The landscape of Yellowstone National Park is the result of many geological processes. Here, glacial erratics (foreground), ground moraines (midground), and Cutoff Mountain (background) appear near Junction Butte.

Geology

Throughout the Greater Yellowstone Ecosystem, many different geologic processes are occurring at the same time, in different proportions. While these mountains and canyons may appear to change very little during our lifetime, they are still highly dynamic and variable.

Yellowstone National Park's landscape has been and is being created by various geological processes. Some of the Earth's most active volcanic, hydrothermal (water + heat), and earthquake systems make this national park a priceless treasure. In fact, Yellowstone was established as the world's first national park primarily because of its extraordinary geysers, hot springs, mudpots and steam vents, as well as other wonders such as the Grand Canyon of the Yellowstone River.

What Lies Beneath

Yellowstone's geologic story provides examples of how geologic processes work on a planetary scale. The foundation to understanding this story begins with the structure of the Earth and how this structure shapes the planet's surface.

The Earth is frequently depicted as a ball with a central core surrounded by concentric layers that culminate in the crust or surface layer. The distance from the Earth's surface to its center or core is approximately 4,000 miles. The core of the earth is divided into two parts. The mostly iron and nickel inner core (about 750 miles in diameter) is extremely hot but solid due to immense pressure. The iron and nickel outer core (1,400 miles thick) is hot and molten. The mantle (1,800 miles thick) is dense, hot, semisolid layer of rock. Above this layer is the relatively thin crust, three to forty-eight miles thick, forming the continents and ocean floors.

The Earth's crust and upper mantle (lithosphere) is divided into many plates, which are in constant motion. Where plate edges meet and one plate may slide past another, one plate may be driven beneath

Yellowstone's Geologic Significance

- One of the most geologically dynamic areas on Earth due to shallow source of magma and resulting volcanic activity.
- One of the largest volcanic eruptions known to have occurred in the world, creating one of the largest known calderas.
- More than 10,000 hydrothermal features, including approximately 500 geysers.
- The largest concentration of active geysers in the world—more than half of the world's total.
- The most undisturbed hydrothermal features left in the world.
- One of the few places in the world where active travertine terraces are found, at Mammoth Hot Springs.
- Site of many petrified trees formed by a series of andesitic volcanic eruptions 45 to 50 million years ago.

another (subduction). Upwelling volcanic material pushes plates apart at mid-ocean ridges. Continental plates are made of less dense rocks (granites) that are thicker than oceanic plates (basalts) and thus, "ride" higher than oceanic plates. Many theories have been proposed to explain crustal plate movement. Currently, most scientific evidence supports the theory that convection currents in the partially molten asthenosphere (the zone of mantle beneath the lithosphere) move the rigid crustal plates above. The volcanism that has so greatly shaped today's Yellowstone is a product of plate movement combined with upwellings of molten rock.

At a Glance

Although a cataclysmic eruption of the Yellowstone volcano is unlikely in the foreseeable future, monitoring of seismic activity and ground deformation by the Yellowstone Volcano Observatory helps ensure public safety. The University of Utah's seismograph stations detected more than 3,200 earthquakes in the park in 2010, the largest count since 1985. New technology contributed to this increase in detected earthquakes by allowing extensive scientific analysis of small earthquakes.

Beginning in 2004, GPS and InSAR measurements indicated that parts of the Yellowstone caldera were rising up to 7 cm per year, while an area near the northern caldera boundary started to subside. The largest vertical movement was recorded at the White Lake GPS station, inside the caldera's eastern rim, where the total uplift from 2004 to 2010 was about 27 cm. The caldera began to subside during the first half of 2010, about 5 cm at White Lake so far. Episodes of uplift and subsidence have been correlated with the frequency of earthquakes in the park.

On March 30, 2014 at 6:34 AM Mountain Daylight Time, an earthquake of magnitude 4.8 occurred four miles north-northeast of Norris Geyser Basin. The M4.8 earthquake was reported felt in Yellowstone National Park, in the towns of Gardiner and West Yellowstone, Montana and throughout the region. This is the largest earthquake at Yellowstone since the early 1980s. Analysis of the M4.8 earthquake indicates a tectonic origin (mostly strike-slip motion).

Energy and groundwater development outside the park, especially in known geothermal areas in Island Park, Idaho, and Corwin Springs, Montana, could alter the functioning of hydrothermal systems in the park.

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Between 542 and 66 million years ago—long before the "supervolcano" became part of Yellowstone's geologic story—the area was covered by inland seas.

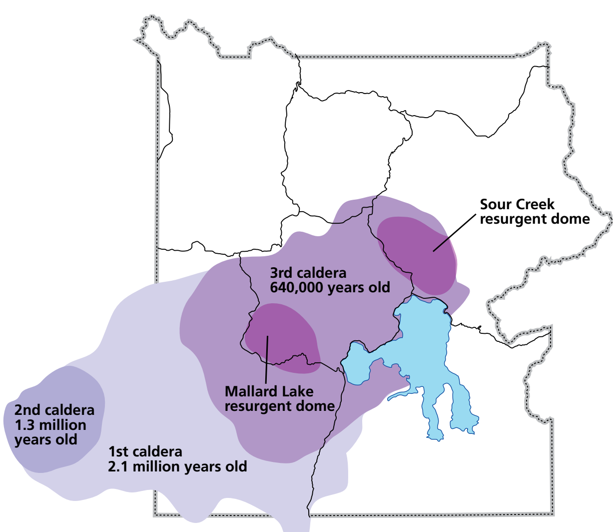
Geologic History of Yellowstone

Most of Earth's history (from the formation of the earth 4.6 billion years ago to approximately 541 million years ago) is known as the Precambrian time. Rocks of this age are found in northern Yellowstone and in the hearts of the Teton, Beartooth, Wind River, and Gros Ventre ranges. During the Precambrian and the subsequent Paleozoic and Mesozoic eras (541 to 66 million years ago), the western United States was covered at times by oceans, sand dunes, tidal flats, and vast plains. From the end of the Mesozoic through the early Cenozoic, mountain-building processes formed the Rocky Mountains.

