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

Protocols for Geological Hazards Response by the Yellowstone Volcano Observatory to Activity within the Yellowstone Volcanic System

Circular 1351
Version 3.0, January 2025

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

Photograph showing damage to the boardwalk following the July 2024 hydrothermal explosion in Biscuit Basin, Yellowstone National Park. Photograph courtesy of the National Park Service.

Front cover. Photograph showing damage to the boardwalk following the July 2024 hydrothermal explosion in Biscuit Basin, Yellowstone National Park. Three sequenced frames showing the Biscuit Basin hydrothermal explosion on July 23, 2024. Background photograph by Mike Poland, September 3, 2024. Three phase explosion photograph frames by Juliet Su.

Inside cover. Photograph showing closure signs in front of the bridge that extends over the Firehole River to Biscuit Basin. The area was closed following a hydrothermal explosion from Black Diamond Pool on July 23, 2024. U.S. Geological Survey photograph by Mike Poland, September 3, 2024.

Protocols for Geological Hazards Response by the Yellowstone Volcano Observatory to Activity within the Yellowstone Volcanic System

By the Yellowstone Volcano Observatory

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

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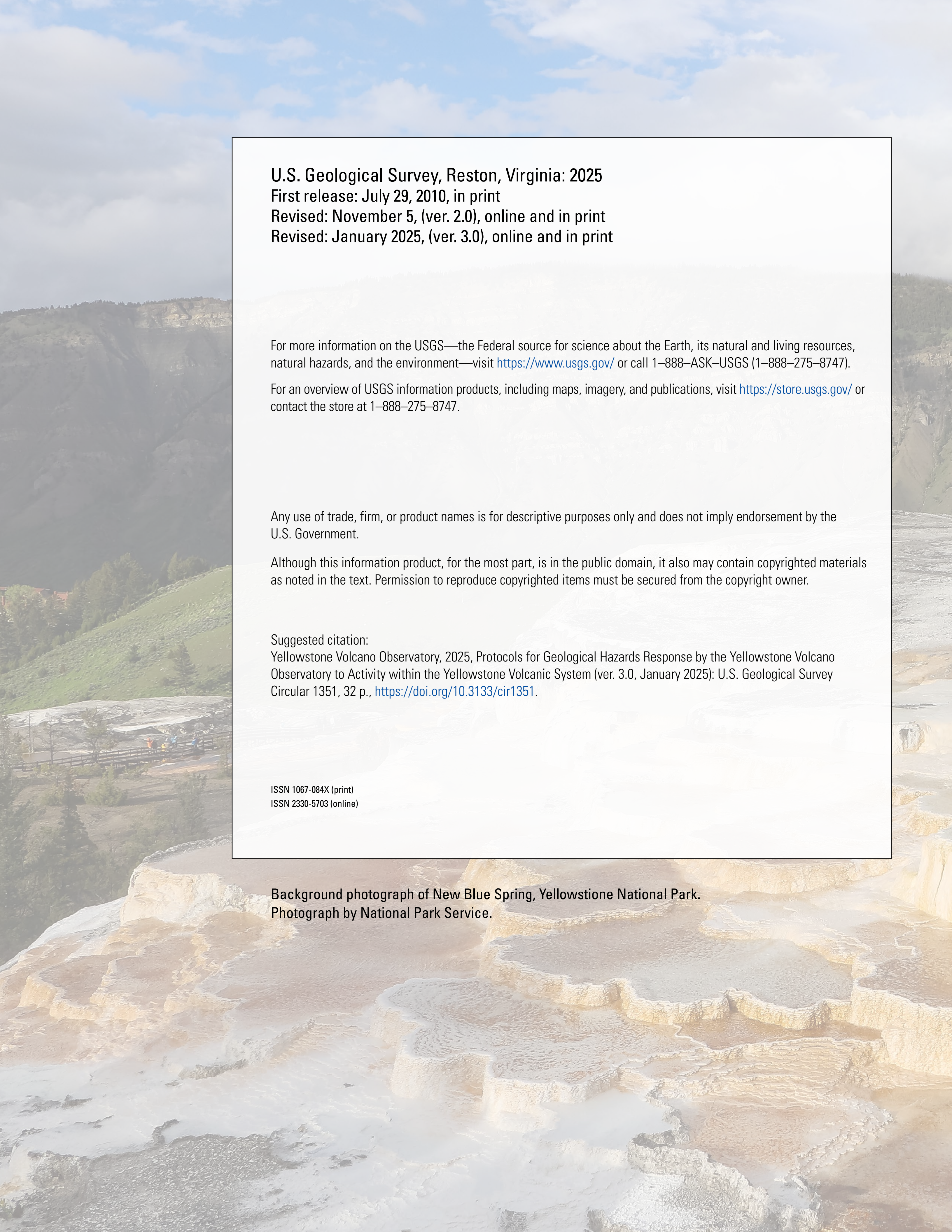

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Background photograph of New Blue Spring, Yellowstione National Park.
Photograph by National Park Service.

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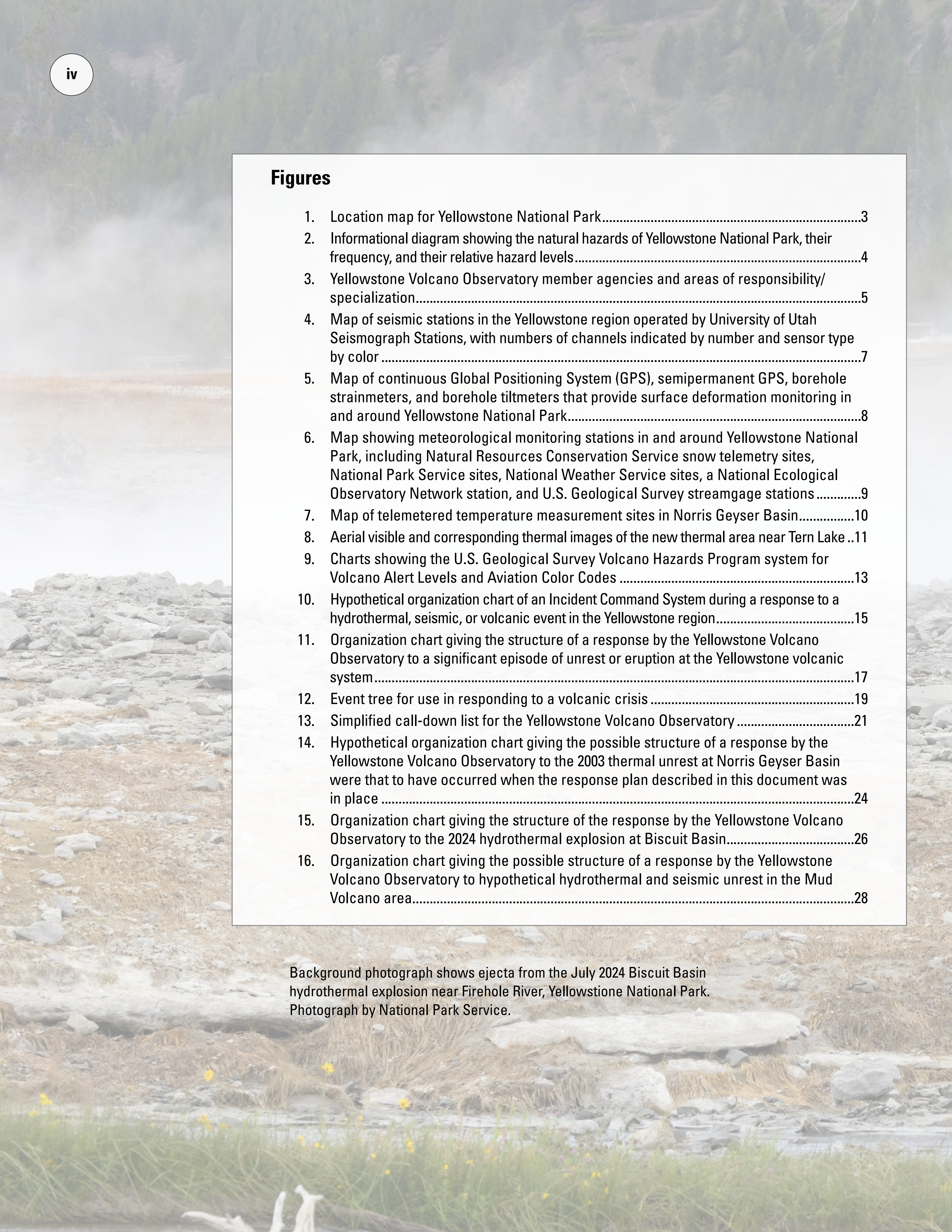

Background photograph shows ejecta from the July 2024 Biscuit Basin hydrothermal explosion near Firehole River, Yellowstone National Park. Photograph by National Park Service.

Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)

Abbreviations

ANSS Advanced National Seismic System

DOI Department of the Interior

DSIC Deputy Scientist-in-Charge

FAA Federal Aviation Administration

FEMA Federal Emergency Management Agency

HANS Hazard Alert Notification System

ICAO International Civil Aviation Organization

ICS Incident Command System

IGS Idaho Geological Survey

MBMG Montana Bureau of Mines and Geology

MSU Montana State University

M_w moment magnitude

NASA National Aeronautics and Space Administration

NEIC National Earthquake Information Center

NEON National Ecological Observatory Network

NEPA National Environmental Policy Act

NOAA National Oceanic and Atmospheric Administration

NOTA Network of the Americas

NPS National Parks Service

NRCS National Resources Conservation Service

NWIS National Water Information System

NWS National Weather Service

PDC pyroclastic density current

SAC Scientific Advisory Committee

SIC Scientist-in-Charge

SNOTEL snow telemetry

UAS Unoccupied Aircraft Systems

USGS U.S. Geological Survey

UU University of Utah

UUSS University of Utah Seismograph Stations

UWyo University of Wyoming

VAAC Volcanic Ash Advisory Center

VAN Volcano Activity Notice

VEI Volcanic Explosivity Index

VNS Volcano Notification System

VONA Volcano Observatory Notice for Aviation

VSC Volcano Science Center

WSGS Wyoming State Geological Survey

YNP Yellowstone National Park

YVO Yellowstone Volcano Observatory

Photograph of the opening phase of the July 23, 2024, hydrothermal explosion at Black Diamond Pool in Biscuit Basin. Photograph courtesy of Sabrina Harris.

Protocols for Geological Hazards Response by the Yellowstone Volcano Observatory to Activity within the Yellowstone Volcanic System

By the Yellowstone Volcano Observatory[1]

Executive Summary

Yellowstone National Park is home to Yellowstone Caldera, the largest volcanic system by volume in the United States, as well as a vigorous hydrothermal system composed of pressurized subsurface boiling waters and active faults capable of generating substantial seismicity. The region is subject to hazards spanning a wide range of intensities, magnitudes, likelihood of occurrence, and geographic extent of impact. These hazards include small and comparatively common hydrothermal explosions, occasional strong earthquakes, rare relatively non-explosive lava flows, and very rare large explosive volcanic eruptions. Addressing the broad style of potential hazards and the vast spatial and temporal scales over which these hazards can occur requires a general plan that outlines the Yellowstone Volcano Observatory (YVO) response to a hazardous or potentially hazardous geological event or unrest (defined as departure from normal activity levels).

The U.S. Geological Survey (USGS) Volcano Science Center (VSC) Response Plan for Significant Volcanic Events in the United States (Moran and others, 2024) forms the basis of any response by YVO but will be modified to suit the specific characteristics of the observatory, which operates as a consortium of nine federal, state, and academic institutions. Decisions on declaring an event response or "activity with potential" (defined as unrest that is not immediately hazardous but that may evolve into a hazardous event), as well as any changes in Volcano Alert Level and Aviation Color Code or the release of formal Information Statements, will be made by the USGS via the YVO Scientist-in-Charge (SIC) in consultation with the leads of the YVO member agencies.

The YVO response to hazardous or potentially hazardous geological activity in or around Yellowstone National Park will focus on the collection and analysis of data relevant to the location and style of the activity. Those data will be interpreted within the existing geological framework for the region to develop probabilistic assessments of potential outcomes. These interpretations and assessments will be used to support decision making by emergency management officials including Yellowstone National Park managers or within the National Incident Management System if an Incident Command System (ICS) is activated. YVO will also convene a communications group open to each member agency to ensure consistent internal and external messaging and that the public is kept informed of the unrest through formal notifications, social media posts, online content, traditional media interviews, and community meetings.

This response plan will be evaluated and updated as needed by the observatory and will be available through the YVO and USGS public websites. Responses to volcanic eruptions and responses outside of the Yellowstone region, but within the YVO area of responsibility (including Arizona, Utah, New Mexico, and Colorado), will follow the U.S. Geological Survey Volcano Science Center Response Plan for Significant Volcanic Events in the United States (Moran and others, 2024).

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[1]Attendees of the 2022 Yellowstone Volcano Observatory biennial coordination meeting, which included a tabletop scenario upon which this response plan is based, included: Michael Poland, Wendy Stovall, John Ewert, Jessica Ball, Dan Dzurisin, Craig Gabrielson, Lauren Harrison, Shaul Hurwitz, R. Blaine McCleskey, Lisa Morgan, Sara Peek, Mark Stelten, W.C. Pat Shanks, David Shelly, R. Greg Vaughan, and Liz Westby (U.S. Geological Survey); Annie Carlson, Jennifer Carpenter, Chris Flesch, Aimee Hanna, Jefferson Hungerford, Hillary Robison, Tim Townsend, Mike Tranel, Linda Veress, and Erin White (Yellowstone National Park); Jamie Farrell and Keith Koper (University of Utah); Yaan Gavillot, Jesse Mosolf, and Mike Stickney (Montana Bureau of Mines and Geology); Erin Campbell, James Mauch, and Seth Wittke (Wyoming State Geological Survey); Laura Dobeck, Stacey Henderson, Behnaz Hosseini, Natali Kragh, Madison Myers, and Ray Salazar (Montana State University); Ken Sims (University of Wyoming); and Scott Johnson (EarthScope). This report was reviewed by Andy Calvert (USGS California Volcano Observatory) and Kristi Wallace (USGS Alaska Volcano Observatory), and benefitted from input by Seth Moran (USGS Cascades Volcano Observatory) and Tina Neal (USGS Volcano Science Center).

Introduction and Scope

Purpose of Plan

Yellowstone National Park, located in the northern Rocky Mountains of Wyoming, Montana, and Idaho (fig. 1), sits atop the largest active volcanic system in the United States and hosts considerable volcanic, seismic, and hydrothermal hazards.

Over the past 2.1 million years, the Yellowstone volcanic system has produced three immense, explosive volcanic eruptions that blanketed large parts of the North American continent with ash and debris. Each eruption created sizable basins, called calderas, formed by surface collapse after evacuation of subsurface magma reservoirs. Yellowstone Caldera covers nearly one third of the land area in Yellowstone National Park and is the result of the most recent large explosive eruption, 631,000 years ago. This event was followed by dozens of smaller eruptions that produced extensive lava flows, most recently about 70,000 years ago.

Tectonic extension of the western United States has created a series of regional faults that are responsible for large and damaging earthquakes in the Yellowstone region. The largest earthquake recorded in the Intermountain West of the United States was a devastating moment magnitude (M_w) 7.3 earthquake in 1959 near Hebgen Lake, just west of Yellowstone National Park, that killed 28 people. Numerous scarps found throughout the greater Yellowstone area cut glacial deposits from the most recent ice age, providing evidence of repeated magnitude 6–7 earthquakes over the past approximately 14,000 years.

Yellowstone's famous geothermally heated waters create hot springs and geysers, but occasional hydrothermal (steam) explosions can form craters ranging from a few meters (yards) to 2.5 kilometers (1.6 miles [km and mi, respectively]) in diameter. Large hydrothermal explosion craters are most commonly found in the geyser basins along the Firehole River, beneath or around Yellowstone Lake, and in the southern part of the Norris-Mammoth corridor, but small events can occur almost anyplace that boiling water is found near the surface. The July 23, 2024, hydrothermal explosion at Biscuit Basin, about 3.5 km (2.15 mi) northwest of Old Faithful Geyser, is an example of a hydrothermal explosion of the size that probably recurs every few years to decades somewhere in Yellowstone National Park (Christiansen and others, 2007).

The Yellowstone volcanic system is unlike most other young and potentially active volcanoes in the United States. It is not a central-vent volcano, like the stratovolcanoes of the Pacific Northwest and Alaska, nor is it characterized by eruptive fissures like those common at Hawaiian volcanoes. Instead, the immense magmatic storage area beneath Yellowstone National Park is associated with volcanic activity over a very broad region and can feed a variety of eruption styles. Furthermore, the magmatic and tectonic setting are responsible for hydrothermal and seismic events that pose more local, but still important, hazards. The volcanic, seismic, and hydrothermal hazards associated with the Yellowstone region are diverse in type, intensity, and likelihood of occurrence, and they range from large and infrequent to small and commonplace (fig. 2; Christiansen and others, 2007). The Yellowstone volcanic system therefore requires a strategic plan that accounts for the unique nature and large geographic footprint of volcanic, seismic, and hydrothermal activity in the region.

The YVO response plan (hereinafter referred to as "the plan") described in this report provides a basic framework for emergency response by YVO that will be used during periods of geological unrest in and around Yellowstone National Park. Key aspects of the plan include rapidly deploying monitoring equipment and staff during periods of volcanic, seismic, and (or) hydrothermal unrest, implementing management structures that are designed to be flexible and comprehensive, developing forecasts of potential future outcomes that can be used by managers for decision making, and establishing robust communications with emergency responders and the public.

