and others, 2013). A network of three infrasonic stations spaced on the outskirts of the Norris Geyser Basin area would provide the needed azimuthal coverage to not only detect but locate sources of infrasonic signal and how that signal varies over time. These stations are best deployed in forested areas, which provide a natural filter against wind noise, and therefore would not have a major visual or environmental impact.

High-resolution topographic data provide base maps for geologic interpretations and hazards assessments and are also a tool for assessing landscape change. Light detection and ranging (lidar) data collected across Yellowstone National Park in 2020 (see, for example, https://portal.opentopography.org/usgsDataset?dsid=WY_YellowstoneNP_3_2020) will provide a benchmark for subsequent measurements. Comparison of future topographic datasets to 2020 lidar data will show how thermal areas change over time. Such comparisons, for example, have documented elevation increases of as much as 2 m between 2013 and 2016 at Palette spring in Mammoth Hot Springs attributed to travertine growth in the spring's outflow region (Yellowstone Volcano Observatory, 2019). Future topographic data can also be collected and developed using a variety of methods, including aerial imagery and structure-from-motion techniques.

Both continuous and campaign gravity measurements could provide a sense of subsurface mass changes owing to water accumulation and transport. For example, there is clearly a connection between Steamboat Geyser and Cistern Spring, given that the spring drains and then refills in the hours following each major eruption of the geyser (Reed and others, 2021; Wu and others, 2021). Gravity monitoring provided equivocal results at Lone Star Geyser (Vandemeulebrouck and others, 2013), but the greater volumes of water involved in Steamboat Geyser eruptions may produce a measurable signal.

Finally, conducting and repeating additional survey-style observations of various types can characterize surface and near-surface conditions, and how those conditions change over time. Electrical resistivity, magnetotellurics, and electromagnetic induction in particular offer insights into hydrothermal processes occurring within a few tens of meters of the ground surface (for example, Pasquet and others, 2016).

Gas Composition and Flux Monitoring

A priority for hydrothermal monitoring is continuous gas measurement. Continuous geophysical monitoring is capable of discerning transient events, like geyser eruptions, but it is yet unclear if there are short-term (hours to weeks) changes in gas emissions in Yellowstone National Park thermal areas. Experimental, summer-only deployments of eddy covariance and Multi-GAS systems near Norris Geyser Basin and the Solfatara Plateau thermal area (Lewicki and others, 2017b, 2019; Yellowstone Volcano Observatory, 2019) have proven successful, and an eddy covariance system operated continuously in an area north of Norris Geyser Basin from 2018 until 2020 (Yellowstone Volcano Observatory, 2021a, b, c). These experiments proved the viability of continuous gas measurements, even during the Yellowstone region's harsh winters, but the only variations in gas compositions and emissions have been tied to weather and environmental conditions.

Multiple continuous gas-monitoring stations (fig. 9) installed in the Norris Geyser Basin area would likely improve overall understanding, and if those deployments are successful, monitoring could be expanded to the Mud Volcano area. As demonstrated by previous experiments (for example, Lewicki and others, 2017b, 2019), coupled eddy covariance and Multi-GAS instruments offer the best combination of capabilities. Eddy covariance instrumentation can measure CO_2, H_2O, CH_4, and sensible and latent heat fluxes over areas of several square kilometers. Multi-GAS instrumentation provides localized concentration measurements for CO_2, H_2O, H_2S, and SO_2 around

Figure 9. Photograph showing a continuous gas-monitoring station deployed near Norris Geyser Basin. The station in the foreground is a Multi-GAS instrument, and behind it is an eddy covariance station. U.S. Geological Survey photograph by Jen Lewicki on October 3, 2016. Research conducted under Yellowstone Research Permit YELL-2016-SCI-7082.

an individual feature or group of features. The developing technology of differential absorption lidar (DIAL) for detecting CO_2 and H_2O could provide new constraints on gas emissions from hydrothermal areas.

Gas emissions can also be quantified using aerial and satellite platforms. In Yellowstone National Park, gas plumes containing CO_2, H_2O, and H_2S are typically found at low altitudes, which are ideal for UAS surveys downwind of geyser basins. Such data could provide important new constraints on temporal variations in H_2S and CO_2 emission rates from individual geyser basins. If atmospheric concentrations are sufficiently high, there is also a possibility of mapping CO_2 emissions from space using the OCO-3 (Orbiting Carbon Observatory-3) sensor aboard the International Space Station, which can provide snapshots of 80 by 80 km areas in a single overpass. Other satellite and aerial monitoring could focus on vegetation stress that might be caused by changes in gas and (or) thermal emissions. From a fixed-wing aircraft, this monitoring could be accomplished via the Airborne Visible-Infrared Imaging Spectrometer-Next Generation (AVIRIS-NG) hyperspectral imaging sensor, which also has the potential to map surface rock and mineral compositions. Vegetative stress can be detected across broad areas via multispectral satellite data, like those data provided by Landsat, and commercial sensors like WorldView-3 that are analyzed using simple vegetation indices—for example, normalized difference vegetation index and solar-induced chlorophyll fluorescence.