During the Cenozoic era (approximately the last 66 million years of Earth's history), widespread mountain-building, volcanism, faulting, and glaciation sculpted the Yellowstone area. The Absaroka Range along the park's north and east sides was formed by numerous volcanic eruptions about 50 million years ago. This period of volcanism is not related to the present Yellowstone volcano.

Approximately 30 million years ago, vast expanses of today's West began stretching apart along an east–west axis. This stretching process increased about 17 million years ago and continues today, creating the modern basin and range topography (north–south mountain ranges with long north–south valleys) characterizing much of the West, including the Yellowstone area.

About 16.5 million years ago, an intense period of volcanism appeared near the intersection of present-day Nevada, Oregon, and Idaho. Repeated volcanic eruptions can be traced across southern Idaho towards Yellowstone. This 500-mile trail of more than 100 calderas was created as the North American plate moved in a southwestern direction over a shallow body of magma. About 2.1 million years ago, the movement of the North American plate brought the Yellowstone area closer to the shallow magma body. This volcanism remains a driving force in Yellowstone today.



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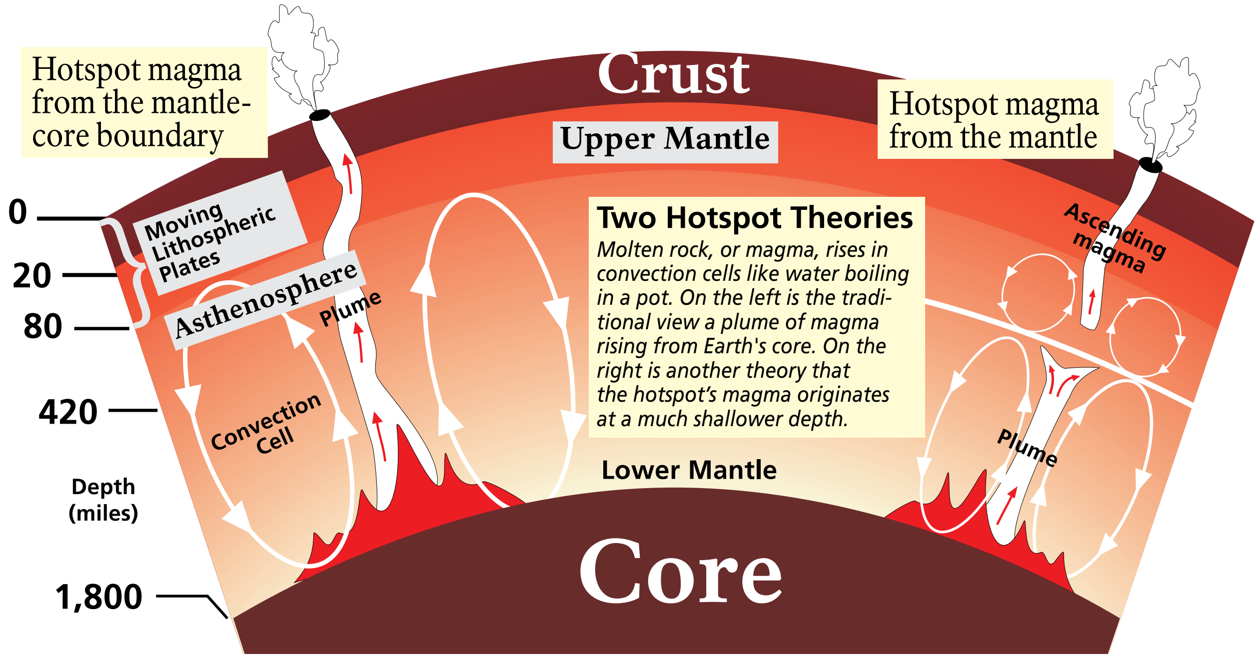
The locations of Yellowstone's three calderas and two resurgent domes.

Yellowstone Geologic History

542 to 66 Ma	Area covered by inland seas
50 to 40 Ma	Absaroka volcanics
30 Ma to present	"Basin and Range" forces creating Great Basin topography
16 Ma	Volcanics begin again in present day Nevada and Idaho
2.1 Ma	1st Yellowstone eruption
1.3 Ma	2nd Yellowstone eruption
640 ka	3rd Yellowstone eruption
174 ka	West Thumb eruption
160 to 151 ka	Bull Lake Glaciation underway
21 to 16 ka	Pinedale Glaciation maximum

Ma = mega annum, or millions of years ago
ka = kilo annum, or one thousand years ago



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This diagram shows the general ideas behind two theories of how magma rises to the surface.

GEOLOGY

FREQUENTLY ASKED QUESTIONS:

Is Yellowstone a volcano?

Yes. Within the past two million years, episodic volcanic eruptions have occurred in the Yellowstone area—three of them major.

What is the caldera shown on the park map?

The Yellowstone caldera was created by a massive volcanic eruption approximately 640,000 years ago. Subsequent lava flows filled in much of the caldera, and it is now measured at 30 x 45 miles. Its rim can best be seen from the Washburn Hot Springs overlook, south of Dunraven Pass. Gibbon Falls, Lewis Falls, Lake Butte, and Flat Mountain Arm of Yellowstone Lake are part of the rim.

When did the Yellowstone volcano last erupt?

An eruption approximately 174,000 years ago created what is now the West Thumb of Yellowstone Lake. The last lava flow was about 70,000 years ago.

Is Yellowstone's volcano still active?

Yes. The park's many hydrothermal features attest to the heat still beneath this area. Earthquakes—1,000 to 3,000 per year—also reveal activity below ground. The University of Utah Seismograph Station tracks this activity closely.

What is Yellowstone National Park doing to stop or prevent an eruption?

Nothing can be done to prevent an eruption. The temperatures, pressures, physical characteristics of partially molten rock, and immensity of the magma chamber are beyond human ability to impact—much less control.

What is a supervolcano?

Some scientists consider Yellowstone to be a "supervolcano," which refers to volcano capable of an eruption more than 240 cubic miles of magma. Two of Yellowstone's three major eruptions met the criteria.

Will the Yellowstone volcano erupt soon?

Current geologic activity at Yellowstone has remained relatively constant since scientists first started monitoring more than 30 years ago. Another caldera-forming eruption is theoretically possible, but it is very unlikely in the next thousand or even 10,000 years. Scientists have also found no indication of an imminent smaller eruption of lava.