An initial response plan was published in 2010 (Yellowstone Volcano Observatory, 2010) and revised in 2014 (Yellowstone Volcano Observatory, 2014) to incorporate organizational changes to both the observatory and to some of the member agencies, and reflect recommendations provided by Pierson and others (2013) in their after-action report of a readiness exercise (referred to hereinafter as a tabletop exercise) held in 2011 in Salt Lake City, Utah. The most recent version of the plan, described herein, accounts for additional organizational changes, as well as input from three new sources: (1) the after-action review of the response to the 2018 eruption at Kīlauea Volcano, Hawaiʻi (Williams and others, 2020), (2) a generalized and scalable U.S. Geological Survey Volcano Science Center Response Plan for Significant Volcanic Events (Moran and others, 2024), and (3) a tabletop exercise held in 2022 in Mammoth Hot Springs, Yellowstone National Park, designed to explore how YVO agencies would interact during a response to geological unrest in the Yellowstone region. As with the previous response plans, this new version identifies the structures and protocols for use within the incident command structure utilized by Yellowstone National Park. For volcanic activity outside Yellowstone National Park but within YVO's area of responsibility (which includes Arizona, Utah, New Mexico, and Colorado), YVO will follow the U.S. Geological Survey Volcano Science Center Response Plan for Significant Volcanic Events in the United States (Moran and others, 2024)

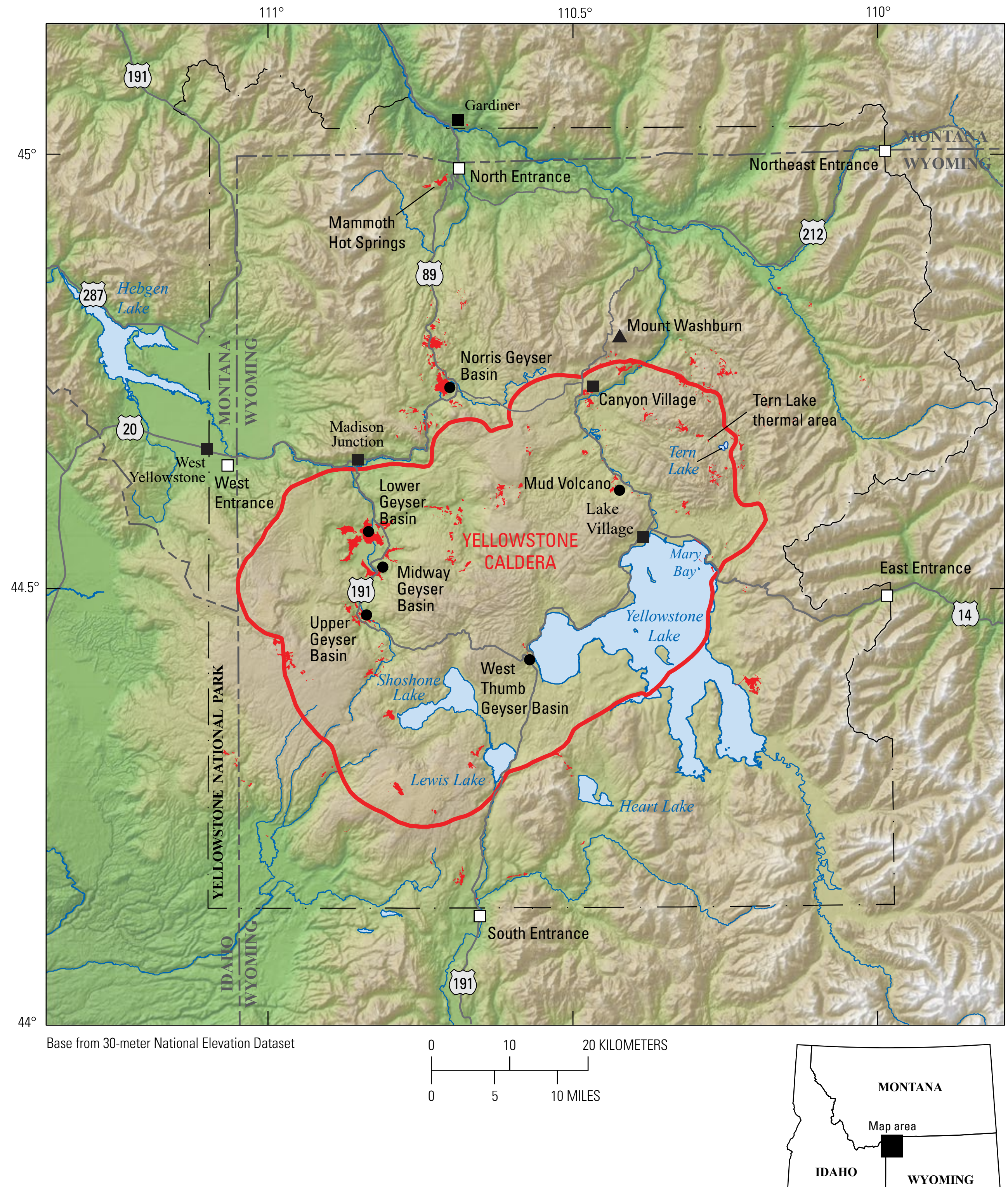


Figure 1. Location map for Yellowstone National Park, including Yellowstone Caldera (red line), roads (gray lines), state and national park boundaries, major lakes and rivers, thermal areas (red areas), and place names mentioned in this document.

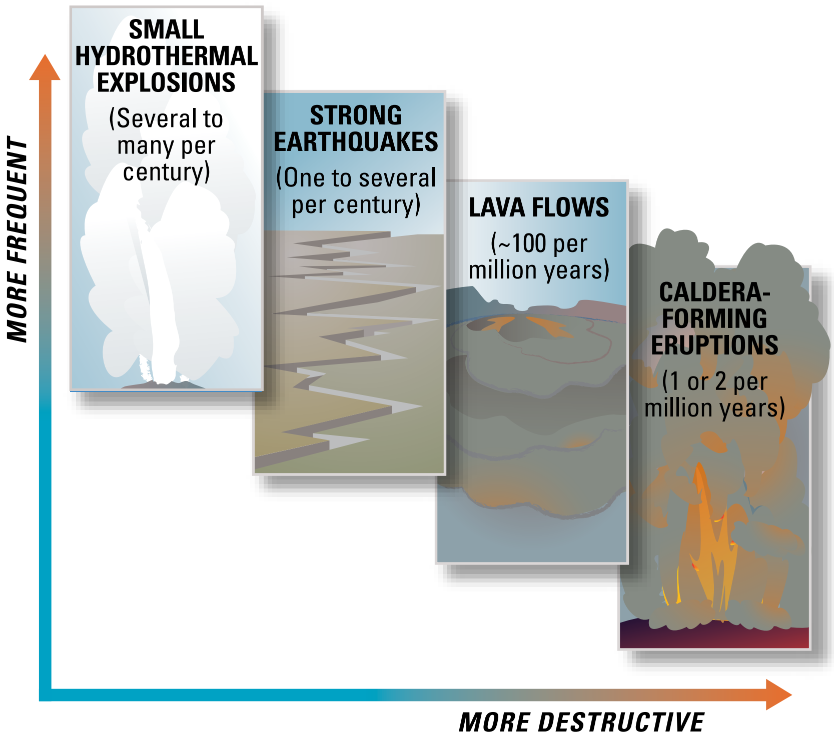


Figure 2. Informational diagram showing the natural hazards of Yellowstone National Park, their frequency, and their relative hazard levels. Scientists evaluate natural-hazard levels by combining their knowledge of the frequency and the severity of hazardous events. In the Yellowstone region, damaging hydrothermal explosions and earthquakes can occur several times a century. Lava flows and small explosive volcanic eruptions occur only rarely—none in the past 70,000 years. Massive caldera-forming eruptions, though the most potentially devastating of the Yellowstone region's hazards, are extremely rare—only three have occurred in the past several million years. Scientists with the Yellowstone Volcano Observatory see no evidence that another such cataclysmic eruption will occur in the Yellowstone area in the foreseeable future. Recurrence intervals of these events are neither regular nor predictable. Modified from U.S. Geological Survey Fact Sheet 2005–3024 (Lowenstern and others, 2005).

Organization and History of Yellowstone Volcano Observatory

In 2001, the USGS, Yellowstone National Park, and the University of Utah (UU) joined together to establish the Yellowstone Volcano Observatory (YVO). The observatory structure was expanded in 2013 to include UNAVCO (now the EarthScope Consortium, a non-profit group that provides access to geophysical instrumentation, observations, and practices, funded by the National Science Foundation), the Wyoming Geological Survey, the Idaho Geological Survey, the Montana Bureau of Mines and Geology, and the University of Wyoming. In 2020, the observatory was further expanded to include Montana State University (fig. 3). Although some United States volcano observatories have office facilities and permanent staff, YVO is primarily a partnership, composed of affiliated staff from the nine member agencies. Each agency has organizational leads that represent its staff to YVO through regularly scheduled meetings and teleconference calls. The YVO consortium is formalized through a Memorandum of Understanding that outlines organizational responsibilities and is renewed every five years or as needed. Yellowstone National Park is both a formal member of YVO and a land manager; therefore, Yellowstone National Park has roles as both a YVO member agency and as the agency that would lead the emergency response to any hazardous geological event within the park.

The USGS has the Federal responsibility to provide warnings of volcanic activity in the United States, codified in Public Law 116-9 (March 12, 2019)—the John D. Dingell, Jr. Conservation, Management, and Recreation Act—and grants the YVO SIC authority over YVO operations, which include leading media interactions and outreach, coordinating scientific investigations, and guiding monitoring efforts. Through the USGS, YVO is also responsible for monitoring and responding to volcanic unrest and eruptions in southwestern states including Arizona, Utah, New Mexico, and Colorado. USGS scientists affiliated with YVO investigate geochemical characteristics and hydrologic changes associated with the Yellowstone magmatic system and conduct space-based measurements of deformation and thermal emissions. Ground-based, real-time geophysical monitoring data, critical for timely detection of changes in seismicity and ground deformation, are provided by UU and the EarthScope Consortium. As the land manager, Yellowstone National Park is responsible for all emergency response to natural disasters within the park boundary, and Yellowstone National Park scientists have substantial expertise in the hydrothermal systems found throughout the region. The state geological surveys offer critical hazards information and outreach products to their respective citizens and, along with the University of Wyoming and Montana State University, possess important geological knowledge. YVO consortium members also aid and collaborate with outside scientists to serve the interest of the greater scientific community.

YVO provides professional and critical earth-science expertise, conducts research on magmatic, hydrothermal, and tectonic processes in the Yellowstone region, operates modern monitoring networks, processes and interprets geophysical, geochemical, and geological data, and rapidly assesses the significance of geological processes that may threaten infrastructure, visitors and staff in Yellowstone National Park,

- Scientist-in-Charge
- Hazards assessment and notification

- Surface deformation monitoring
- Geodesy research

- Montana geology
- Earthquake monitoring and research

- Chief seismologist
- Earthquake monitoring and research

- Idaho geology
- Hazards research

- Hydrothermal systems research
- Geophysics and geochemistry research

- Geological research
- Thermal biology research

- Land manager
- Hydrothermal systems monitoring

- Wyoming geology
- GIS hazards expertise

Figure 3. Yellowstone Volcano Observatory member agencies and areas of responsibility and (or) specialization.

and the public beyond the borders of the park. Collectively, these capabilities ensure that YVO can offer the vital information and support needed to react rapidly to geological hazards associated with the Yellowstone volcanic system and respond to requests for information from land managers, emergency responders, the media, and the public.

Monitoring Strategy

The Yellowstone Volcano Observatory monitors geological activity and potential hazards in the Yellowstone region using a combination of ground-based monitoring instruments, remote sensing, and episodic sampling of waters and gases. The monitoring approach, described in detail in the 2022–2032 volcano and earthquake monitoring plan for the Yellowstone Caldera system (Yellowstone Volcano Observatory, 2022), prioritizes defining baseline levels of activity from which to compare anomalous changes that may precede a hazardous event. Deviations from baseline activity could trigger a response that includes more focused monitoring, with installation of additional geophysical stations, scientific observations, sampling, and acquisition of aerial remote sensing data to understand the source of unrest and better inform hazards assessments.

Continuous Ground-based Monitoring

Real-time geophysical monitoring of the Yellowstone volcanic system is conducted using a combination of equipment operated and maintained by YVO member agencies. The Yellowstone Seismic Network (fig. 4) is maintained by the University of Utah Seismograph Stations (UUSS), which, with the Montana Bureau of Mines and Geology (MBMG) that operates a seismic network in Montana, determine locations and magnitudes for earthquakes in the region. Both the UUSS and MBMG networks are part of the USGS Advanced National Seismic System (ANSS; Filson and Arabasz, 2016; U.S. Geological Survey, 2017; Wald, 2020). Within the ANSS framework of regional seismic networks across the country, magnitudes of earthquakes larger than M_w 6.0 in the Yellowstone region are determined by the USGS National Earthquake Information Center (NEIC), which provides full-time backup to the UUSS, MBMG, and other ANSS regional seismic networks and is responsible for rapidly and accurately determining the location and size of large earthquakes that occur worldwide. In the Yellowstone region, all epicenters of earthquakes of M_w 1.5 and larger are located. Detecting and locating earthquakes smaller than M_w 1.5 is possible in areas of the park where seismic station coverage is dense but, in some locations, would require the installation of additional seismometers.

In the Yellowstone region, continuous Global Positioning System (GPS[1]) stations (fig. 5) are used to track ground deformation and are maintained by the EarthScope Consortium, which operates the National Science Foundation's Geodetic Facility for the Advancement of Geoscience. Additional semipermanent GPS stations are installed seasonally by USGS in and around Yellowstone National Park to densify the deformation monitoring network without requiring major power and telemetry infrastructure (Dzurisin and others, 2017). Multiple organizations and universities record and process data from the GPS stations and make the data available online to the public (for example, https://www.earthscope.org, https://earthquake.usgs.gov/monitoring/gps/YellowstoneContin_ITRF2014, and http://geodesy.unr.edu/). The EarthScope Consortium also maintains strainmeters, tiltmeters, and seismometers, all within boreholes drilled in 2007–2008 through the National Science Foundation's EarthScope program (fig. 5).

[1]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.

Photograph of the West Yellowstone lava flow taken along Highway 20 (between the West entrance of Yellowstone National Park and Madison Junction). The West Yellowstone lava flow is approximately 111,000 years old and has a volume of about 41 km^3 (10 mi^3). U.S. Geological Survey photograph by Mark Stelten, June 2017.