Continuous in-situ and intermittent remote measurements of gas emissions will be supplemented by discrete gas sampling—a practice that has been ongoing at Yellowstone National Park for decades (Lowenstern and others, 2015) and has helped to characterize compositional differences across the Yellowstone volcanic system (see "Backbone Monitoring" section). This monitoring method would not only detect changes over time, but would also offer a more integrated understanding of the magmatic volatile budget of the hydrothermal system in the Yellowstone region. In other words, to answer the question: how are the magmatic and hydrothermal systems connected?

Hydrological Monitoring

The chloride flux in the major rivers draining Yellowstone National Park has been monitored since the 1970s (for example, Norton and Friedman, 1985; Hurwitz and others, 2007); thus, a long-term baseline has been established to potentially detect anomalous hydrothermal activity. Since 2010, efforts have been focused on testing and developing a method using specific conductance as a surrogate for chloride concentrations (McCleskey and others, 2012, 2016, 2019). The method is robust and capable of high-resolution measurements (McCleskey and Stevens, 2019), and data are readily transmitted via satellite or other telemetry platforms. Specific conductance is a surrogate for many other solutes, including arsenic and fluoride, which are a public-health concern at high concentrations (World Health Organization, 2006). In addition, synoptic sampling of the major rivers has provided insight into the primary sources of chloride and hydrothermal discharge, which serves as baseline information for future monitoring.

The current monitoring network provides information at several scales (the entire park, 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 nearly the entire hydrothermal discharge from the park. Additional monitoring sites along tributaries provide higher spatial resolution and can be used to identify changes in geyser basin or hot-spring activity. The proposed new monitoring sites in and around Yellowstone Lake (see “Thermal Emissions” and “Lake Monitoring” subsections of “Backbone Monitoring” section above) aim to specifically capture the hydrothermal discharge from large active hydrothermal areas and basins and downstream from areas that are geologically active (meaning that they are characterized by seismicity, ground deformation, and hydrothermal explosions) and that are not monitored by the existing network.

Geological and Thermal Monitoring

Monitoring the changes in any hydrothermal system requires knowledge of baseline activity—for example, the thermal output from a individual hydrothermal area as well as from the entire volcanic system. It is also important to establish the spatial distribution of elevated thermal output for comparison against the surficial expression of volcanic activity as a means of better understanding the geological controls on hydrothermal activity. Satellite monitoring is the most practical means of assessing park-wide changes in thermal output (Vaughan and others, 2012) and has resulted in the discovery of new thermal areas, like that near Tern Lake, which was recognized in 2018 (Vaughan and others, 2020). In addition to thermal infrared data, satellite imagery can provide visual data, which are useful for detecting vegetative stress—a potential indicator of changing thermal and gas emissions (see “Gas Composition and Flux Monitoring” section). For detailed investigations of individual thermal areas, however, higher spatial resolution is needed, requiring fixed-wing aircraft, helicopter, or UAS thermal surveys (for example, fig. 8), as demonstrated by Jaworowski and others (2020) around Old Faithful Geyser and by Heasler and Jaworowski (2018) for Norris Geyser Basin. These flights can also be used to collect photographs that can be combined using structure-from-motion techniques to detect topographic changes caused by hydrothermal activity (for example, Yellowstone Volcano Observatory, 2019), as well as to collect multispectral imagery for surface rock and mineral composition.

Ground-based remote sensing techniques can also be employed in both campaign and continuous monitoring of individual hydrothermal areas. Imaging spectroscopy can be used to detect surface alteration mineralogy, which is a direct consequence of subsurface hydrothermal activity (Livo and others, 2007). Variations in alteration mineralogy over time will reflect changes in hydrothermal activity. Because hydrothermally altered rocks are mechanically weaker than fresh, unaltered rocks, mapping their distribution over time is crucial for planning and designing park infrastructure, like roads, pipelines, and bridges. Camera systems—both telemetered webcams and less invasive trail cameras—could also be deployed to monitor variations in landscapes and hydrothermal features over time.

High-resolution bare-earth topographic data are another important baseline for detecting changes. Lidar provides the best such data, and complete coverage of Yellowstone National Park, including all thermal areas, was achieved in 2020. These data will not only serve monitoring efforts and scientific studies but will also help to guide efforts by Yellowstone National Park in resource presentation and infrastructure development.