How do scientists know the Yellowstone volcano won't erupt?

Scientists from the Yellowstone Volcano Observatory (YVO) watch an array of monitors in place throughout the region. These monitors would detect sudden or strong movements that would indicate increasing activity. No such evidence exists at this time.

In addition, YVO scientists collaborate with scientists from all over the world to study the hazards of the Yellowstone volcano. To view current data about earthquakes, ground movement, and stream flow, visit the YVO website at volcanoes.usgs.gov/yvo/.

If Old Faithful Geyser quits, is that a sign the volcano is about to erupt?

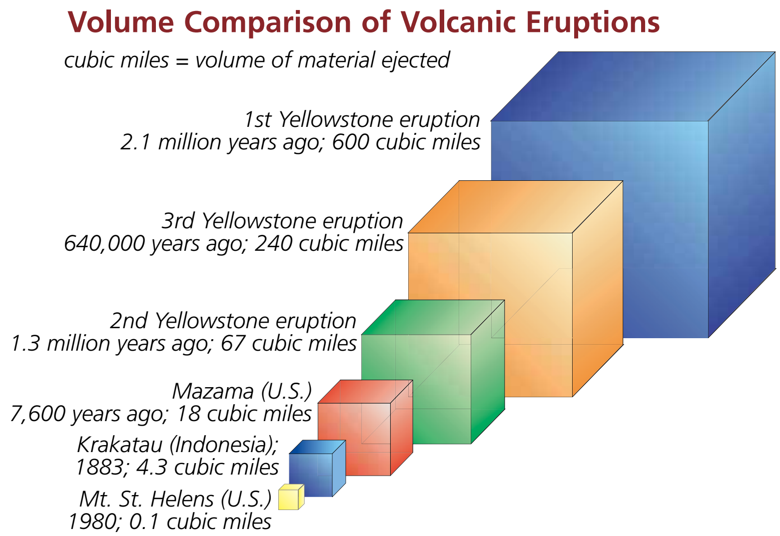
All geysers are highly dynamic, including Old Faithful. We expect Old Faithful to change in response to the ongoing geologic processes associated with mineral deposition and earthquakes. Thus, a change in Old Faithful Geyser will not necessarily indicate a change in volcanic activity.

Magma and Hot Spots

Magma (molten rock from Earth's mantle) has been close to the surface in Yellowstone for more than 2 million years. Its heat melted rocks in the crust, creating a magma chamber of partially molten, partially solid rock. Heat from this shallow magma caused an area of the upper crust to expand and rise. The Yellowstone Plateau became a geomorphic landform shaped by episodes of volcanic activity. Stress also caused rocks overlying the magma to break, forming faults and causing earthquakes. Eventually, these faults reached the deep magma chamber. Magma oozed through these cracks, releasing pressure within the chamber and allowing trapped gases to expand rapidly. A massive volcanic eruption then occurred along vents, spewing volcanic ash and gas into the atmosphere and causing fast super-hot debris (pyroclastic) flows on the ground. As the underground magma chamber emptied, the ground above it sunk, creating the first of Yellowstone's three calderas.

The volume of material ejected during this first eruption is estimated to have been 6,000 times the size of the 1980 eruption of Mt. St. Helens in Washington, and ash has been found as far away as Missouri. Approximately 1.3 million years ago, a second, smaller volcanic eruption occurred within the western edge of the first caldera. Then 640,000 years ago, a third massive volcanic eruption created the Yellowstone Caldera, 30 by 45 miles in size. A much smaller eruption approximately 174,000 years ago forming what is now the West Thumb of Yellowstone Lake. In between and after these eruptions, lava flowed—with the last being approximately 70,000 years ago.

Over time, the pressure from magma has formed two resurgent domes inside the Yellowstone Caldera. Magma may be as little as 3–8 miles beneath Sour Creek Dome and 8–12 miles beneath Mallard Lake Dome; they both lift up and subside as magma or hydrothermal fluids upwell or subside beneath them. The entire caldera floor lifts up or subsides, too, but not as much as the domes. In the past century, the net result has been to tilt the caldera floor toward the south. As a result, Yellowstone Lake's southern shores have subsided and trees stand in water.



Volume comparison of volcanic eruptions.

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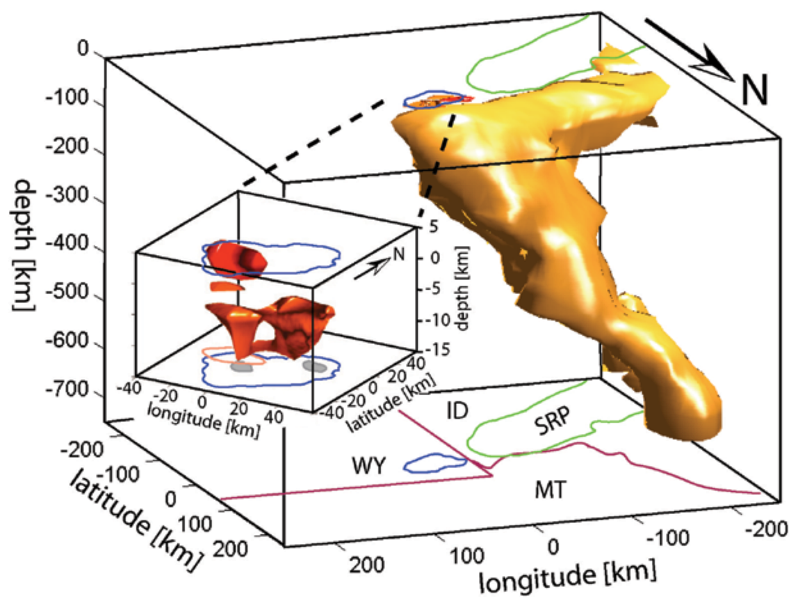


New technology has allowed scientists to map a magma plume (orange) originating several hundred miles away from Yellowstone, and far deeper than previously thought. It feeds magma into a reservoir (red in detail) beneath Yellowstone. Diagram courtesy Robert B. Smith; appeared in *Journal of Volcanology and Geothermal Research*, 2009.