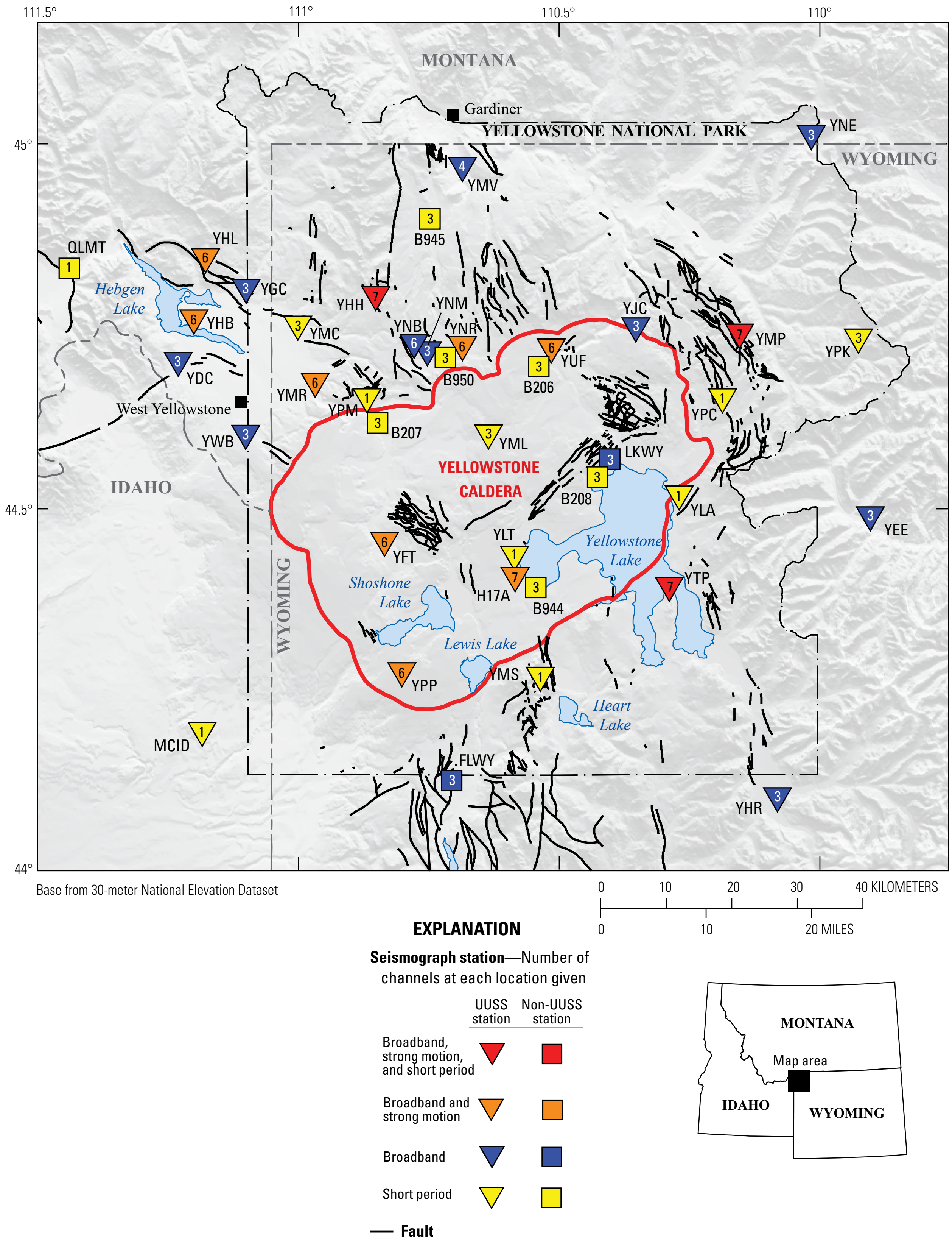
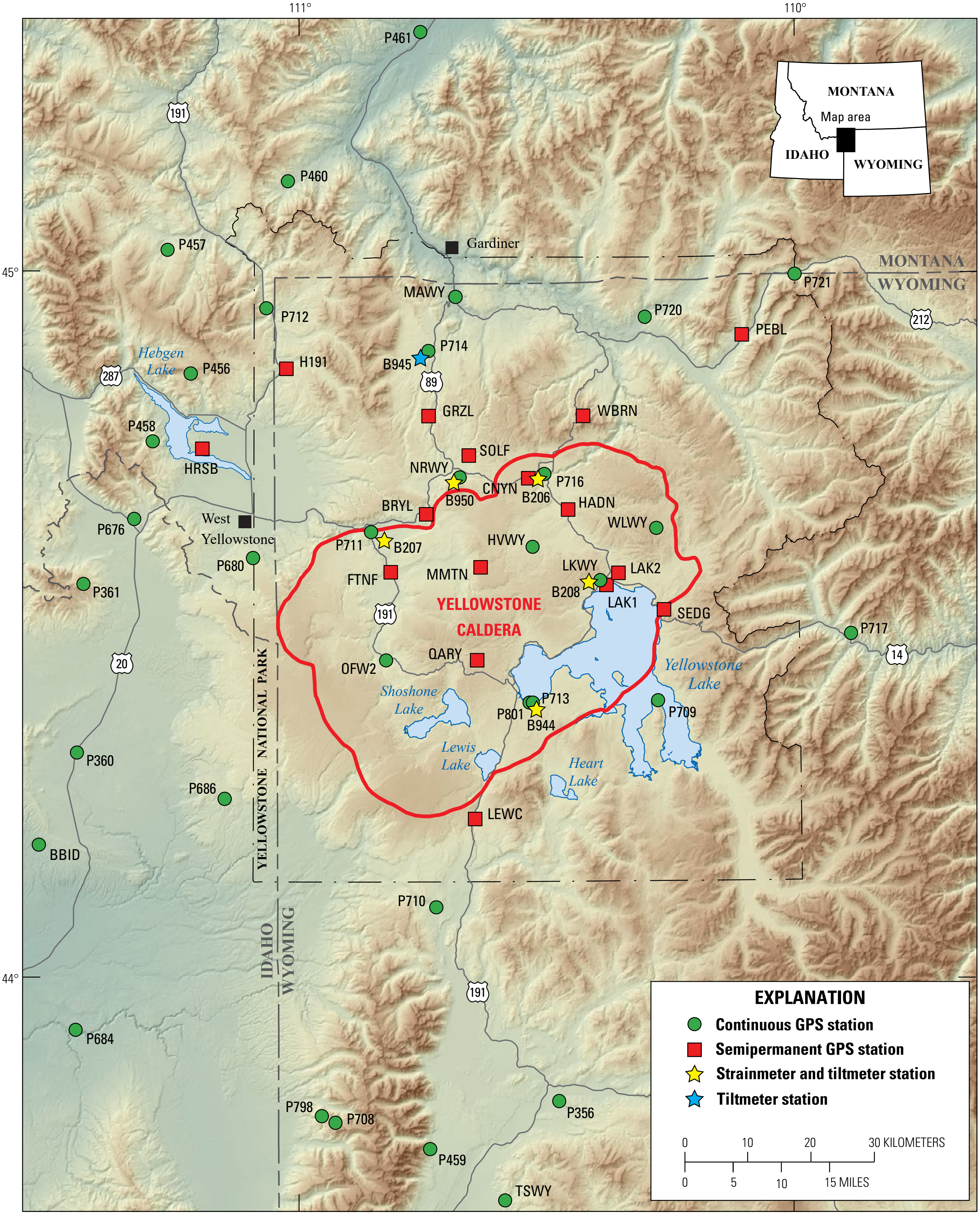


Figure 4. Map of seismic stations in the Yellowstone region operated by University of Utah Seismograph Stations (UUSS), with numbers of channels indicated by number and sensor type by color.



Base from 30-meter National Elevation Dataset

Figure 5. Map of continuous Global Positioning System (GPS), semipermanent GPS, borehole strainmeters, and borehole tiltmeters that provide surface deformation monitoring in and around Yellowstone National Park.

Real-time and on-site records of stream flow, conductivity (a proxy for chloride content and an indicator of thermal output from hydrothermal features), and meteorological data are collected by the USGS Water Science Centers in Montana, Wyoming, and Idaho, through the National Water Information System (NWIS), as well as by other agencies like the National Weather Service, National Park Service, Natural Resources Conservation Service, and National Ecological Observatory Network (fig. 6). Many of these data streams are available online and can be found at https://www.usgs.gov/volcanoes/yellowstone. YVO also operates a network of telemetered temperature sensors in selected thermal features of Norris Geyser Basin that supplements temperature monitoring conducted throughout the park by Yellowstone National Park geologists

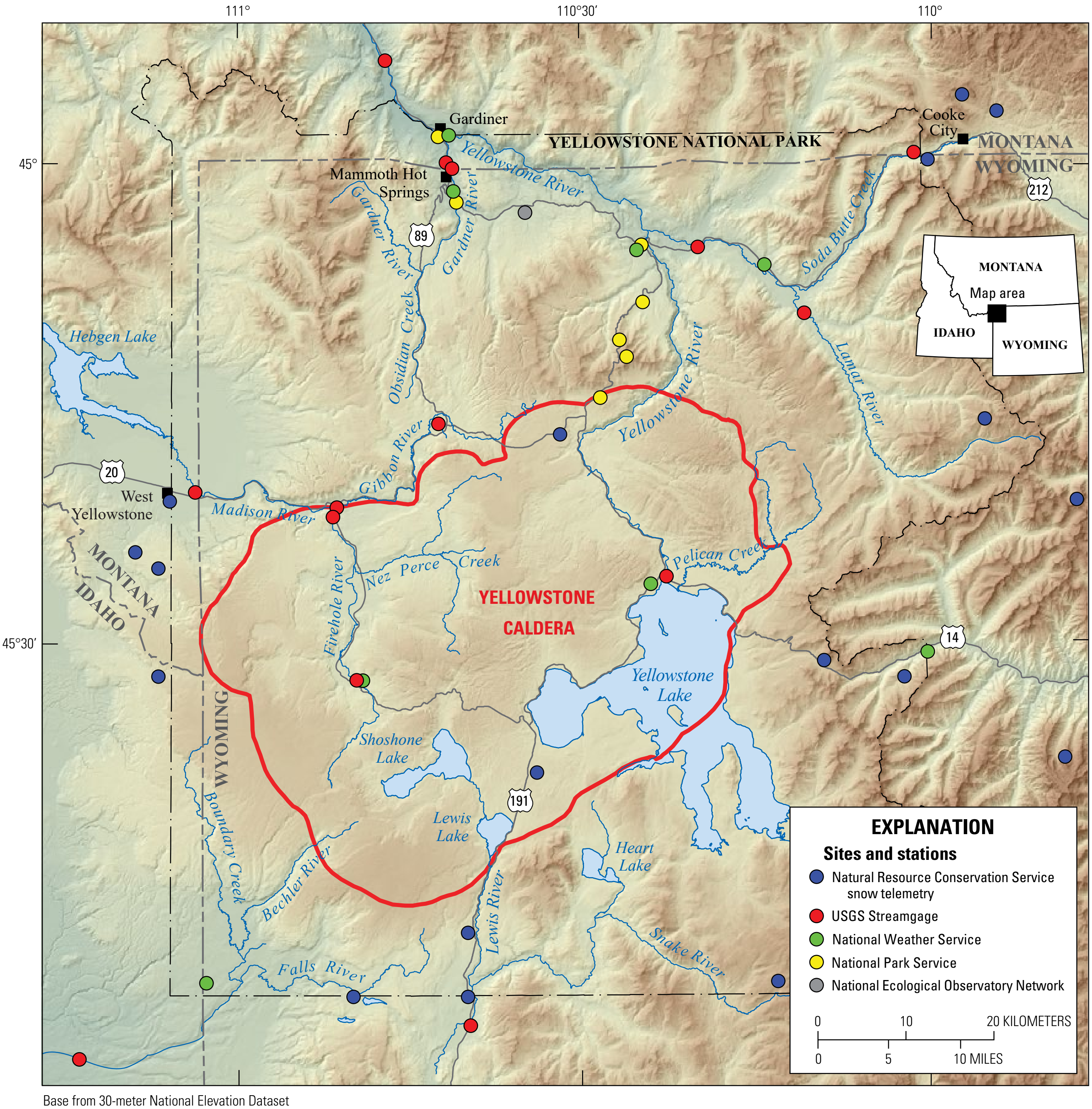
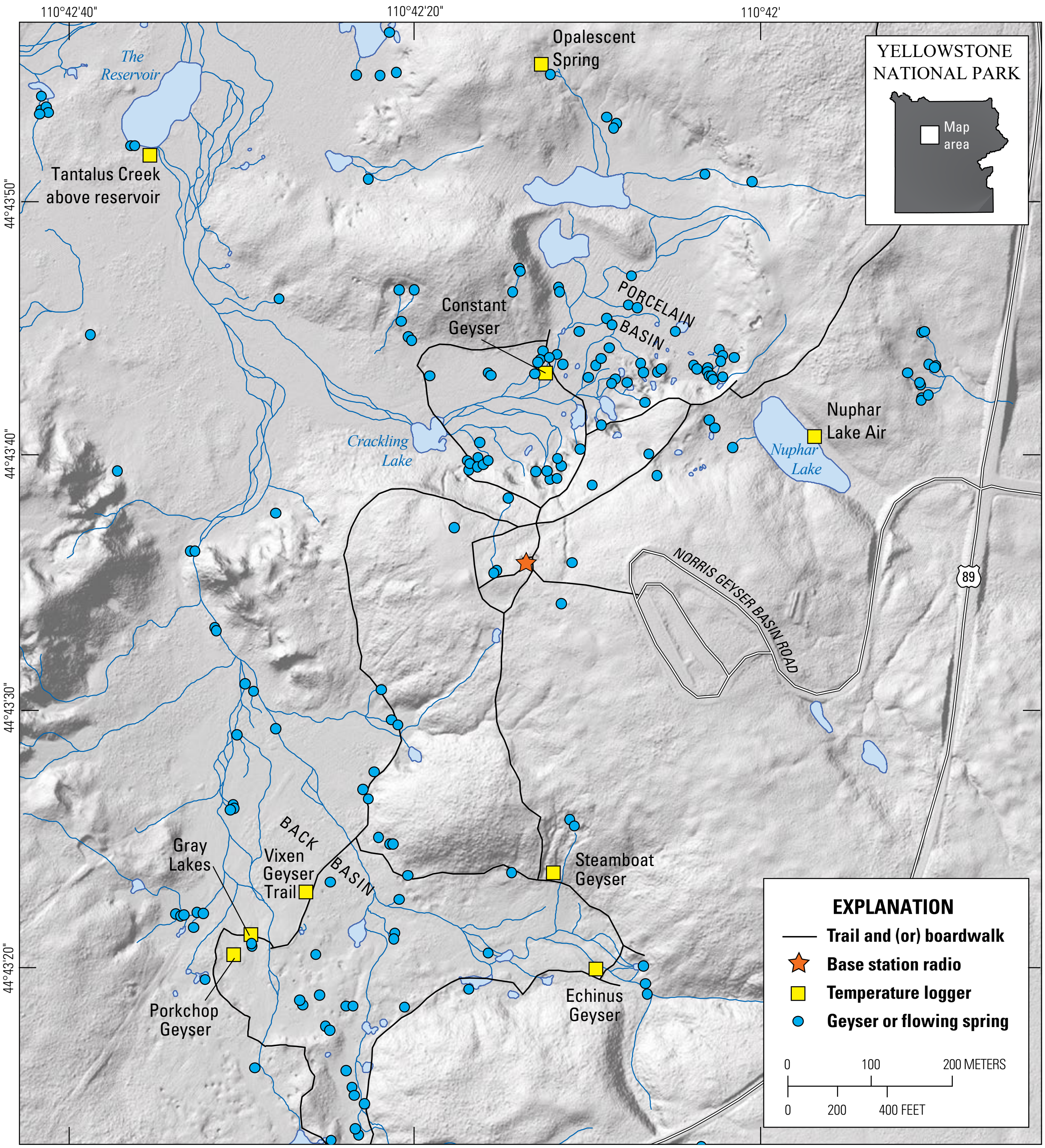


Figure 6. Map showing meteorological monitoring stations in and around Yellowstone National Park, including Natural Resources Conservation Service (NRCS) snow telemetry (SNOTEL) sites, National Park Service (NPS) sites, National Weather Service (NWS) sites, a National Ecological Observatory Network (NEON) station, and U.S. Geological Survey (USGS) streamgage stations.

(fig. 7). Continuous gas monitoring stations have been deployed for few-month to few-year periods in specific thermal areas in Yellowstone National Park, including Norris Geyser Basin (2016 and 2018–2020), Solfatara Plateau (2017), and Mud Volcano (since 2021), to track the emission rate and concentrations of gas species, including sulfur dioxide (SO_2; which has never been detected in Yellowstone National Park), carbon dioxide (CO_2), hydrogen sulfide (H_2S), and water vapor (H_2O).



Base from 2009 EarthScope 0.5-meter lidar data

Figure 7. Map of telemetered temperature measurement sites in Norris Geyser Basin.

Geological Observations

Hazard assessments are based on geologic mapping and a thorough understanding of regional geological history (for example, Christiansen and others, 2007). Although the Yellowstone National Park region has been systematically mapped (Christiansen and others, 2001), YVO geologists continue to refine our understanding of the Yellowstone region's geological history by determining the character, distribution, chemical composition, and ages of past eruptions. Geological observation also provides insights into the structure of the region, including the locations and styles of faults and how they relate to past eruptive vents. Comprehensive geological observations early and throughout the course of any prolonged activity, such as volcanic unrest, eruptions, or following large earthquakes or landslides, are critical for understanding hazards and how they can propagate and relate to each other. For example, alignment of ground cracks or new hydrothermal features might indicate the geometry of subsurface fluid pathways. These observations provide critical records of geological change and can be conducted by personnel on the ground or in aircraft, remote cameras and observation stations, and high-resolution satellite imagery.

Geochemical Sampling

Yellowstone Volcano Observatory and collaborating scientists have long utilized episodic survey-style sampling of waters and gases from thermal areas throughout the Yellowstone region to monitor variations in regional water and gas chemistry. Sampling surveys are typically repeated every 2–5 years at thermal areas with the highest potential hazard impact (based on patterns of past activity and public visitation) and as needed at other locations. Although some components of water and gas chemistry can also be determined using continuous and (or) remote measurements, direct sampling provides the most comprehensive assessment of how chemical and isotopic compositions change over time—vital information for monitoring variations in subsurface magmatic activity.

Remote Sensing

Remote data collection is a critical component of any monitoring approach during a response to unrest, especially in isolated or inaccessible areas of the Yellowstone region that lack ground-based monitoring. YVO uses a combination of aerial and satellite platforms that carry sensors capable of tracking thermal and gas emissions, ground deformation, and (or) changes in surface and vegetation characteristics. The spatial resolution of satellite data is often only capable of detecting broad changes; therefore, aerial measurements are often necessary to achieve the fine-scale monitoring data needed during any response to geological unrest.

Broad changes in thermal radiance are measured using satellite-based thermal infrared sensors, such as the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument on National Aeronautics and Space Administration (NASA) Terra satellite, the Thermal Infrared Sensor on Landsat 8, or the Thermal Infrared Sensor 2 on Landsat 9. High-resolution thermal infrared images can also be acquired using aerial platforms like helicopters, fixed-wing aircraft, or Unoccupied Aircraft Systems (UAS), operated with Yellowstone National Park oversight. Aerial imagery is vital for tracking the evolution of thermal features because the trends of these changes could provide important information about the state of the hydrothermal and magmatic systems. The combined utility of satellite and aerial thermal imagery was demonstrated by the discovery and exploration of a new thermal area near Tern Lake (Vaughan and others, 2020), first identified from satellite data but more fully investigated using thermal imagery acquired from helicopter (fig. 8). Without satellite imagery, the thermal area

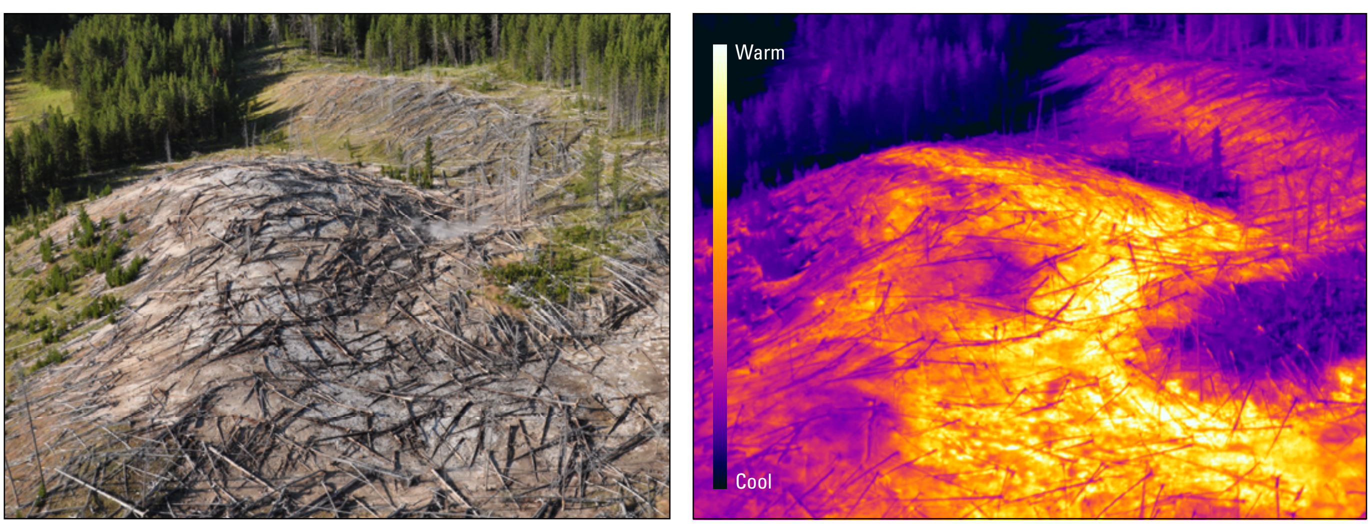


Figure 8. Aerial visible (left) and corresponding thermal (right) images of the new thermal area near Tern Lake (see figure 1 for location). U.S. Geological Survey photographs by Mike Poland (visible) and R. Greg Vaughan (thermal) August 19, 2019.

would not have been discovered, and airborne images were crucial for mapping the characteristics of this newly discovered thermal area and the overall thermal characteristics of the region.