Finally, better understanding of the evolution of past hydrothermal activity in the Yellowstone region—a challenging endeavor, given the difficulty in obtaining dates on siliceous material (Churchill and others, 2020)—will greatly improve hazard assessments. For example, the post-glacial histories of individual geyser basins are poorly known, and the chronology of large hydrothermal explosions is clouded by the lack of dateable material in explosion deposits. A potential means of addressing this knowledge gap is dendrochronology. Sampling trees that are both affected by and isolated from hydrothermal activity within an individual thermal area may provide insights into how the activity of an area, or even specific features, has evolved over time (Evans and others, 2010; Hurwitz and others, 2020). Such information would provide important context for the interpretation of any future changes, while also indicating how hydrothermal areas have responded to past changes in climate related to deglaciation.

Telemetry Systems and Data Availability

Expanding the monitoring backbone in the Yellowstone region, as well as initiating more focused monitoring of hydrothermal areas, will require discrete sampling and campaign deployments of geophysical instruments and continuous monitoring by a variety of sensors. To maximize utility and allow for short-term forecasting of volcanic and hydrothermal hazards, the continuous data must be telemetered and made available for analysis in a timely manner—real time for seismic and camera data, and at least daily for geodetic and geochemical data, but with potential for real time in the event of a crisis. Seismic, geodetic, and some gas flux data from the Yellowstone region are already telemetered using a mix of radio and satellite systems, and new backbone sites could largely take advantage of the existing communications infrastructure. Installation of monitoring equipment that targets the Norris Geyser Basin hydrothermal system would require upgrading telemetry systems to handle higher levels of data from an area that does not have reliable radio or cellular service (although cellular coverage in Yellowstone National Park may expand in coming years, making this telemetry option more viable). Such upgrades could be done by adding additional telemetry infrastructure to an existing tower on the hillside southeast of Norris Geyser Basin or by employing satellite telemetry, as was done for the eddy covariance system operating at the northern edge of Norris Geyser Basin during 2018–2020 (Yellowstone Volcano Observatory, 2021a, b, c) and for several specific conductance monitoring stations, including at Tantalus Creek in the Norris Geyser Basin area (fig. 6).

Data collected from new backbone sites as well as from installations that target specific hydrothermal areas must be freely available not only to the diverse research community but also to the public. In addition to being hosted by the operating institutions (like the University of Utah and UNAVCO), monitoring data are currently compiled and displayed on the YVO website (https://www.usgs.gov/volcanoes/yellowstone/monitoring). NVEWS implementation (Cervelli and others, 2021) will involve the development of a data portal that could serve as a data clearinghouse, especially for time-series data. Some datasets that require quality assessment and control may be delayed in posting or made available via the USGS ScienceBase database, as is currently the practice with discrete gas and water geochemistry sampling data (for example, Bergfeld and others, 2019). Map-based data will be added to the Wyoming State Geological Survey online “Geology of Yellowstone” map portal.

Summary

The goals of the 2006–2015 Yellowstone Volcano Observatory (YVO) monitoring plan have largely been met, resulting in a strong backbone monitoring system for detecting changes in volcanic and tectonic activity within and around Yellowstone National Park. The 2022–2032 monitoring plan builds on this success by proposing enhanced volcano and earthquake monitoring capabilities in the Yellowstone region in parallel with implementation of National Volcano Early Warning System (NVEWS) at under-monitored volcanoes in the United States. Proposed improvements to the backbone monitoring system in and around Yellowstone National Park include:

- the addition of digital seismic sensors where only analog systems currently exist,
- adding permanent, continuously recording Global Positioning System stations in the area of Norris Geyser Basin and other regions of recognized under-monitored deformation,
- expanding the use of continuous gas monitoring, and
- deploying additional hydrological-, environmental-, and lake-monitoring stations.

Additional monitoring will focus on hydrothermal sites, with deployments of geophysical, geochemical, and hydrological sensors to better track activity in Yellowstone National Park’s thermal areas. This work will include a continuation of campaign-style measurements of gas and water composition and flux, as well as aerial and satellite surveys of thermal and gas emissions. All data will be publicly available via the YVO website or those of YVO member institutions, as well as the NVEWS data portal, and the design of monitoring systems will continue the tradition of stewardship for the natural, cultural, and historical resources in Yellowstone National Park.

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Photograph of campaign GPS station in Hot Springs Basin, Yellowstone National Park. GPS monitoring was conducted under permit YELL-2003-SCI-0114. Photograph taken by Jamie Farrell, University of Utah, September 7, 2003.

Photograph of campaign GPS station in Hayden Valley, Yellowstone National Park. GPS monitoring was conducted under permit YELL-2003-SCI-0114.
Photograph taken by Jamie Farrell, University of Utah, August 13, 2003.

Photograph of campaign GPS station in Norris Geyser Basin, Yellowstone National Park. GPS monitoring was conducted under permit YELL-SCI-0114. Photograph taken by Beth Bartel, UNAVCO, July 10, 2003.

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