ROBERT B. SMITH

Volcano

A plume of molten rock that rises beneath Yellowstone creates one of the world's largest active volcanoes, evident in the frequency of earthquakes in the area, the thousands of hydrothermal features, and the measurable ground deformation over time. The first major eruption of the Yellowstone volcano, which occurred 2.1 million years ago, is among the largest volcanic eruptions known, covering over 5,790 square miles (15,000 km^2) with ash. After the most recent major eruption, 640,000 years ago, the ground collapsed into the magma reservoir, leaving a caldera 75 km long and 55 km wide. Since then, 80 smaller eruptions have occurred, most recently 70,000 years ago, partially filling the caldera. Although a cataclysmic eruption is unlikely in the foreseeable future, continuous monitoring of seismic activity, ground deformation, and changes in underground strain rates helps ensure public safety.

Recent Activity

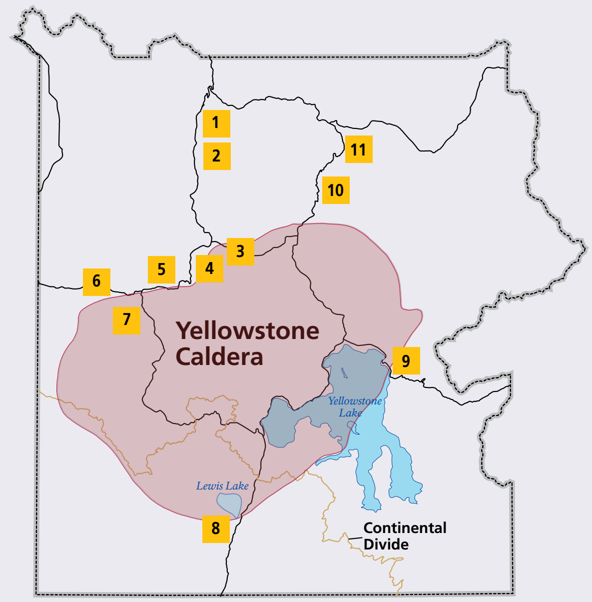
Ground deformation has been documented along the central axis of the caldera between Old Faithful and White Lake in Pelican Valley. The largest vertical movement was recorded at the White Lake GPS station, inside the caldera's eastern rim, where the total uplift from 2004 to 2009 was about 25 cm. The rate of rise slowed in 2008 and the caldera began to subside during the first half of 2010. The uplift is believed to be caused by the movement of deep hydrothermal fluids or molten rock at a depth of about 10 km beneath the surface. A caldera may undergo episodes of uplift and subsidence for thousands of years without erupting. Episodes of uplift and subsidence have been correlated with earthquake occurrence.

Future Volcanic Activity

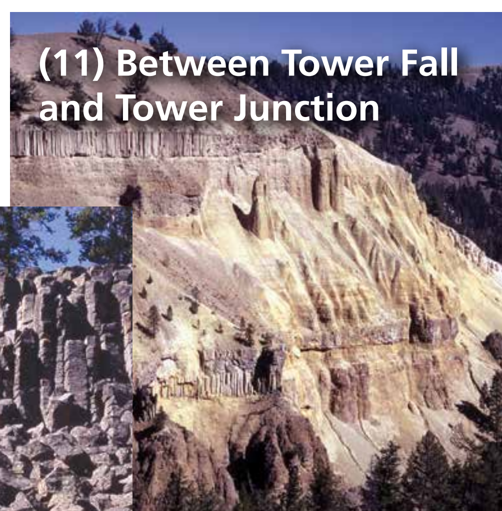
Will Yellowstone's volcano erupt again? Over the next thousands to millions of years, probably. In the next few hundred years? Not likely.

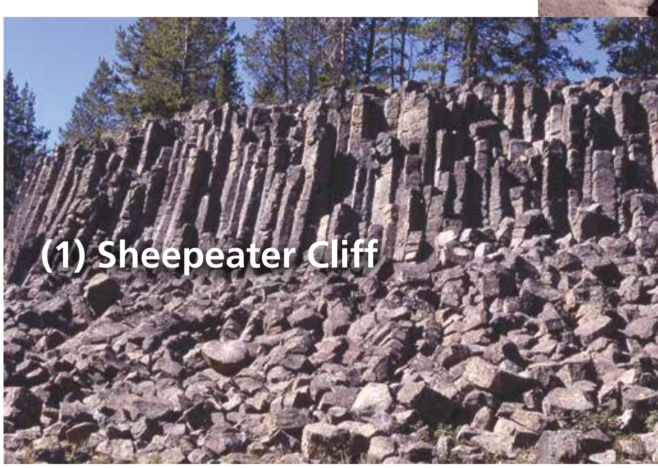
The most likely activity would be lava flows, such as those that occurred after the last major eruption. A lava flow

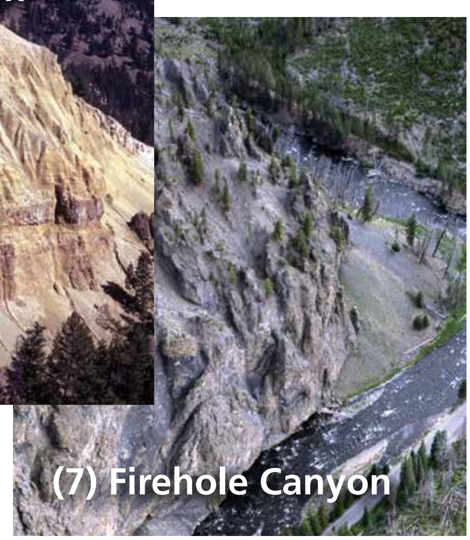
Where to See Volcanic Flows



1. Sheepeater Cliff: columnar basalt
2. Obsidian Cliff: lava
3. Virginia Cascades: ash flow
4. Gibbon Falls: Near caldera rim
5. Tuff Cliff: ash flow
6. West Entrance Road, Mt. Haynes and Mt. Jackson: columnar rhyolite, Lava Creek tuff
7. Firehole Canyon: lava
8. Lewis Falls: Near caldera rim
9. Lake Butte: On edge of caldera, overall view of caldera
10. Washburn Hot Springs Overlook: overall view of caldera
11. Between Tower Fall and Tower Junction: columnar basalt


(11) Between Tower Fall and Tower Junction


(1) Sheepeater Cliff


(7) Firehole Canyon

Yellowstone Volcano Observatory

Increased scientific surveillance of Yellowstone has detected significant changes in its vast underground volcanic system. The system is centered on an enormous caldera that is characterized by geologically infrequent but very large volcanic eruptions.