Gas emissions can also be quantified using aerial and satellite data. Current satellite measurements are mostly restricted to SO_2 and require significant gas emission rates to be detectable (several hundred metric tons per day)—a condition that can occur when magma reaches within a few kilometers of the ground surface. Aerial platforms such as helicopters, fixed-wing aircraft, or UAS can detect smaller concentrations or fluxes of gases that include not just SO_2, but also species like CO_2, H_2O, and H_2S that are typically found in low-altitude plumes around the Yellowstone region. These measurements can be used to investigate early stages of unrest and assess the state of the magmatic and hydrothermal systems. Other satellite and aerial monitoring could use multispectral or hyperspectral imaging sensors to map vegetation stress or surface characteristics potentially indicative of changes in gas or thermal emissions that impact vegetation health.

Surface deformation data can be tracked using radar measurements from both satellite and airborne sensors. High-resolution satellite radar data, with pixel sizes of ~1 meter (m), are available for the Yellowstone region from several satellites but are only acquired when a satellite is overhead. Aerial systems are more flexible and can collect data where and when needed. Ground-based deformation measurements, like those provided by continuous GPS stations, remain an essential tool for year-round monitoring of surface displacements when radar measurements are not possible due to snow coverage.

Geological Unrest, Volcano Alert Levels and Aviation Color Codes, Information Products, and the Incident Command System

YVO responds to a variety of geological events that can signal unrest preceding a hydrothermal explosion or volcanic eruption, including large earthquakes, earthquake swarms, changes in thermal and geyser activity, significant surface deformation, and increased gas emissions. The nature and frequency of these hazards are discussed in USGS Open-File Report 2007–1071 (Christiansen and others, 2007) and USGS Fact Sheet 2005–3024 (Lowenstern and others, 2005). In conjunction with various collaborators and other parts of USGS, YVO also provides rapid response to other hazardous geological events like floods or earthquake-induced landslides as needed or requested.

Regardless of the nature of potentially hazardous geological events, strategic early communication helps to establish a clear and effective response. The first communication steps YVO takes during a response are initiating a pre-determined call-down list to alert partners, stakeholders, and decision makers of hazardous or potentially hazardous events, and then using the Hazard Alert Notification System (HANS) and Volcano Notification Service (VNS) to quickly disseminate critical information products to land managers, emergency responders, the media, and the public. HANS messages are compliant with the Common Alerting Protocol, an international standard for sharing emergency alerts and public warnings used by government agencies worldwide. Users who have registered to receive alerts via VNS—a public communications tool developed by the USGS Volcano Hazards Program—will automatically receive the HANS messages via email. Further response structures and actions will broadly follow the U.S. Geological Survey Volcano Science Center Response Plan for Significant Volcanic Events (Moran and others, 2024), modified as needed for specific application to the Yellowstone volcanic system and YVO's structure as a consortium (see "Responding to Hazardous Events and Activity with Potential in the Yellowstone Region" section).

Volcanic, Seismic, and Hydrothermal Unrest Classifications—Event and Activity with Potential

Geophysical and geological activity at Yellowstone may fall into one of two categories based on rate of onset and area of impact: "event" and "activity with potential." An event has a sudden onset and may have a wide area of actual or possible impact. An example of an event would be a strong earthquake, like the 1959 M_w 7.3 Hegben Lake earthquake, which caused at least 28 fatalities, was responsible for widespread damage both in Yellowstone National Park and the surrounding region, and had a strong impact on geyser and hydrothermal activity in the park. Activity with potential refers to geophysical or geological unrest with a gradual onset and (or) minimal initial impact. Although this style of activity does not constitute a sudden-onset hazardous event, it could escalate into unrest that requires a formal response from YVO. Activity with potential, like seismic swarms or thermal unrest that last for weeks to months with no clear acceleration or deceleration of activity and an uncertain outcome, may require installation of new monitoring equipment and focused study to assess possible future hazards. An example is the 2003 thermal activity at Norris Geyser Basin (see "Example Scenarios" section) that occurred over several months and involved the formation of new thermal features, changes in activity at existing geysers and hot springs, and increases in ground temperature in the southwest part of the basin, with some formerly cool areas reaching boiling temperatures just beneath the surface. Both an event and activity with potential will prompt regular communication between YVO member agencies, discussions with Yellowstone National Park management, and dissemination of information to the public. If warranted, information statements and (or) changes in the Volcano Alert Level or Aviation Color Code will be issued via the HANS system.

Notification System for Volcanic Activity

Notices and warnings of volcanic unrest and eruptions use an alert-level notification system implemented in 2006 by the USGS Volcano Hazards Program (Gardner and Guffanti, 2006; https://doi.org/10.3133/fs20063139). The alert-level notification consists of parallel warnings for two types of hazards: airborne ash and gas hazards affecting aviation, and ground-based hazards (see figure 9 for alert level classifications). Airborne hazard alerts are given by four Aviation Color Codes: Green, Yellow, Orange, and Red. Ground-based hazard status is indicated by four Volcano Alert Levels: Normal, Advisory, Watch, and Warning. Typically, the two four-stage alert levels are raised and lowered in parallel—Normal/Green, Advisory/Yellow, Watch/Orange, and Warning/Red. Flexibility is built in to the alert-level notification system, however, and the Volcano Alert Level of an ongoing eruption can remain Warning while the Aviation Color Code drops to Orange if a volcano poses a significant ground hazard (such as lava flows or lahars) but has no significant gas plume or ash cloud that could endanger aircraft. Since the alert-level notification system was adopted by YVO in 2006, the status of Yellowstone Caldera has remained Normal/Green.

Not all departures from baseline activity, which is defined by monitoring data, result in changes to the alert level. Some geological activity, such as large earthquakes, earthquake swarms, or small hydrothermal explosions (like that which occurred on July 23, 2024, at Biscuit Basin), would not necessarily cause a change in Volcano Alert Level or Aviation Color Code unless monitoring data indicated that those events were part of an ongoing process that could culminate in a volcanic eruption or major hydrothermal explosion. Furthermore, the Volcano Alert Level and Aviation Color Code may be raised to Advisory/Yellow following the detection of activity with potential and lowered back to Normal/Green if the observed activity is determined to not pose a hazard.

Volcano Alert Levels Used by USGS Volcano Observatories

Alert Levels are intended to inform people on the ground about a volcano's status and are issued in conjunction with the Aviation Color Code. Notifications are issued for both increasing and decreasing volcanic activity and are accompanied by text with details (as known) about the nature of the unrest or eruption and about potential or current hazards and likely outcomes.

Term	Description
NORMAL	Volcano is in typical background, noneruptive state **OR**, *after a change from a higher level,* volcanic activity has ceased and volcano has returned to noneruptive background state.
ADVISORY	Volcano is exhibiting signs of elevated unrest above known background level **OR**, *after a change from a higher level,* volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.
WATCH	Volcano is exhibiting heightened or escalating unrest with increased potential of eruption, timeframe uncertain, **OR** eruption is underway but poses limited hazards.
WARNING	Hazardous eruption is imminent, underway, or suspected.

Aviation Color Code Used by USGS Volcano Observatories

Color codes, which are in accordance with recommended International Civil Aviation Organization (ICAO) procedures, are intended to inform the aviation sector about a volcano's status and are issued in conjunction with an Alert Level. Notifications are issued for both increasing and decreasing volcanic activity and are accompanied by text with details (as known) about the nature of the unrest or eruption, especially in regard to ash-plume information and likely outcomes.

Color	Description
GREEN	Volcano is in typical background, noneruptive state **OR**, *after a change from a higher level,* volcanic activity has ceased and volcano has returned to noneruptive background state.
YELLOW	Volcano is exhibiting signs of elevated unrest above known background level **OR**, *after a change from a higher level,* volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.
ORANGE	Volcano is exhibiting heightened or escalating unrest with increased potential of eruption, timeframe uncertain, **OR** eruption is underway with no or minor volcanic-ash emissions [ash-plume height specified, if possible].
RED	Eruption is imminent with significant emission of volcanic ash into the atmosphere likely **OR** eruption is underway or suspected with significant emission of volcanic ash into the atmosphere [ash-plume height specified, if possible].

Figure 9. Charts showing the U.S. Geological Survey Volcano Hazards Program system for Volcano Alert Levels (ground hazards) and Aviation Color Codes (aviation hazards), adapted from Gardner and Guffanti (2006).

Information Products

Currently, YVO uses HANS to release a scheduled monthly status update and event-driven Information Statements through websites, social media platforms, and VNS. Scheduled monthly updates summarize seismicity, ground deformation, and other activity for the preceding month. An event-driven Information Statement is a formal public statement outside of the standard monthly summary updates and may contain descriptions of changes in monitoring systems, recent non-volcanic activity of note, or other information about the Yellowstone volcanic system. If volcanic activity or a very large hydrothermal explosion becomes likely or occurs, YVO may release two additional information products: the Volcano Activity Notice (VAN) and the Volcano Observatory Notice for Aviation (VONA), both of which are designed to communicate changes in volcano alert levels (see "Notification System for Volcanic Activity" section) or hazardous changes in volcanic activity when the alert levels are already elevated. All event-driven information products (table 1) are released electronically through HANS and automatically forwarded to a variety of government agencies, to the YVO and Volcano Hazards Program websites, and to collaborating agencies. The public and media can subscribe to VNS on the Volcano Hazards Program website (http://volcanoes.usgs.gov/vns/). A similar service is offered for earthquakes through the Earthquake Hazards Program (https://earthquake.usgs.gov/ens/). In addition to these official information products, a weekly educational essay called Caldera Chronicles, which often describes non-hazardous geological events and changes in seismic and hydrothermal activity, is available on the YVO website (at https://www.usgs.gov/volcanoes/yellowstone/caldera-chronicles), social media, local media outlets, and via an email subscription service. Three plausible scenarios and potential responses by YVO are outlined in the "Example Scenarios" section to demonstrate event responses and these information products in action.

Table 1. Information products available from the Yellowstone Volcano Observatory.

Time-driven products	Event-driven products
Monthly update	Information Statement
Daily update	Volcano Activity Notice (VAN)
Caldera Chronicles	Volcano Observatory Notice for Aviation (VONA)

Yellowstone Volcano Observatory and the Incident Command System

In the event of a volcanic eruption, large earthquake, or hydrothermal explosion where lives are at risk, infrastructure is threatened, and (or) access needs to be controlled, Yellowstone National Park may activate an Incident Response using the Incident Command System (ICS)—a standardized management system that allows emergency responders from different agencies to work together effectively. The response may be run entirely by park staff or as a collaboration of multiple organizations such as nearby counties, states, or federal land management agencies depending on the needs of the event. The ICS response would be structured using the framework of the National Incident Management System (NIMS) developed by the Federal Emergency Management Agency of the U.S. Department of Homeland Security (defined at http://www.fema.gov/national-incident-management-system). NIMS is a systematic, proactive approach designed to promote seamless collaboration between departments and agencies at all levels of government, nongovernmental organizations, and the private sector to manage incidents that involve threats and (or) hazards of any cause, size, location, or complexity, to reduce loss of life, destruction of property, and environmental harm.

During hazardous geological events in the Yellowstone region, when personnel and financial resources need coordination, an ICS can organize logistics (for example, establishing a temporary headquarters or procuring helicopter access), aiding YVO in its mission to provide timely hazards assessments to Yellowstone National Park managers and the public. The establishment of an ICS would also allow YVO to deliver information to a larger organizational structure intended to provide public safety, clear communication, transportation, and other critical needs. A schematic diagram of how the ICS may be organized and where YVO could provide input into such a system is found in figure 10. For example, the YVO SIC could provide information directly to ICS personnel, such as the incident commander and liaison officer; the YVO communications group could share information directly with the ICS public information officer; YVO staff serving in emergency operations centers could provide situational awareness of seismic and volcanic activity to the ICS Planning Section; and YVO aerial, facilities, and safety operations could align with corresponding ICS branches and officers. YVO would also act as an advisor on geological conditions, potential scenarios for future activity, and hazards assessment, mitigation, and monitoring, and can be consulted for information and expertise as needed by emergency managers and (or) emergency operations centers organized within the ICS.

Declaration by YVO of an "event" or "activity with potential" does not obligate Yellowstone National Park management to implement an ICS. It is also possible that Yellowstone National Park could implement an ICS without YVO declaring an official event response, as there are situations where geological and geophysical activity are unlikely to result in additional hazards—for example, a landslide that blocks road access, or a large earthquake without volcanic consequences.

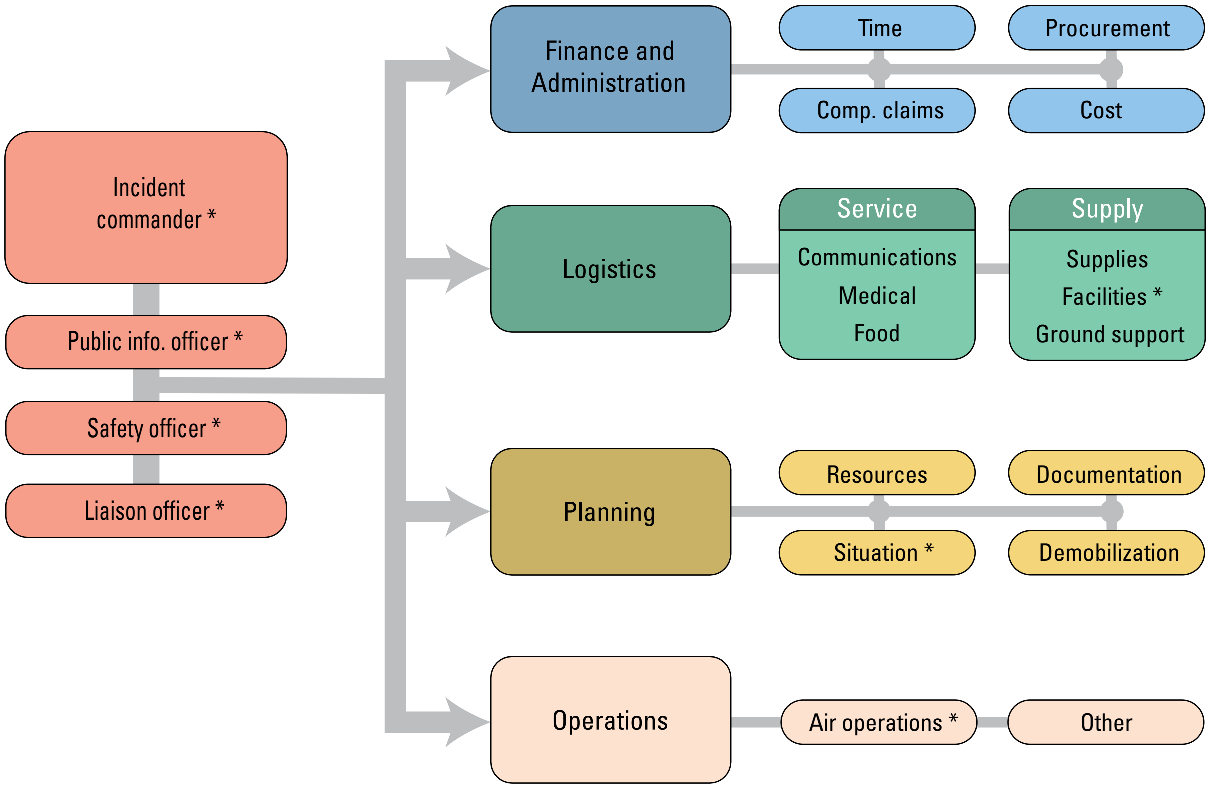


Figure 10. Hypothetical organization chart of an Incident Command System (ICS) during a response to a hydrothermal, seismic, or volcanic event in the Yellowstone region. Each section consists of multiple branches. ICS positions marked with an asterisk (*) indicate positions most likely to interact with the Yellowstone Volcano Observatory during a response. Info., information; comp., compensation.

Volcano Alert Notification Scheme and Decision Criteria

The Volcano Hazards Program criterion for changing the Volcano Alert Level and Aviation Color Code from Normal/Green to Advisory/Yellow is summarized by: “Volcano is exhibiting signs of elevated unrest above known background level” (Gardner and Guffanti, 2006). Assessing what constitutes both background and elevated unrest is subjective and requires consideration of both the type and intensity of activity, as well as the past behavior of the volcanic and hydrothermal systems. For example, earthquake swarms are considered part of the normal background level of activity at the Yellowstone volcanic system and are a result of regional tectonism, hydrothermal pressurization, and deep magmatic processes, all of which have occurred for thousands of years without an associated volcanic eruption. Additionally, similar activity that does not culminate in an eruption has been noted at other large caldera systems around the world, like Long Valley (California), Taupō (New Zealand), and Laguna del Maule (Chile).