To strengthen the ability of scientists to track and respond to changes in Yellowstone's activity, the Yellowstone Volcano Observatory (YVO) was created here in 2001. YVO is a cooperative partnership between the University of Utah, the U.S. Geological Survey (USGS), and Yellowstone National Park, National Park Service (NPS).

The observatory is a long-term, instrument-based monitoring program designed for observing volcanic and earthquake activity in the Yellowstone National Park region.

The principal goals of the Yellowstone Volcano Observatory are:

- provide seismic and GPS monitoring that enables reliable and timely warnings of possible renewed volcanism and related hazards in the Yellowstone region,
- notify the NPS, other local officials, and the public of significant seismic or volcanic events,
- improve scientific understanding of tectonic and magmatic processes that influence ongoing seismicity, surface deformation, and hydrothermal activity,
- assess the long-term potential hazards of volcanism, seismicity, and explosive hydrothermal activity in the region,
- communicate effectively the results of these efforts to responsible authorities and to the public, and
- improve coordination and cooperation among the Univ. of Utah, NPS, and the USGS.

Current real-time-monitoring data are online at volcanoes.usgs.gov/yvo/monitoring.html.

would ooze slowly over months and years, allowing plenty of time for park managers to evaluate the situation and protect people. No scientific evidence indicates such a lava flow will occur soon.

To monitor volcanic and seismic activity in the Yellowstone area, the US Geological Survey, National Park Service, and University of Utah established the Yellowstone Volcano Observatory in 2001. The near real-time monitoring network consists of 26 seismic stations, 16 GPS receivers, and 11 stream gauging stations. Information is also collected on temperature, chemistry, and gas concentrations at selected hydrothermal features and chloride concentrations in major rivers. A monthly activity summary, real-time monitoring of seismicity and water flow, and near real-time monitoring of ground deformation, can be found at the Yellowstone Volcanic Observatory website.

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Grand Prismatic Stream is one of more than 10,000 thermal features in Yellowstone. Research on heat-resistant microbes in the park's hydrothermal areas has led to medical, forensic, and commercial uses.

Hydrothermal Systems

Yellowstone was set aside as the world's first national park because of its hydrothermal wonders. The park contains more than 10,000 thermal features, including the world's greatest concentration of geysers as well as hot springs, mudpots, and steam vents. Research on heat-resistant microbes in the park's thermal areas has led to medical, forensic, and commercial uses. Oil, gas, and groundwater development near the park and drilling in "Known Geothermal Resources Areas" identified by the US Geological Survey in Island Park, Idaho, and Corwin Springs, Montana, could alter the functioning of hydrothermal systems in the park.

Under the Surface

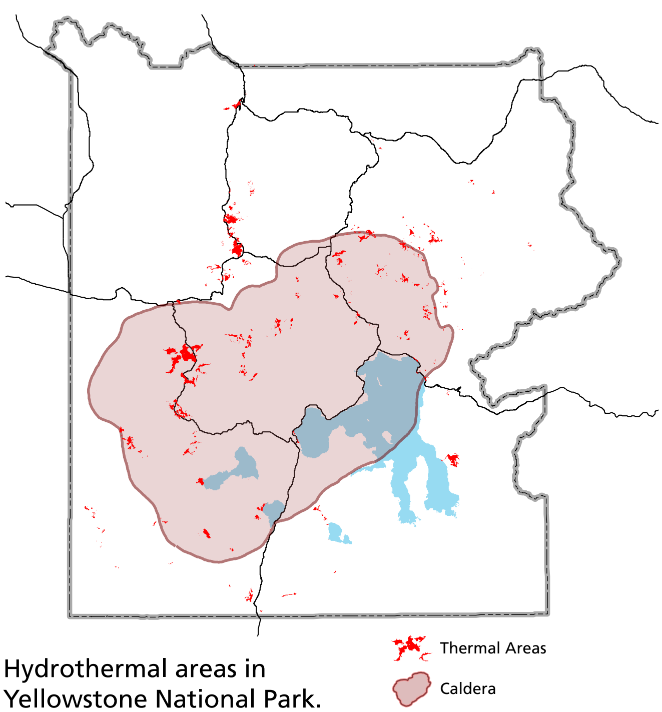
The park's hydrothermal system is the visible expression of the immense Yellowstone volcano; they would not exist without the underlying partially molten magma body that releases tremendous heat. They also depend on sources of water, such as the mountains surrounding the Yellowstone Plateau. There, snow and rain slowly percolate through layers of permeable rock riddled with cracks. Some of this cold water meets hot brine directly heated by the shallow magma body. The water's temperature rises well above the boiling point but the water remains in a liquid state due to the great pressure and weight of the overlying water. The result is superheated water with temperatures exceeding 400°F.

The superheated water is less dense than the colder, heavier water sinking around it. This creates convection currents that allow the lighter, more buoyant, superheated water to begin its journey back to the surface following the cracks and weak areas through rhyolitic lava flows. This upward path is the natural "plumbing" system of the park's hydrothermal features.

As hot water travels through this rock, it dissolves some silica in the rhyolite. This silica can precipitate in the cracks, increasing the system's ability to withstand the great pressure needed to produce a geyser.

The silica coating the walls of Old Faithful's geyser tube did not form a pressure-tight seal for the channel of upflow. Lots of water pours through the "silica-lined" walls after an eruption stops. Amorphous silica is a lot less strong than the rock it might coat. The pressure in the geyser tube is not contained by the strength of the wall, rather the water pressure in the tube is contained by the greater pressure of colder water outside of the tube.

At the surface, silica precipitates to form siliceous sinter, creating the scalloped edges of hot springs and the seemingly barren landscape of hydrothermal basins. The siliceous sinter deposits with bulbous or cauliflower-like surfaces are known as geyserite.



Hydrothermal areas in Yellowstone National Park.