The following five guidelines will inform the YVO response during future episodes of geological activity:

1. YVO may choose to declare a response to an event or activity with potential following the occurrence of a large earthquake, an intense earthquake swarm, an episode of rapid ground displacement, a significant hydrothermal explosion that generates a large crater (several tens to hundreds of meters in diameter), unusual gas emissions, or a pronounced increase in thermal or gas discharge.

2. A Volcano Alert Level change from Normal to Advisory (with accompanying change of Aviation Color Code from Green to Yellow) may be declared when monitoring parameters exceed normal background activity levels in the Yellowstone region. For example, the Volcano Alert Level would likely be raised to Advisory following an intense earthquake swarm (many thousands of earthquakes, several with M_w>4.5) accompanied by rapid ground displacement (such as >10 centimeters [4 inches; in]) over the course of a few weeks or a large hydrothermal explosion that is followed by elevated

seismicity, surface uplift, and (or) increased rates of gas and thermal emissions. In contrast, the Volcano Alert Level is unlikely to be raised to **Advisory** for a single large earthquake and its sequence of aftershocks without considerable associated ground displacement or hydrothermal explosions. Additionally, although the hydrothermal system normally releases abundant CO_2 and H_2S, it does not normally release high-temperature SO_2; therefore, any measurable flux of SO_2 (for example, tens to hundreds of metric tons per day) would merit serious consideration for raising the Volcano Alert Level. Subsequent increases in alert level to Watch/Orange and potentially and ultimately to Warning/Red would be based on the progression of unrest and interpretation of monitoring data.

3. An increase in Volcano Alert Level and Aviation Color Code from **Normal/Green** to a higher level will always trigger a formal event response by YVO, including HANS generated notifications, a formal call-down to directly inform partners and stakeholders (see "Communications Strategy" section), and enhancements to monitoring networks as needed.
4. Changes in Volcano Alert Level and Aviation Color Codes or declaration of an event response are the responsibility of the YVO SIC, in close consultation with YVO member agency leads. During a rapidly evolving event, full consultation with all YVO member agency leads may not be possible; therefore, communication will be between the SIC and YVO member agency leads and scientists who are available at the time.
5. Lowering of the Volcano Alert Level and Aviation Color Code will be at the discretion of the YVO SIC, in consultation with YVO member agency leads. The criteria for such a decision are variable depending on the nature of the unrest.

Responding to Hazardous Events and Activity with Potential in the Yellowstone Region

Part of the YVO response plan involves strategic organization and deployment of personnel and equipment to investigate ongoing activity and assess possible outcomes and impacts. The YVO response will follow the overall U.S. Geological Survey Volcano Science Center Response Plan for Significant Volcanic Events (Moran and others, 2024), modified to account for (1) the organizational structure of YVO as a consortium of nine federal, state, and academic institutions, and (2) the broad geographical extent of the Yellowstone volcanic system.

Organization of Yellowstone Volcano Observatory During an Event Response

The U.S. Geological Survey Volcano Science Center Response Plan for Significant Volcanic Events (Moran and others, 2024) provides a scalable approach for responding to volcanic unrest and eruptions in the United States. Any response to activity associated with the Yellowstone volcanic system will be led by the YVO SIC, assisted by the YVO Deputy Scientist-in-Charge (DSIC), and with an organizational structure that follows guidelines established by the VSC plan. The scalable nature of the VSC response plan allows elements of the plan to be activated as needed in response to the specific ongoing event or unrest. The main elements of the response plan include logistical support, hazards and forecasting, public information, science, monitoring, documentation and data management, and external science coordination (fig. 11). Leaders for each element will be designated by the SIC and DSIC, and positions within each element will be activated as needed. For example, if significant new monitoring infrastructure is installed, the monitoring lead will be assisted by teams dedicated to field instrumentation, 24/7 watch, and geophysical alarms, while the science lead may be aided by discipline experts in geology, seismology/infrasound, geodesy, gas and water chemistry, remote sensing, and hydrology. Some of these positions may be filled by experts from UUSS, Yellowstone National Park, and the state geological surveys of Idaho, Montana, and Wyoming, because these YVO member agencies have formal agreements to work with USGS on hazards responses. The University of Wyoming, Montana State University, and the EarthScope Consortium lack these formal agreements, but staff from these institutions could serve as members of response teams. The SIC, DSIC, and element leads, or their designees, will also provide input to an ICS (fig. 10) if one is established in response to the unrest or eruption. Roles and responsibilities for all positions are defined by Moran and others (2024). Specific responsibilities and delegation of authority will be further described by the SIC upon implementation of the response plan.

Need for Enhanced Monitoring

The Yellowstone volcanic system is monitored by a variety of geophysical, geochemical, and geological methods, ranging from continuous ground-based stations to a diverse suite of satellite imagery covering the entire region (see "Monitoring Strategy" section). The regional monitoring system provides excellent baseline coverage of seismicity and ground deformation throughout the Yellowstone region (Yellowstone Volcano Observatory, 2022), quantifies changes associated with seismic or hydrothermal events, and will detect any unrest preceding future volcanic activity.

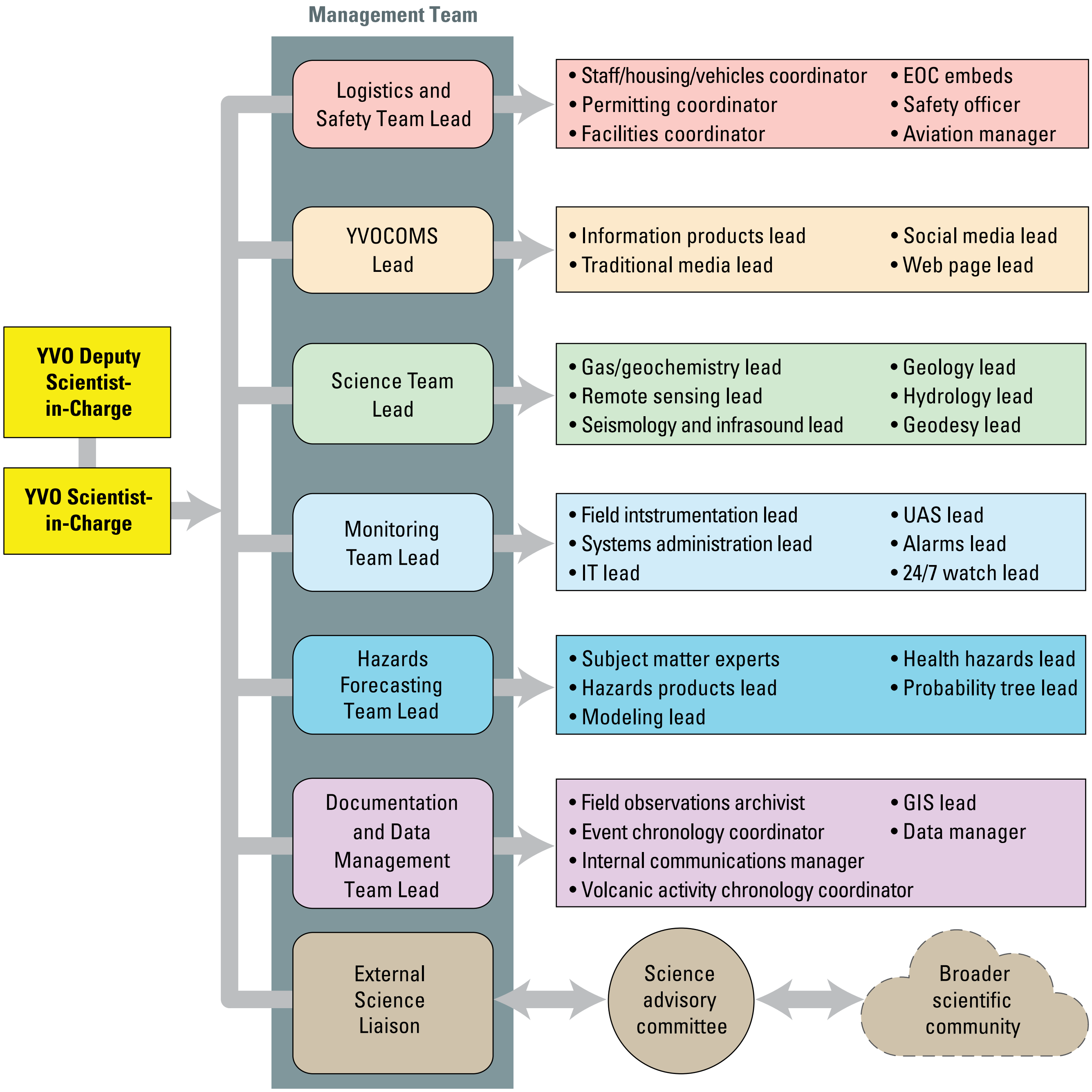


Figure 11. Organization chart giving the structure of a response by the Yellowstone Volcano Observatory to a significant episode of unrest or eruption at the Yellowstone volcanic system. The strategy is scalable and can be adapted to meet the needs of the event response. Chart follows the Observatory Volcanic Event Response Team structure in the U.S. Geological Survey Volcano Science Center Response Plan for Significant Volcanic Events (Moran and others, 2024). EOC, Emergency Operations Center; UAS, Unoccupied Aircraft Systems; YVO, Yellowstone Volcano Observatory; YVOCOMS, YVO communications group.

Following detection of unrest or the occurrence of a geological event, enhanced and targeted monitoring along with geological observations conducted throughout the unrest or event may be needed to aid hazard assessment and forecasts of future activity. Enhanced monitoring could require the installation of temporary ground-based equipment to better track anomalous activity. For example, deploying additional seismometers in response to seismic unrest can increase the ability to locate small earthquakes, allowing for a more thorough understanding of variations in rates of seismicity. Collection of water and gas samples from nearby thermal features may be necessary to assess changes in normal baseline activity and establish short-term baselines against which future samples could be compared. If anomalous gas or thermal emissions are evident, airborne observations systems (such as helicopters, fixed-wing aircraft, or UAS) can provide a means of determining their areal extent and emission rate (UAS operation requires special permission because UAS flights are typically not allowed in Yellowstone National Park). For example, following the July 23, 2024, hydrothermal explosion at Biscuit Basin, YVO scientists collected water samples and deployed ground-based infrasound, seismic, temperature, and electrical sensors to assess post-explosion behavior of the hydrothermal system in that area.

All research and monitoring operations in Yellowstone National Park are subject to review and approval by the park's Research Permitting Office and generally include a National Environmental Policy Act (NEPA) review to ensure that decisions made by Federal agencies are environmentally sound. If a hazardous or emergency situation exists, however, NEPA regulations allow for immediate actions to mitigate harm to life, property, and resources as long as efforts are made to minimize the environmental impacts of the response (see the National Park Service NEPA Handbook at https://www.nps.gov/subjects/nepa/upload/NPS_NEPAHandbook_Final_508.pdf, page 11, for more information). Any follow-up actions not needed to mitigate immediate harm to life, property, or resources—for example, post-event research efforts—would be subject to the normal NEPA process. Given that an event response may require additional data collection on short notice, YVO will work with the Yellowstone National Park Research Permitting Office and park managers to ensure that the environmental impact of the installation of new equipment, aerial surveys, and sampling is minimal.

Probabilistic Hazards Assessment

YVO published a preliminary geological hazards assessment in 2007 (Christiansen and others, 2007). This assessment evaluates overall hazard sources, their potential impacts, and their frequency (fig. 2). The greatest impact would be from a caldera-forming volcanic eruption, but such an event is also the least likely to occur. More likely events are strong earthquakes, like the 1959 M_w 7.3 Hebgen Lake earthquake just west of Yellowstone National Park, or a hydrothermal explosion caused by subsurface water flashing to steam without direct interaction with magma, like the July 23, 2024, hydrothermal explosion at Biscuit Basin. The most likely magmatic event is a small-magnitude and short-duration explosive eruption followed by lava flow, the most recent of which occurred about 70,000 years ago.

Upon the recognition of a geological event or activity with potential, YVO will conduct a more focused hazards assessment. The published assessment (Christiansen and others, 2007) provides a general background on the types of hazards that may occur in Yellowstone; however, each event or activity with potential will require a specific hazards assessment that accounts for the nature of activity and likely outcomes. The specific hazards assessments will be completed via initial communications with Yellowstone National Park managers as well as formal peer-reviewed reports that will describe current activity and address potential outcomes, hazards, and uncertainty. These reports will be shared with the public following the example of volcanic hazards analyses completed by the Hawaiian Volcano Observatory in response to specific events during 2017–2018 (Neal and Anderson, 2020).

A key component of a focused hazards assessment is a probabilistic analysis of the future course of the activity. This analysis is most often accomplished using an event tree approach (Newhall and Hoblitt, 2002; Newhall and Pallister, 2015). An event tree provides a framework for evaluating the relative likelihoods of possible outcomes of volcanic unrest within a stated time frame (fig. 12). The first branches of the tree highlight mutually exclusive options—for example, is the event driven by magma or not? Farther into the tree, non-mutually exclusive hazardous phenomena and areas of impact are considered. Each node of the tree is assigned a probability, ultimately allowing for the calculation of overall probabilities for specific outcomes. Probabilities can be assigned using a variety of methods, ranging from elicitation of expert volcanologists to the outputs of numerical hazard models (Poland and Anderson, 2020). When time is short, expert opinion offers the fastest way to populate an event tree; all available YVO scientists would be involved in such an exercise to ensure that the greatest possible range of experience and knowledge is represented. Detailed notes are captured during the event tree discussion to record the reasoning behind the probability assigned at each branch of the tree. The event tree exercise would be repeated as needed over the course of the volcanic unrest as more data are collected and as models are developed concerning potential hazards. The continued evaluation of the causes of the unrest and potential outcomes offers a means of continually refining the probabilistic assessment and providing emergency managers with Yellowstone National Park, the ICS, or other decision makers with up-to-date evaluations.

Engagement with Outside Scientists

The Yellowstone volcanic system is a premier natural laboratory for Earth science; as such, any geological event or activity with potential in Yellowstone National Park is likely to attract substantial research interest from academic groups in the United States and around the world. Scientific research in Yellowstone National Park is conducted under the supervision

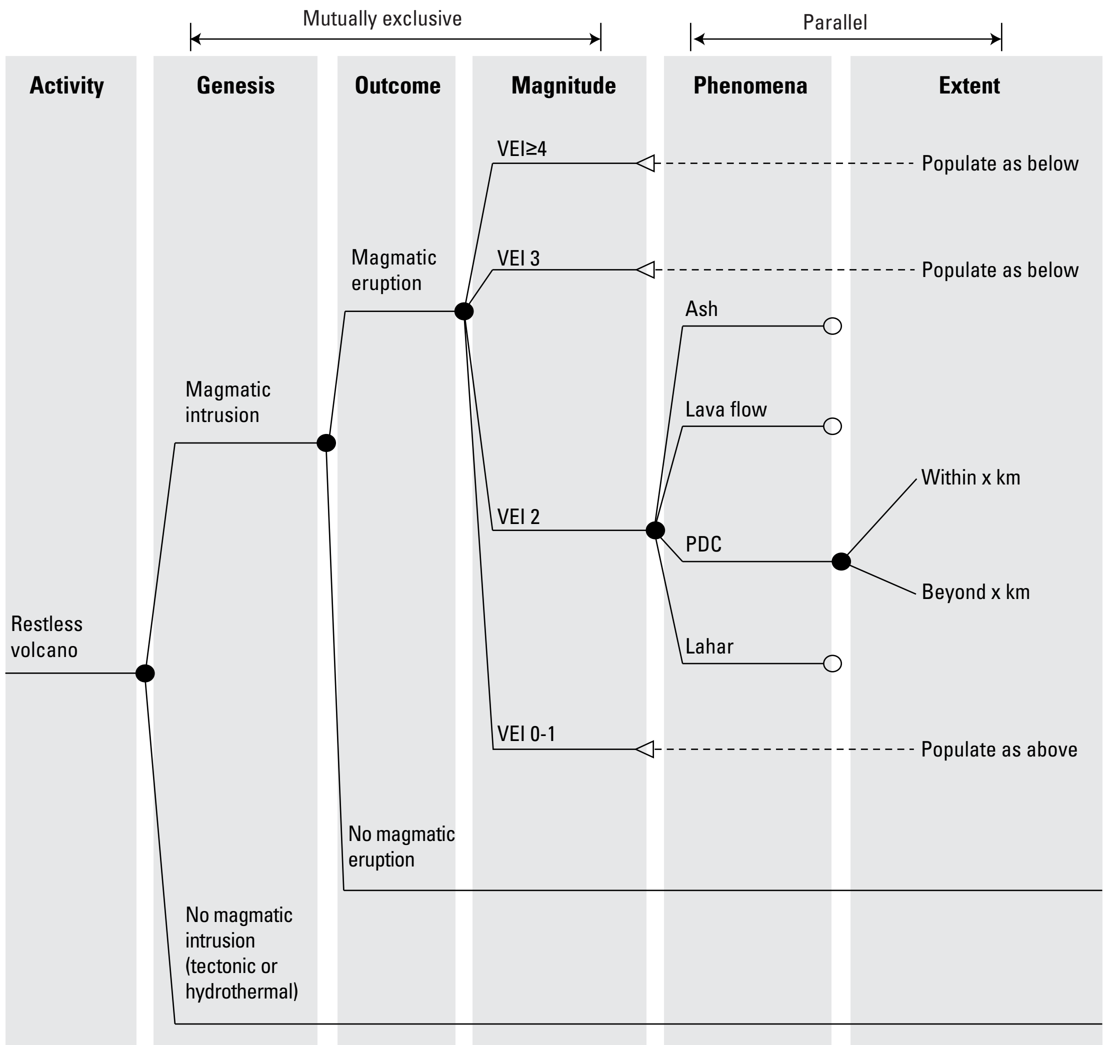


Figure 12. Event tree for use in responding to a volcanic crisis. Each branch (or node) in the tree is assigned a probability; multiplying these probabilities across the tree results in the probability of specific outcomes (in other words, that certain hazards will impact specific areas). The first several branches are mutually exclusive, while the branches dealing with eruption hazards are not. VEI, Volcanic Explosivity Index (Newhall and Self, 1982); PDC, pyroclastic density current. Adapted from Newhall and Hoblitt (2002), Wright and others (2018), and Poland and Anderson (2020).

of the park's Research Permitting Office; however, during a crisis the demand for research permits is likely to outweigh the response capabilities of the Research Permitting Office, especially if an ICS has been organized and the geological event or unrest poses hazardous conditions. Nonetheless, collection of scientific data is critical to ensure the best-possible information is available to researchers and decision makers. To assist with managing scientific access during a geological event or activity with potential, YVO would follow the general U.S. Geological Survey Volcano Science Center Response Plan for Significant Volcanic Events (Moran and others, 2024) by establishing a Scientific Advisory Committee (SAC; fig. 11). The YVO SIC is responsible for determining when a SAC is needed and for recruiting 4–5 scientists who are familiar with the Yellowstone region, the style of geological unrest, and with volcano monitoring and research to sit on the committee.