Hydrothermal Activity

No basin-wide changes in hydrothermal activity have been observed in the park in recent years. The average Old Faithful eruption interval is 88 minutes as of January 2013, but remained at 90 to 91 minutes for several years. Steamboat Geyser had a major eruption on September 3, 2014. Echinus Geyser, one of the largest acid-water geysers known, has had a period of limited activity. Work continues on the park's hydrothermal monitoring program, with progress made in documenting the status of the hydrothermal system by measuring the total amount of thermal water and the total heat output for selected geyser basins. Aircraft and helicopter thermal infrared images are being used to determine a baseline and document changes in the hydrothermal areas.

The widely dispersed locations of the park's hydrothermal areas make a systematic monitoring program to protect the features difficult. The most visible changes in individual thermal features receive the most public attention but do not necessarily represent human influences or changes in the entire hydrothermal system. In order to distinguish human influences from natural changes, the natural variability of the hydrothermal system must be characterized by gathering reproducible data over many years. The park's geothermal monitoring strategy therefore includes remote sensing, field studies of groundwater flow, measurement of individual hydrothermal feature temperatures and surface water flow, and

FREQUENTLY ASKED QUESTIONS:

Why are geysers in Yellowstone?

Yellowstone's volcanic geology provides the three components for geysers and other hydrothermal features: heat, water, and a natural "plumbing" system. Magma beneath the surface provides the heat; ample rain and snowfall seep deep underground to supply the water; and underground cracks and fissures form the plumbing. Hot water rises through the plumbing to surface as hydrothermal features in Yellowstone, including geysers.

What exactly is a geyser basin?

A geyser basin is a geographically distinct area containing a "cluster" of hydrothermal features that may include geysers, hot springs, mudpots, and fumaroles. These distinct areas often (but not always) occur in low places because hydrothermal features tend to be concentrated around the margins of lava flows and in areas of faulting.

Where can I see mudpots?

Small mudpot areas occur at West Thumb Geyser Basin, Fountain Paint Pot, and Artists' Paintpots. The largest group of mudpots can be found at Mud Volcano, at the southern end of Hayden Valley.

What is the oldest thermal area in the park, active or inactive?

Terrace Mountain, near Mammoth Hot Springs, is evidence of carbonate hot spring deposits up to 406,000 years old.

What is the most active thermal area in the park?

Norris Geyser Basin is the hottest and most dynamic of Yellowstone's active hydrothermal areas. The highest temperature yet recorded in any Yellowstone hydrothermal area was measured in a scientific drill hole at Norris: 459°F (237°C) just 1,087 feet below the surface. Norris shows evidence of having had hydrothermal activity prior to the last great ice age. The features change often, with frequent disturbances from seismic activity and water fluctuations. Norris is so hot and dynamic primarily because it sits at the intersection of three major faults, two of which intersect with a ring fracture zone from the Yellowstone caldera eruption 640,000 years ago.

Were Native Americans afraid of geysers?

Native Americans in general were not afraid of geysers. Many of the associated tribes of Yellowstone say their people have used the park as a place to live, to collect food and other resources, and as a passage through to the bison hunting grounds of the Great Plains. Archeologists and historians have also uncovered ample evidence that people lived in and visited Yellowstone for thousands of years before historic times.

Is Yellowstone's geothermal energy used to heat park buildings?

Yellowstone National Park's hydrothermal areas cannot be tapped for geothermal energy because such use could destroy geysers and hot springs, as it has done in other parts of the world.

Why can't I bring my dog on geyser basin trails?

Dogs have died diving into hot springs. They also disturb wildlife and are prohibited from all park trails. In the few places pets are permitted, they must be leashed at all times. Ask at a visitor center where you can walk a pet.

Is it really dangerous to walk off the boardwalks in geyser basins?

YES. Geyser basins are constantly changing. Boiling water surges just under the thin crust of most geyser basins, and many people have been severely burned when they have broken through the fragile surface. Some people have died.

Why can't I smoke in the geyser basins?

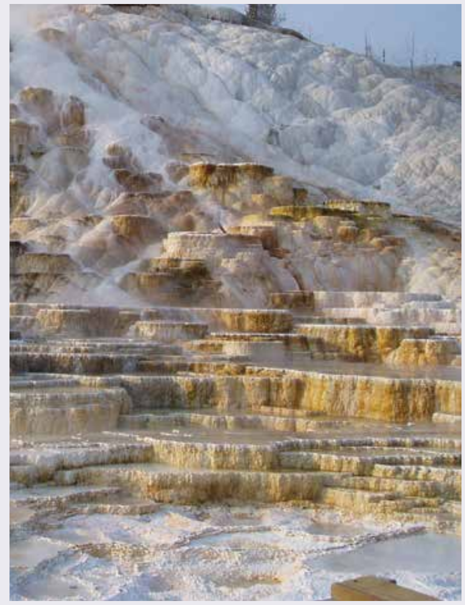
Cigarette butts quickly accumulate where smoking is allowed, and they—like any litter—can clog vents, thus altering or destroying hydrothermal activity.

Hydrothermal Features in Yellowstone

Fumaroles or steam vents, are the hottest hydrothermal features in the park. The limited amount of water flashes into steam before reaching the surface. At places like Roaring Mountain (above), the result is a loud hissing of steam and gases.

Mudpots such as those near Mud Volcano (above) are acidic features with a limited water supply. Some microorganisms use hydrogen sulfide, which rises from deep within the earth, as an energy source. They help convert the gas to sulfuric acid, which breaks down rock into clay minerals. Various gases escape through the wet clay mud, causing it to bubble. Mudpot consistency and activity vary with the seasons and precipitation.

Cone geysers, such as Riverside in the Upper Geyser Basin (left), erupt in a narrow jet of water, usually from a cone. **Fountain geysers**, such as Great Fountain in the Lower Geyser Basin (right), shoot water in various directions, typically from a pool.



Travertine terraces, found at Mammoth Hot Springs (above), are formed from limestone (calcium carbonate). Water rises through the limestone, carrying high amounts of dissolved carbonate minerals. At the surface, carbon dioxide is released and carbonate minerals like calcite are deposited, forming travertine, the chalky white rock of the terraces. Due to the rapid rate of deposition, these features constantly and quickly change.

Hot springs such as this one at West Thumb (above) are the most common hydrothermal features in the park. Their plumbing has no constrictions. Superheated water cools as it reaches the surface, sinks, and is replaced by hotter water from below. This process, called convection, prevents water from reaching the temperature needed to set off an eruption.

Hydrothermal Feature: Geysers

Geysers are hot springs with constrictions in their plumbing, usually near the surface, that prevent water from circulating freely to the surface where heat would escape. The deepest circulating water can exceed the surface boiling point (199°F/93°C). Surrounding pressure also increases with depth, similar to the ocean. Increased pressure exerted by the enormous weight of the overlying water prevents the water from boiling. As the water rises, steam forms. Bubbling upward, steam expands as it nears the top of the water column. At a critical point, the confined bubbles actually lift the water above, causing the geyser to splash or overflow. This decreases pressure on the system, and violent boiling results. Tremendous amounts of steam force water out of the vent, and an eruption begins. Water is expelled faster than it can enter the geyser's plumbing system, and the heat and pressure gradually decrease. The eruption stops when the water reservoir is depleted or when the system cools.

collaboration with many researchers from outside the National Park Service.

National Park Service policy generally prohibits any interference with geothermal activity in Yellowstone. New road or other construction through hydrothermal areas is designed to mitigate impacts. In 1994, the National Park Service and State of Montana established a water rights compact and controlled groundwater area to protect geothermal resources in the park from groundwater or geothermal development that could occur in a designated area north and west of the park in Montana.

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The geology below Yellowstone Lake reflects shaping by lava flows where the lake lies within the caldera and shaping by glacial and other processes in the southern half of the lake that lies outside the caldera.

Yellowstone Lake Geology

Until the late 1990s, few details were known about the geology beneath Yellowstone Lake. In 1996, researchers saw anomalies on the floor of Bridge Bay as they took depth soundings. They deployed a submersible remotely operated vehicle (ROV) equipped with photographic equipment and sector-scan sonar. Large targets appeared on the sonar image, then suddenly very large, spire-like structures appeared in the photographic field of view. These structures looked similar to hydrothermal structures found in deep ocean areas, such as the Mid-Atlantic Ridge and the Juan de Fuca Ridge. The structures also provided habitat for aquatic species such as fresh-water sponges and algae.

Lake-bottom Surveys

From 1999 to 2007, scientists from the US Geological Survey and a private company, Eastern Oceanics, surveyed the bottom of Yellowstone Lake using high-resolution, multi-beam swath sonar imaging, seismic reflection profiling, and a ROV. The survey confirmed the northern half of the lake is inside the 640,000-year-old Yellowstone Caldera and mapped previously unknown features such as large hydrothermal explosion craters, siliceous spires, hundreds of hydrothermal vents and craters and fissures. The survey also mapped young previously unmapped faults, landslide deposits, and submerged older lake shorelines. These features are part of an undulating landscape shaped by rhyolitic lava flows that filled the caldera. The southern half of the lake lies outside the caldera and has been shaped by glacial and other processes. The floor of the Southeast Arm has many glacial features, similar to the glacial terrain seen on land in Jackson Hole, south of the park.

These new surveys give an accurate picture of the geologic processes shaping Yellowstone Lake and