The SAC will ideally be chaired by a scientist from a YVO member agency and will include scientists and land managers not intimately involved with the event response to serve as impartial coordinators for diverse groups seeking to undertake fieldwork, deploy instrumentation, acquire data, or collect samples. The SAC will evaluate requests to conduct scientific work related to the event or unrest and will pass those evaluations to the YVO SIC and Yellowstone National Park Research Permitting Office, who will then provide a recommendation to the ICS team or Yellowstone National Park management, as appropriate, regarding potential support for the proposed work. The SAC is not intended to bar the work of non-YVO researchers from being considered; rather, the SAC provides a streamlined method for ensuring that efforts are not duplicated, the work would not interfere or burden ICS operations that are intended to save lives and ensure public safety, proposers are aware of any access restrictions or environmental and other factors that may inhibit their efforts, and research plans consider potentially hazardous conditions. The SAC provides a means of communication between YVO and academic scientists interested in doing research related to the event or unrest—especially important when the YVO SIC and Yellowstone National Park managers are not available for consultations. The SAC model was used successfully at Mount St. Helens in 1980 and by the Hawaiian Volcano Observatory and partners during eruptions of Kīlauea starting in 2020 (Fischer and others, 2021; Cooper and others, 2023). The approach has also been tested in virtual tabletop exercises, including simulations of eruptions at Mount Hood, Oregon (Fischer and others, 2021), and in the southwestern United States at the San Francisco Volcanic Field, Arizona (Lin and others, 2023).

Communications Strategy

Because YVO is a consortium of institutions, careful coordination among member agencies and emergency managers is required to provide consistent messaging during any response to geological unrest. Communication between YVO, the public, and other stakeholders like state and local governments, is likewise essential to ensure a good understanding of the unrest and any potential hazards.

Call Down and Related Communications Lists

Upon declaring an event response or activity with potential, or when announcing a change in the Volcano Alert Level or Aviation Color Code, YVO will conduct a formal call down, whereby staff will notify colleagues and stakeholders (for example Yellowstone National Park managers and National Weather Service Meteorological Watch and Weather Forecasting Offices) of the event or unrest through specific, scalable telecommunication schemes (fig. 13). Initial coordination will be held between the YVO SIC, DSIC, Chief Seismologist at the University of Utah, and Yellowstone Center for Resources Director or their designees to determine the appropriate scope of the call down. Call downs will not be uniform, but will differ according to the type and intensity of activity. For example, activity with potential might only involve notifications to key individuals, like the USGS Volcano Science Center Director and Volcano Hazards Program Coordinator, but not necessarily all the way to the Director of the USGS. Call downs also may initiate from staff at Yellowstone National Park to the SIC and Chief Seismologist if the activity of concern is not immediately detected by monitoring networks—for example, a hydrothermal explosion, like that which occurred at Biscuit Basin on July 23, 2024. In the event of an alert-level change, the full call down represented in figure 13 would be completed.

Concurrent with or shortly following the call down, most individuals on the call down list will be sent an automatic VNS-generated email or text message at the time of the Information Statement and (or) alert-level change and accompanying information products (VAN/VONA). In the current plan, Yellowstone National Park or the ICS staff (if in place) will contact state and local emergency managers, as well as relevant personnel within Yellowstone National Park. UUSS will be responsible for contacting managers of regional seismic networks and the EarthScope manager for the Network of the Americas. The SIC will be responsible for contacting the state geologists of Montana, Idaho, and Wyoming (which may be redundant if an ICS is already in place), as well as the VSC Director, who in turn notifies the Volcano Hazards Program coordinator and USGS leadership. In the event of an alert-level change, the DSIC would contact National Weather Service (NWS) meteorological watch and weather forecast offices, the Washington Volcanic Ash Advisory Center, Federal Aviation Administration offices, the Federal Emergency Management Agency regional office, and relevant YVO disciplinary experts. The YVO call down list will be revised as staff and response requirement changes occur and will be maintained by the YVO SIC and DSIC, and practice call downs will be held as needed to ensure phone numbers are accurate and staff are aware of their responsibilities.

Schedule of Official Updates During an Event Response

After a notable earthquake, earthquake swarm, hydrothermal explosion, or other geological event, YVO may choose to release a formal Information Statement (see “Information Products”) that provides details on the event, geological background, and possible outcomes. During an event response, the frequency of updates will be at the discretion of the YVO SIC. If an increase in Volcano Alert Level or Aviation Color Code occurs, YVO will release frequent (daily or more) updates as needed, depending on activity.

UUSS policy is to issue a press release after any earthquake greater than M_w 3.5 within the Yellowstone region (fig. 4), as well as after the onset of any significant earthquake swarm, especially those that attract public interest or include felt events. YVO then re-issues the press release as an Information Statement and may include additional content as it relates to potential volcanism or related hazards; however, YVO defers to the USGS NEIC and any regional earthquake network (for example, UUSS) for information specifically related to non-volcanic earthquake activity and would only issue HANS messages as needed to emphasize that the activity is not associated with volcanism.

YVO Provisional Calldown List

Used when changing a Volcano Alert Level / Aviation Color Code or declaring an event response

- YVO Scientist-in-Charge calls:
  - Volcano Science Center Director → Volcano Hazards Program Coordinator; USGS Executive Leadership; USGS Office of Communications
  - Wyo., Idaho, and Mont. State Geologists → Relevant State Government Offices (Governor, Homeland Security) NOTE: may be redundant to ICS lines of communication

- YVO Deputy Scientist-in-Charge calls (for alert level changes only):
  - Discipline experts as needed
  - NWS Meteorological Watch Office, Kansas City, Mo.
  - FAA Regional Office, Salt Lake City, Utah
  - NWS Weather Forecast Office, Riverton, Wyo.
  - NOAA Washington VAAC, Washington, D.C.
  - FEMA Region VIII contact, Denver, Colo.

- YVO Chief Seismologist (University of Utah) calls:
  - UUSS Director → UUSS Associate Director
  - UUSS Network Manager → Manager, Montana Seismic Network; Manager, INL Network
  - NEIC Director → NEIC 24/7 Watch Office Staff
  - EarthScope Network Manager for NOTA

- Yellowstone National Park Geologist / Yellowstone Center for Resources Director calls:
  - YNP Communications Center → Affected local communities
  - YNP Superintendent
  - YNP Deputy Superintendent
  - YNP Chief Ranger

Alerts also released through the VNS (http://volcanoes.usgs.gov/vns/) and YVO website activity page (https://www.usgs.gov/volcanoes/yellowstone/volcano-updates)

Figure 13. Simplified call-down list for the Yellowstone Volcano Observatory. Actual call-down list may differ from this example depending on the type and intensity of activity. DOI, Department of Interior; FAA, Federal Aviation Administration; FEMA, Federal Emergency Management Agency; ICS, Incident Command System; NEIC, National Earthquake Information Center; NOAA, National Oceanic and Atmospheric Administration; NWS, National Weather Service; USGS, U.S. Geological Survey; UUSS, University of Utah Seismograph Stations; VAAC, Volcanic Ash Advisory Center; VNS, Volcano Notification Service; YNP, Yellowstone National Park; YVO, Yellowstone Volcano Observatory.

Communications Among Yellowstone Volcano Observatory Member Agencies

To properly inform the public during a response to geological unrest in and around Yellowstone National Park, YVO member agencies will coordinate communication throughout the consortium to deliver a consistent message to stakeholders and the public. If an event response or activity with potential is declared, the agencies that make up YVO will designate an individual staff member to coordinate internal communication and who will also serve as the lead of the communications element in the response structure (fig. 11). This communications group, YVOCOMS, incorporates representatives from YVO member agencies (including Yellowstone National Park) and will meet regularly or as needed to develop talking points, ensure public and stakeholder awareness of hazards messages, and discuss the best means of disseminating information to the public in coordination with emergency managers and leadership of Yellowstone National Park. Up-to-date talking points will be distributed via email and an internal weblog system to all YVO member agencies for use in their communications with stakeholders and the public.

Internal communications will occur on a log system that provides a forum for discussion and interpretation of monitoring data during periods of both quiescence and unrest and will provide a searchable archive of data plots, observations, and discourse related to geological activity in the Yellowstone region. The internal log system ensures consistent information and that ideas can be shared, discussed, and vetted in an organized manner. The internal log system also contains a record of phenomena, ideas, and decision making in the aftermath of events and can be used by observatory staff to evaluate operational protocols (Pierson and others, 2013).

During an event response, access to the log system could be cumbersome, and numerous groups may be in the field collecting data and evaluating activity. To manage the influx of information, an online data distribution and communication system (for example, Mattermost or Slack, Microsoft Teams) may be utilized to ensure easy and rapid communication between response teams at different agencies. These types of communication proved advantageous during the 2018 response to eruptive activity at Kīlauea, Hawai‘i (Williams and others, 2020), and at the Alaska Volcano Observatory for all responses since 2016 (Coombs and others, 2018). Similar efforts were utilized during tabletop scenario exercises by the Cascades Volcano Observatory and Yellowstone Volcano Observatory (Lin and others, 2023).

Communications with the Public and Broader Stakeholder Community

In addition to official communications via VNS messages, such as Information Statements and VANs/VONAs (table 1), YVO is committed to providing information directly to the public using a wide range of tools during a geological event or activity with potential. All YVO member agencies operate social media channels, and YVOCOMS will ensure that data and information are posted regularly to these channels. Social media posts and website updates will include text, photographs, videos, and updates from scientists directly involved with monitoring and observational data. Videos will follow the format of the YVO monthly video updates, which discuss data collected by YVO and have been published on the YVO website, USGS YouTube channel and USGS volcanoes (@USGSVolcanoes) social media accounts at the beginning of every month since March 2019. Social media posts made to USGS volcanoes accounts and also the accounts of YVO member agencies will be based on YVO talking points and can be tailored to the specific audiences of each agency—for example, posts from the Wyoming State Geological Survey would focus on the impacts of the event or activity with potential as they pertain to Wyoming, specifically. Longer-format essays describing geological unrest and interpreting data can be published as part of the weekly “Caldera Chronicles” series (table 1), which has been a fixture of the YVO communications strategy since January 2018. The series has been widely reproduced online and by local, Yellowstone region news media. To best serve the information requests of the public, FAQs will be constructed and posted online to the YVO website and the websites of member agencies, and YVO scientists from all member agencies would be available for traditional media interviews (for example, radio, television, and the print media). Interview requests will be managed by the USGS Office of Communications and Publishing, which will collect requests and coordinate with YVOCOMS to ensure that each request is assigned to an appropriate YVO representative. Such an approach ensures that the YVO member agencies are well represented and that the range of expertise within the consortium is leveraged to the greatest extent possible.

Of particular importance during any response to a geological event or activity with potential will be direct communication with potentially impacted local communities. Community meetings were a vital form of direct communication during eruption crises at Kīlauea in Hawai‘i (Poland and others, 2016; Brantley and others, 2019; Williams and others, 2020) and will be utilized in the Yellowstone area to ensure open lines of communication between local communities and YVO. Although community meetings will be coordinated by YVOCOMS, the meetings themselves will be organized and led by the state geological surveys of Idaho, Montana, and Wyoming—the authoritative sources of geoscience information in each respective state. Community meetings may include participation by YVO scientists from member agencies and Yellowstone National Park management to add additional information, but the state geological surveys will coordinate communications in affected communities located outside Yellowstone National Park.

Example Scenarios

Four scenarios demonstrate how the YVO response plan will be used to guide an event response. The first scenario describes thermal unrest at Norris Geyser Basin in 2003. The second explores the response to a noteworthy geological event: the 2024 hydrothermal explosion at Biscuit Basin. The third is a hypothetical seismic sequence coupled with hydrothermal activity on the north side of Yellowstone Lake. The fourth scenario, also hypothetical, is based on the 2022 YVO tabletop exercise held in Mammoth Hot Springs, Yellowstone National Park, and details a progression of activity that culminates in a volcanic eruption.

Scenario 1—Thermal Unrest at Norris Geyser Basin in 2003

Thermal unrest at Norris Geyser Basin during 2003 occurred before earlier versions of the YVO response plan had been developed. That unrest provides an excellent example of what would now be designated as "activity with potential" and that would motivate a response from YVO but that would not involve implementation of the ICS nor changes in volcano alert level.

Description of 2003 Norris Geyser Basin Thermal Unrest and Yellowstone Volcano Observatory Response

In spring–summer 2003, a series of anomalous changes around Norris Geyser Basin were noted, including the formation of new thermal features, the first eruptions of Porkchop Geyser since 1989, vegetation die off, and an increase in near-surface ground temperatures to near boiling in areas that had previously been cool. In response to these changes, Yellowstone National Park closed the Back Basin area of Norris Geyser Basin to public visitation. Because there was no imminent threat to life or property nor evidence that the unrest would lead to a hazardous geological event (as determined by USGS and UUSS scientists who responded to the activity), the park did not implement an ICS. According to response plan outlined in this report, the sequence of changes in the Norris Geyser Basin area in 2003 would qualify as "activity with potential" given the small possibility of it culminating in a hydrothermal event, like a minor steam explosion that could pose a hazard to anyone nearby.

YVO responded to the 2003 unrest at Norris Geyser Basin with rapid and temporary deployments of 7 broadband seismometers, 5 GPS stations, and a network of temperature dataloggers to track changes in specific thermal features (Farrell and others, 2003; Lowenstern and others, 2003). At the time of the unrest, the YVO consortium consisted of USGS, Yellowstone National Park, and UUSS. All three organizations collaborated on data collection and interpretation and were in frequent contact. Results and interpretations developed by YVO were communicated to Yellowstone National Park managers to aid in understanding the current activity and its likely future course as a basis for decision making. The activity ultimately stabilized, and Yellowstone National Park reopened portions of the Back Basin area in October 2003. Some of the boardwalks were rerouted to avoid new areas of thermal ground and ensure visitor safety; those areas reopened to visitors in 2004.

Differences Between the 2003 Response and a Potential Present-Day Response

The response to the 2003 Norris Geyser Basin thermal unrest generally followed the plan as outlined in this report, with YVO member agencies collaborating with Yellowstone National Park managers to enhance monitoring in support of hazards assessment. The work of YVO member agencies was highly coordinated to deliver information to park managers and support their decision making. If the 2003 Norris Geyser Basin thermal unrest was to happen today, the response would be modified in two ways. First, the YVO consortium now includes more organizations, so internal communications would require more attention, even if not all YVO member agencies are involved in the response (given the localized nature of the activity). Second, because social media was less prevalent than traditional media in 2003, a greater emphasis would be placed on public communications, and the YVOCOMS group would be implemented. YVOCOMS would ensure that all consortium members and collaborators had up-to-date talking points, coordinate media and public outreach, post official updates, and actively share information and videos on the social media accounts of member agencies. The unrest would be the subject of regular Caldera Chronicles articles, and updates could be provided during in-person, interagency community meetings in places like Gardiner, Montana, and West Yellowstone, Montana—the two towns closest to Norris Geyser Basin.

YVO would implement the response structure outlined in figure 11, which follows the U.S. Geological Survey Volcano Science Center Response Plan for Significant Volcanic Events (Moran and others, 2024), but staffing would be limited because the minor nature of the unrest would not require a fully staffed response. An example of the roles that might be designated, and the YVO consortium institutions that might fill those roles is given in figure 14. In this scenario, the support element would not be staffed because the minor nature of the unrest would not require those positions, whereas public communications would be critical, and that element would be fully staffed and led by the YVOCOMS director. The science element would also be fully staffed because scientific studies would be critical in understanding the nature of the unrest and its potential future evolution. A monitoring lead would be designated and given the responsibility of overseeing any expansion of monitoring capabilities. The hazards forecasting lead would be supported by experts in probability trees (to provide information on the potential outcome to the unrest), health hazards (to determine

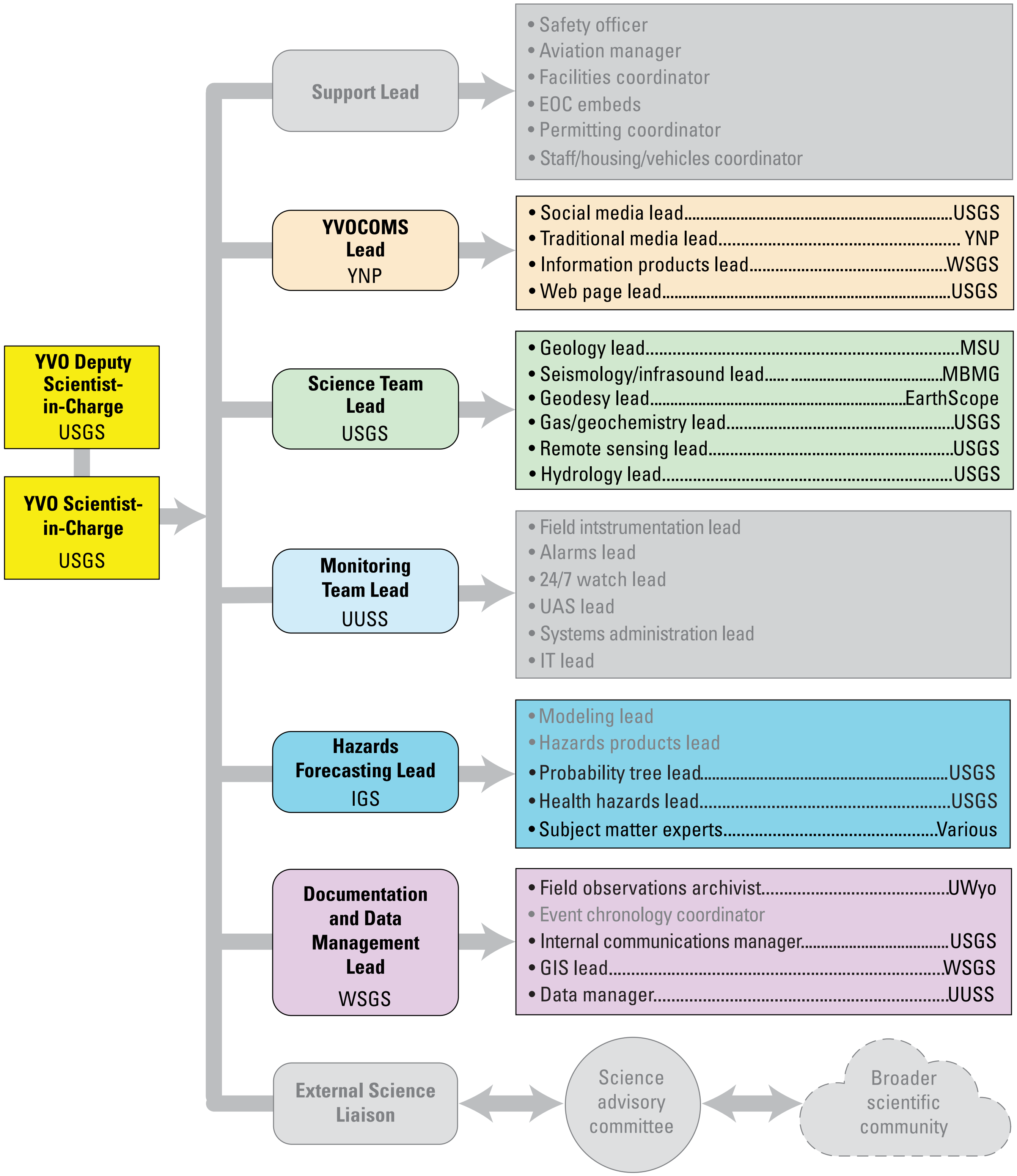


Figure 14. Hypothetical organization chart giving the possible structure of a response by the Yellowstone Volcano Observatory to the 2003 thermal unrest at Norris Geyser Basin were that to have occurred when the response plan described in this document was in place. Elements of the response that would not be implemented are in gray, and YVO agencies are associated with the roles they might play in the response. EOC, Emergency Operations Center; UAS, Unoccupied Aircraft Systems; USGS, U.S. Geological Survey; YNP, Yellowstone National Park, UUSS, University of Utah Seismograph Stations; IGS, Idaho Geological Survey; WSGS, Wyoming State Geological Survey; MBMG, Montana Bureau of Mines and Geology; UWyo, University of Wyoming; MSU, Montana State University. Chart follows the Observatory Volcanic Event Response Team structure in the U.S. Geological Survey Volcano Science Center Response Plan for Significant Volcanic Events (Moran and others, 2024).

the health impacts on both the public and responding scientists and officials), and subject matter experts as needed. The documentation and data lead would be supported by staff to archive field observations, oversee internal communications, lead GIS, and manage data, but a chronology coordinator would probably not be necessary. The minor nature of the unrest would probably not require an external science liaison, but that element of the plan could be activated if Yellowstone National Park received numerous proposals for new data collection and science and requested YVO input to facilitate work by non-YVO scientists.

Scenario 2—Hydrothermal Explosion at Biscuit Basin in 2024

The 2024 hydrothermal explosion at Biscuit Basin occurred while this response plan was being revised and provided an opportunity to test its implementation on a limited scale. The explosion also demonstrated a complication to any response to activity in Yellowstone National Park—that the SIC will not necessarily be among the first YVO scientists to know about the event. Parts of the call-down notification may therefore need to happen in reverse, with park staff informing YVO scientists of a geological event. Although it was broadcast widely thanks to spectacular videos posted on social media, the explosion was relatively small, and Yellowstone National Park did not initiate an ICS because there were no injuries and no major impact on infrastructure outside the immediate area. YVO still engaged in a limited response to address media requests, better understand the source of the explosion, and assess the potential for future hazardous activity.

Description and Chronology of 2024 Biscuit Basin Explosion

The Biscuit Basin hydrothermal explosion took place on July 23, 2024, at 9:53 a.m. MDT from Black Diamond Pool, located about 3.5 km (2.15 mi) northwest of Old Faithful Geyser in the Upper Geyser Basin of Yellowstone National Park. There were no recognized precursors, and the explosion, which reached several hundred feet in height, sent more than a dozen park visitors scrambling for safety. The only damage was to a boardwalk that was destroyed by rocks ejected during the explosion. The first reports of the explosion were communicated to the Yellowstone National Park dispatch office by 9:56 a.m. MDT, and park staff that responded to the call immediately closed Biscuit Basin to visitors to assess damage and hazards.

The Yellowstone National Park geologist was notified by park staff soon after the explosion, and he communicated the limited information that was available at that time—that a hydrothermal explosion had occurred—to the YVO SIC and Chief Seismologist. Shortly before noon MDT, social media posts attracted attention, resulting in numerous media requests for interviews. USGS and Yellowstone National Park staff coordinated public communication efforts via Microsoft Teams channels, and the USGS Office of Communications and Publishing logged interview requests so that YVO scientists could respond efficiently. YVO developed talking points and used HANS to issue an Information Statement at 1:24 p.m. MDT that was also delivered to VNS subscribers. An informational video explaining the causes and consequences of the hydrothermal explosion was produced and posted to the YVO website and social media channels the following day, along with a second Information Statement that summarized the activity and aftermath and that emphasized there was no continued hazard.

Enacting the Yellowstone Volcano Observatory Response Plan

Because the Biscuit Basin explosion impacted a limited area and did not involve any subsequent activity or hazards, YVO did not declare an event nor activity with potential, and there was no change in the Alert Level or Aviation Color Code. Nevertheless, once the importance of the explosion became apparent from videos circulating on social media, a limited call down was completed to alert USGS managers. Only a few elements of the YVO response plan were activated (fig. 15). Much of the immediate need involved responding to media requests and providing information to the public, therefore the YVOCOMS component of the response plan was almost fully staffed, with USGS employees organized to help with traditional media requests, post to social media and answer questions, and develop information products like videos and talking points.

A science team was assembled to conduct research into the mechanism of the explosion, record subsequent activity, and test new tools for tracking potentially hazardous changes in hydrothermal activity. Within hours of the explosion, geologists from Yellowstone National Park and collaborating institutions were on site assessing activity, and by the following day a team that included geologists from multiple institutions began several days of work that included mapping explosion deposits, deploying sensors, and collecting water samples. Documentation and data management were largely done by the YVO SIC using the internal logs system.

The 2024 Biscuit Basin explosion provided a test of the YVO response plan with a real geological event that fortunately did not cause any injuries, and it demonstrated how unforeseen challenges can complicate any event response. For example, the Yellowstone National Park geologist, who is the primary liaison between YVO and park management, was on travel at the time of the explosion, so that line of communication was limited for several hours following the event. Consequently, YVO broadened interactions with park staff to ensure there are always multiple lines of communication available—especially important when the first calls related to an event response have to come from Yellowstone National Park to YVO scientists. In addition, a major email outage occurred on that day across the Department of the Interior, including both USGS and Yellowstone National Park. Some email messages were not delivered until up to 24 hours after

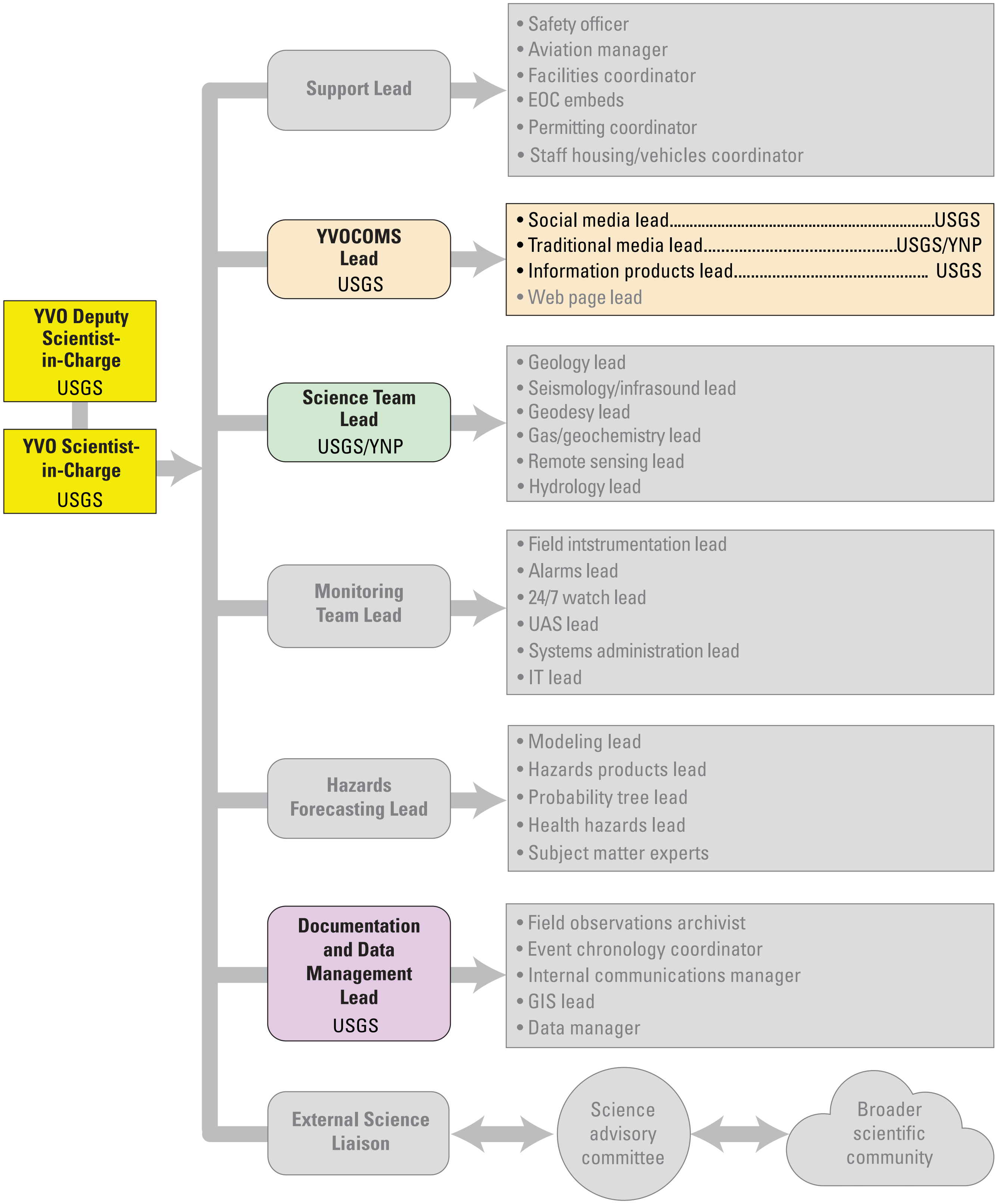


Figure 15. Organization chart giving the structure of the response by the Yellowstone Volcano Observatory (YVO) to the 2024 hydrothermal explosion at Biscuit Basin. Elements of the response that were not implemented are in gray, and YVO agencies are associated with the roles they played in the response. Chart follows the Observatory Volcanic Event Response Team structure in the U.S. Geological Survey Volcano Science Center Response Plan for Significant Volcanic Events (Moran and others, 2024). EOC, Emergency Operations Center; UAS, Unoccupied Aircraft Systems; USGS, U.S. Geological Survey; YNP, Yellowstone National Park.

being sent; thus, many YVO scientists from partner institutions did not receive the talking points or formal communications until a day after the event had occurred. Such an unanticipated problem demonstrates the need for multiple independent lines of contact—for example, use of alternate communications tools (as outlined in the section "Communications Among Yellowstone Volcano Observatory Member Agencies"). These lessons were integrated into this response plan.

Scenario 3—Hypothetical Seismicity, Deformation, Gas Emissions, and Hydrothermal Explosions

In this hypothetical scenario, four M_w 5–6 earthquakes occur on the north side of Yellowstone Lake during a six-hour period, with hundreds of smaller events occurring over the hours and days that follow. Landslides of varying severity impact several roads in the area, creating access problems to Lake Village and Fishing Bridge, and fully blocking the East Entrance Road. Yellowstone National Park initiates an ICS to help manage transportation around the affected area, restore infrastructure, and assist park visitors. YVO initiates an event response, and the SIC and DSIC begin to develop the staffing organizational chart that will guide the response (fig. 11) and provide scientific expertise on the seismicity and its likely future evolution to the ICS, if needed. UUSS issues a press release about the seismicity, which YVO expands upon and shares in an Information Statement.

The following day, strainmeter and tiltmeter data from a site near Lake Village indicate local deformation, and high-rate GPS data from a collocated station indicate the possibility of deformation on the order of several centimeters (a few inches), although high noise levels make the interpretation uncertain. Small hydrothermal explosions occur from both new and existing features in the Mud Volcano area. The largest resulting crater is 20 m (66 feet [ft]) in diameter. Increases in the flux of H_2S and CO_2 are detected by the continuous gas monitoring station at the Obsidian Pool area of Mud Volcano, but no SO_2 is detected. In response to the seismicity, hydrothermal explosions, potential deformation, and changes in gas emissions, the YVO SIC convenes a meeting to consult with the leads of the YVO member agencies. After this meeting, the decision is made by the YVO SIC to change the Volcano Alert Level and Aviation Color Code for the Yellowstone volcanic system to Advisory and Yellow, respectively. A call down is completed and a VAN/VONA is issued by the YVO SIC. The YVOCOMS group is organized, drafts talking points, and begins releasing information through social media channels and web sites, while also working with the USGS Office of Communications and Publishing to respond to requests for media interviews. YVO scientists participate in press conferences organized by the ICS to pass information directly to the public. The VSC response plan is activated, with the YVO SIC appointing specific YVO member-agency scientists to lead specific elements of the response. The YVO SIC also appoints a SAC to provide input regarding requests from non-YVO scientists and agencies to conduct research related to the unrest. The majority of the response elements are eventually filled, drawing on the expertise of the YVO member institutions to ensure both responding scientists and the ICS have the logistical support they need, communications are well coordinated, scientific data are collected and analyzed, monitoring data are expanded and utilized in alarms and in any 24/7 watches, hazards forecasts are completed and shared with the ICS, Yellowstone National Park, and the public, and that all activity, observations, and data are documented (fig. 16).

In the days that follow, low-level seismicity and deformation continue, as do heightened levels of H_2S and CO_2 emissions, but no other major changes are detected. YVO works with Yellowstone National Park to install new monitoring equipment in the area around Mud Volcano and the north side of Yellowstone Lake, including telemetered GPS, seismic, and gas monitoring stations. The stations are located to minimize environmental and resource impacts without sacrificing monitoring utility and scientific accuracy. Data are shared openly to ensure non-YVO scientists and the public can view the results, and new and existing datasets are used to design alarms that notify of sudden anomalous changes and feed into the 24/7 monitoring operated by the USGS NEIC in Golden, Colorado. In addition, geochemists collect water and gas samples from hydrothermal features in the region and Yellowstone National Park managers evaluate the YVO request to conduct a UAS survey of gas and thermal emissions. The SAC provides feedback on proposals to study the unrest from non-YVO scientists, and some proposals result in new research and monitoring efforts in the area—efforts that will help inform the hazards response and gather critical scientific data for use in understanding the causes of the unrest. Scientists within the YVO consortium meet daily (online and in person) to discuss activity and monitoring data. A group of scientists focused on hazards forecasting also meets to develop an event tree and assign probabilities of specific outcomes and impacts—information that is communicated to managers and emergency response officials within the ICS and Yellowstone National Park. Daily updates of activity are issued by YVO, and YVOCOMS coordinates frequent social media posts and traditional media interviews to provide a steady stream of information to the public. The state geological surveys of Montana, Idaho, and Wyoming organize community meetings in towns bordering or near Yellowstone National Park in their respective states, drawing on YVO scientific expertise as needed.

Activity gradually diminishes over the following weeks (indicated by the densified monitoring network on the north side of Yellowstone Lake). Elements of the response plan stand down as they are no longer needed and the ICS, if it is still in place, no longer requires specific input from those decommissioned elements of the response. When seismicity and gas emissions return to background levels and deformation is no longer detected, the YVO SIC convenes the member agency leads to discuss returning to Normal Volcano Alert Level and Green Aviation Color Code. Once the alert-level change is made, the frequency of formal YVO updates diminishes to monthly or as needed. Equipment installed in sensitive areas as part of the response is removed, and any new requests for monitoring instrumentation, field work, and maintenance of newly installed equipment are evaluated by the Yellowstone National Park Research Permitting Office and subject to the usual NEPA review.

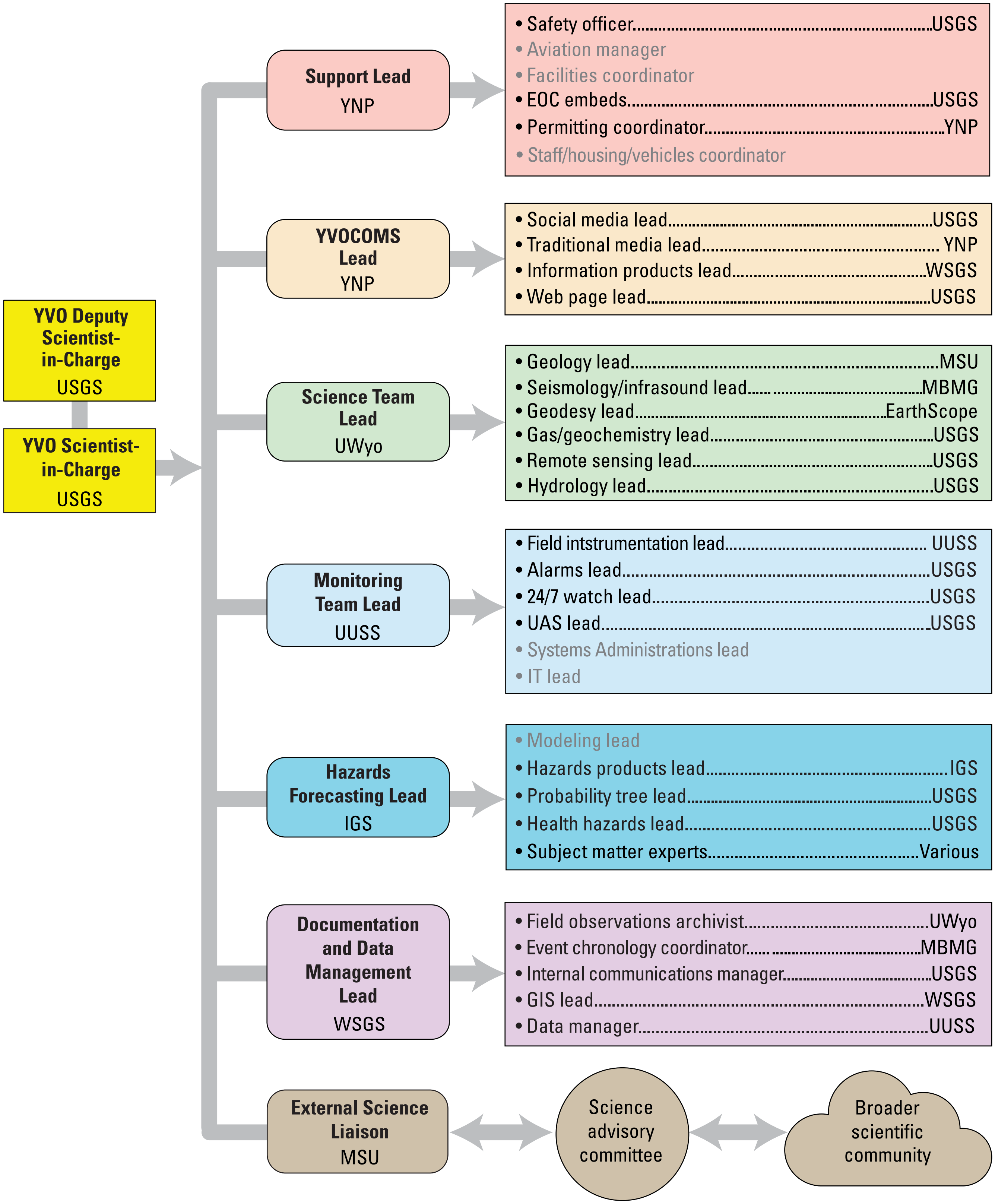


Figure 16. Organization chart giving the possible structure of a response by the Yellowstone Volcano Observatory to hypothetical hydrothermal and seismic unrest in the Mud Volcano area. Elements of the response that would not be implemented are in gray, and YVO agencies are associated with the roles they might play in the response. EOC, Emergency Operations Center; UAS, Unoccupied Aircraft Systems; USGS, U.S. Geological Survey; YNP, Yellowstone National Park, UUSS, University of Utah Seismograph Stations; IGS, Idaho Geological Survey; WSGS, Wyoming State Geological Survey; MBMG, Montana Bureau of Mines and Geology; UWyo, University of Wyoming; MSU, Montana State University. Chart follows the Observatory Volcanic Event Response Team structure in the U.S. Geological Survey Volcano Science Center Response Plan for Significant Volcanic Events (Moran and others, 2024).

Scenario 4—Hypothetical Unrest Culminating in a Volcanic Eruption

This hypothetical scenario begins slowly, with types of unrest commonly observed in the Yellowstone region. An earthquake swarm consisting of dozens of events, maximum M_w 4.3, starts in mid-January at a few kilometers (miles) depth near Obsidian Cliff, between Norris Geyser Basin and Mammoth Hot Springs. In response to the felt earthquake, UUSS issues a press release providing contextual information about the earthquake and its effects, and YVO expands upon and shares the press release in an Information Statement. In late January, with the earthquakes continuing, Yellowstone National Park rangers discover six dead bison in a low-lying area of a meadow along the Mammoth-Norris highway. The bison show no signs of trauma, and the deaths occurred during a period of unusually calm winds, leading Yellowstone National Park biologists and YVO to conclude that they were killed by accumulation of CO_2 gas. These sorts of deaths have occurred previously in Yellowstone National Park, most recently in 2004 near Norris Geyser Basin (Christiansen and others, 2007). After a call among YVO partner agency leads, USGS scientists are dispatched on snowmobiles to measure gas emissions at Roaring Mountain, a few miles south of Obsidian Cliff. The scientists find elevated CO_2 concentrations compared to previous measurements in the same area, but similar to measurements obtained over time from features in Norris Geyser Basin.

The swarm intensifies in early March, with a M_w 5.5 earthquake accompanied by the first eruption of Semi-Centennial Geyser, near Roaring Mountain, in more than a century. In addition, some springs are flowing stronger than usual, and several streams in the area are running abnormally high. GPS stations near Mammoth Hot Springs and Norris Geyser Basin are showing some deviations from their normal trends, although the deviations are close to the level of uncertainty. There are no GPS stations in the immediate vicinity of the seismicity. The M_w 5.5 earthquake prompts another UUSS press release; the accompanying YVO Information Statement details the bison deaths, gas measurements, and possible ground deformation. After another phone call among YVO partner agency leads, YVO declares “activity with potential,” and plans are made to increase monitoring capabilities in the region as soon as feasible. The YVOCOMS group is organized and drafts talking points, releasing information though social media channels and web sites, while also working with the USGS Office of Communications and Publishing to respond to media interview requests. With help from the Yellowstone National Park Research Permitting Office, NEPA regulations that allow for emergency responses are cited as the UUSS, USGS, and EarthScope Consortium install new seismic, GPS, and gas monitoring instruments near Roaring Mountain to aid with locating small earthquakes, assessing ground deformation, and providing continuous gas measurements. This work is completed by the middle of March thanks to low snow levels, unseasonably mild temperatures, and assistance from Yellowstone National Park staff. Near-daily ground-based observations of conditions in the area of unrest are conducted by YVO personnel temporarily stationed in Mammoth Hot Springs to supplement satellite and airborne monitoring. YVO communicates findings to the public and stakeholders, including Yellowstone National Park managers as they develop and coordinate responses.

By early April, the new monitoring data indicate low-frequency tremor and long-period seismicity, often associated with magma movement, and uplift of a few centimeters (1–2 in) between Roaring Mountain and Obsidian Cliff. Models of ground deformation indicate an intrusion of magma may be underway several kilometers (miles) beneath the surface. YVO declares a formal event response, and the decision is made by the YVO SIC, in consultation with YVO member agency representatives, to change the Volcano Alert Level for the Yellowstone volcanic system from Normal to Advisory and the Aviation Color Code from Green to Yellow. A call down is completed and a VAN/VONA is issued by the YVO SIC, and the YVOCOMS group is tasked with developing and regularly updating talking points used by those answering media interviews and talking with the public.

The VSC response plan is activated (fig. 11), with the YVO SIC appointing specific scientists from YVO member agencies to lead individual teams—including the “Hazards Assessment and Forecasting” team, tasked with developing a probabilistic assessment of the future course of the activity, maps of hazard zones, and other GIS products to support the emergency response. Although the plan is not fully staffed at this point, element leads are established and meet regularly to coordinate activities and share information. The YVO SIC also appoints a SAC to provide input to YVO and Yellowstone National Park regarding requests from non-YVO scientists and institutions for access and permits to conduct research related to the unrest, especially as the area becomes more easily accessible with the arrival of warmer temperatures and melting of snow. All research requests are evaluated on the basis of scientific merit, logistical requirements, safety, and whether the proposed work will support the emergency response. Regardless of the status of proposals to the SAC, all data collected by YVO scientists are made available to the public, and non-YVO scientists are able to offer additional perspectives, models, and products in support of hazards assessment efforts.

In late April, a M_w 5.6 earthquake occurs in the area, prompting another UUSS press release and YVO Information Statement. CO_2 emissions measured by the continuous gas monitoring site are climbing, and on-site geologists have observed previously undocumented ground cracks near Obsidian Cliff, recently exposed by melting snow.

Although most of Yellowstone National Park opens for the season in April, the Norris-Mammoth highway remains closed to visitors given the uncertain outcome of the unrest. In early May, seismic tremor appears on all seismic stations, and phreatic explosions occur, lofting pulverized rock and steam a few thousand feet above the ground, creating small craters along a north-south trend at the base of Obsidian Cliff. The YVO SIC, upon consultation with YVO member agency representatives, changes the Volcano Alert Level for the Yellowstone volcanic system to Watch and the Aviation Color Code to Orange. A call down is completed, and a VAN/VONA is issued by the YVO SIC. YVOCOMS expands its staffing to deal with the magnitude of media requests and social media outreach, and YVO begins issuing daily updates to keep the public appraised of the evolving situation. The state geological surveys of Montana, Idaho, and

Wyoming organize community meetings in towns bordering or near Yellowstone National Park in their respective states, drawing on YVO member agency scientists and expertise as needed. The VSC response plan is fully staffed (fig. 11), and Yellowstone National Park initiates an ICS to help manage the response, control access to the region as the closure area expands, and assist park visitors. YVO provides scientific expertise on the likely future course of the unrest to the incident commander and coordinates with other ICS branches as needed to support response efforts, for example, volcanology field operations that include helicopter transportation and aerial observations. Additional monitoring stations are scheduled for installation, and YVO requests permission from Yellowstone National Park to conduct UAS surveys of gas and thermal emissions.

Phreatic explosions and pulses of seismicity wax and wane throughout May and into June. In early June, SO_2 gas is detected by UAS flights, indicating the presence of magma at shallow levels. GPS and radar interferograms from satellite data indicate gradually accelerating uplift of the region—up to rates of several centimeters (inches) per week—which indicates continued magmatic intrusion at shallowing depths. Seismicity includes hundreds to thousands of small earthquakes per day. This level of activity continues through the rest of June and July; the long timescale of the response requires the USGS to draw resources from other volcano observatories and the state geological surveys of Idaho, Montana, and Wyoming to mitigate employee burnout and distribute the workload of collecting monitoring data, tracking activity, responding to media requests, and advising the ICS on probable outcomes of activity. Hazards assessments, maps, and probabilistic forecasts are frequently updated to provide emergency managers with the most current assessments of the likely evolution of activity, which could culminate in a volcanic eruption or subside with no eruption. Volcanologists are assigning a roughly equal probability to the two outcomes, and despite the uncertainty the ICS finds this information useful, since it allows for a calculation of the probability of specific hazards, like ashfall, and the areas of potential impact.

At the end of July, satellite images reveal a thermal anomaly concurrent with strong tremor detected in seismic data across the region. Direct observation by field volcanologists and remote cameras confirms the start of a volcanic eruption as magma arrives at the surface and a lava dome forms. A call down is initiated, and the YVO SIC issues a VAN/VONA as the Volcano Alert Level for the Yellowstone volcanic system is changed to Warning and the Aviation Color Code to Red. Shortly after the call down is completed, a small explosive eruption begins, sending ash and gas to an elevation of 9,000 m (about 30,000 ft) and causing light ashfall in communities downwind, with a few centimeters (1–2 inches) of ash accumulating in the immediate vicinity north and east of the eruption site, including at Mammoth Hot Springs, and trace amounts of ash in eastern Montana and Wyoming. Calls are placed to the FAA and NWS, who inform the aviation community of the airborne ash hazard and downwind ashfall hazard. After a few hours of ash emission, the explosive activity stops and the eruption transitions to extrusion of thick, pasty lava that accumulates around the vent.

By early August, seismicity has stabilized at a moderate level, and lava flow activity has reached a steady state of activity with a constant eruption rate. The lack of any further buildup of seismicity and ground deformation that could indicate an impending explosion prompts the YVO SIC, in consultation with YVO member agency leads, to lower the Volcano Alert Level for the Yellowstone volcanic system to Watch and the Aviation Color Code to Orange, a call down is completed, and a VAN/VONA is issued. The SAC has processed numerous requests for research data collection, which the ICS and Yellowstone National Park managers evaluate in collaboration with YVO in the context of the updated hazards assessment and probability forecasts. Although not all proposals receive permission, several are granted, including those that leverage the scientific opportunity to learn more about this hazardous event, and that directly address the potential course of future hazards from the eruption. YVO geologists collect lava samples (made available to the greater scientific community) to assess conditions in the magmatic system, and these data aid the Hazards Assessment and Forecasting team in refining their models of the future course of the activity. The effusion of lava continues until the following year, gradually diminishing and ultimately ceasing by March. The lava flow has created a natural dam across Obsidian Creek, leading to the formation of a small lake in the meadow south of Obsidian Cliff, and covered a segment of the Norris-Mammoth highway. The YVO SIC, after consulting with YVO agency leads, lowers the Volcano Alert Level for the Yellowstone volcanic system to Advisory and the Aviation Color Code to Yellow, and a VAN/VONA is issued. The heightened alert levels are maintained until the following year, when all monitoring data have returned to background levels and the Volcano Alert Level and Aviation Color Code are lowered to Normal and Green, respectively. Yellowstone National Park establishes interpretive trails from both ends of the closed road for the public to visit the recent lava flow, and research access is broadened, with the Yellowstone National Park Research Permitting Office evaluating proposals for studying the activity. Monitoring equipment installed in sensitive areas during the unrest and eruption is removed because NEPA regulations governing emergency responses are no longer in place.

Summary and Protocols for Updating this Plan

This plan summarizes protocols and tools to be used by the Yellowstone Volcano Observatory (YVO)—a consortium of agencies led by a U.S. Geological Survey (USGS) employee who is designated as the Scientist-in-Charge (SIC)—during episodes of unusual geological unrest at Yellowstone Caldera. The broad range of potential volcanic, seismic, and hydrothermal hazards in the Yellowstone region requires a specific response plan that utilizes and builds upon the general U.S. Geological Survey Volcano Science Center Response Plan for Significant Volcanic Events (Moran and others, 2024). The YVO response plan for the Yellowstone volcanic system may be activated upon the declaration of an event or activity with potential by the YVO SIC. A response to volcanic unrest or eruptions in regions of YVO responsibility outside the area of Yellowstone National Park, including Arizona, Utah, New Mexico, and Colorado, will follow the Moran and others (2024) plan.

A YVO response to activity associated with Yellowstone Caldera may require the collection of additional monitoring or field data to better understand the nature of an event or activity with potential, as well as a specific hazards analysis to support emergency managers and inform probabilistic assessments of outcomes. YVO expertise will be incorporated into any Incident Command System that may be activated as part of the response, and a YVOCOMS group will ensure continuity of both internal and external communications. Depending on the nature of the activity, Volcano Alert Levels and Aviation Color Codes for the Yellowstone volcanic system may be changed, but this is not a requirement of an event declaration.

The YVO response plan for activity in the Yellowstone region will be modified as needed to account for changes in staff, organizational structures, and protocols. The current version of this plan will be available through the official USGS publications website.

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Photograph showing distinctly layered, columnar-jointed lava flows in the Narrows of the Grand Canyon of the Yellowstone River in Yellowstone National Park. The flows are about 1.3 million years old and are separated and overlain by glacial deposits and river gravels. U.S. Geological Survey photograph by Mike Poland, May 15, 2022.

Photograph showing Earthquake Lake, Montana, just west of Yellowstone National Park. The lake formed in 1959 after a landslide brought on by the *M*7.3 Hebgen Lake earthquake dammed the river and flooded the valley. Trees that were inundated when the lake formed still protrude from the lake surface. The landslide, which destroyed a campground and caused 28 fatalities, is the rocky, barren ground visible behind the lake. A U.S. Forest Service visitor center was built on the landslide debris to commemorate the tragedy. U.S. Geological Survey photograph by Mike Poland, August 17, 2019.

Aerial photograph of Biscuit Basin after the July 23, 2024, hydrothermal explosion. Photograph by Jacob W. Frank of the National Park Service, July 2024.

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