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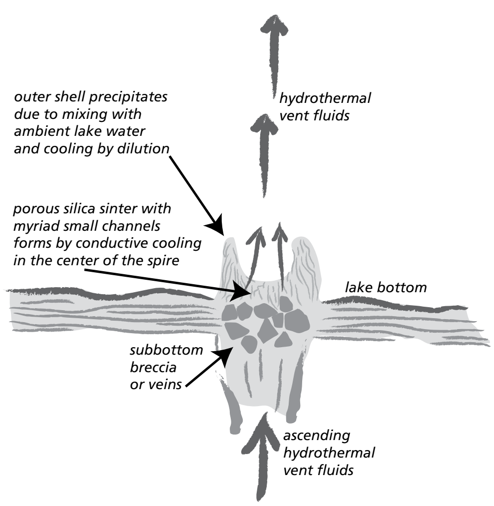
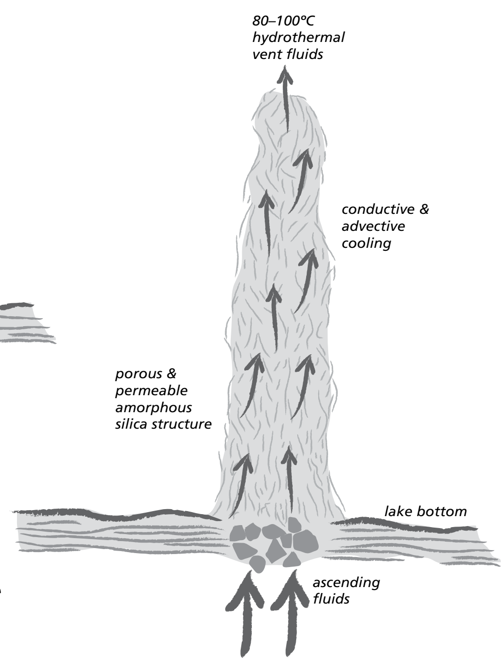
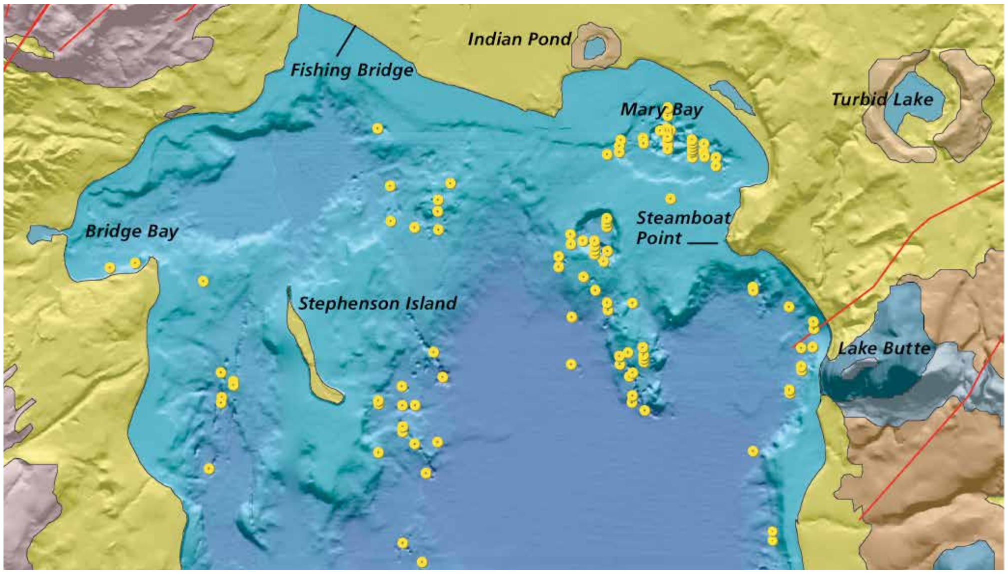
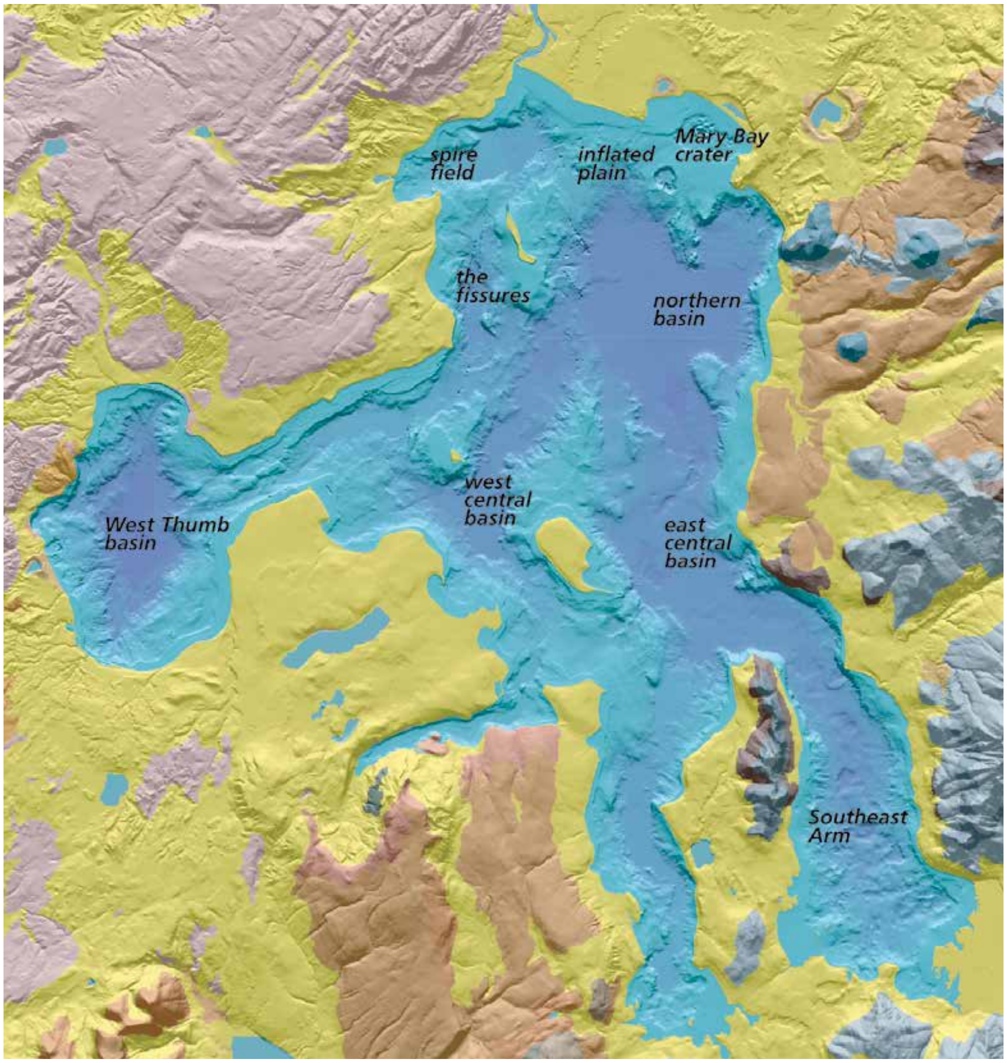




A photo of a Bridge Bay spire, initial spire growth (center), and a mature spire (right). Illustrations adapted from originals by Yellowstone National Park researcher and US Geological Survey research geologist Lisa Morgan.





Yellowstone Lake has existed since the end of the Pinedale glaciation. The lake drains north from its outlet at Fishing Bridge, into the vast Atlantic Ocean drainage via the Yellowstone River. The elevation of the lake's north end does not drop substantially until LeHardy's Rapids, which is considered the northern geologic boundary of the lake. The top map shows locations of hydrothermal vents in northern Yellowstone Lake; the map below shows the geologic features of the lake bottom. Both maps resulted from the five-year survey project.

determine geologic influences affecting the present-day aquatic biosphere. For example, hydrothermal explosions formed craters at Mary Bay and Turbid Lake. Spires may form similarly to black smoker chimneys, which are hydrothermal features associated with oceanic plate boundaries.

Spire analysis

With the cooperation of the National Park Service, scientists from the University of Wisconsin–Milwaukee collected pieces of spires and a complete small spire for study by several teams. They conducted a CAT scan of the spire, which showed structures seeming to be conduits, perhaps for hydrothermal circulation. When they cut open the spire, they confirmed the presence of conduits and also saw a layered structure.

Tests by the US Geological Survey show that the spire is about 11,000 years old, which indicates it was formed after the last glaciers retreated. In addition to silica, the spire contains diatom tests (shells) and silica produced by underwater hydrothermal processes. The spire's interior shows evidence of thermophilic bacteria. Scientists say this suggests that silica precipitated on bacterial filaments, thus playing an important role in building the spire.

Both research projects expanded our understanding of the geological processes at work beneath Yellowstone Lake. Additional study of the spires and other underwater features will continue to contribute to our understanding of the relationship between these features and the aquatic ecosystem.

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Approximately 1,000 to 3,000 earthquakes occur each year in the Yellowstone area; most are not felt. The 1959 Hebgen Lake earthquake (M7.3) caused significant damage to park roads, show here near Gibbon Falls.

Earthquakes

Yellowstone is one of the most seismically active areas in the United States. Approximately 1,000 to 3,000 earthquakes occur each year in the Yellowstone area; most are not felt. They result from the enormous number of faults associated with the volcano.

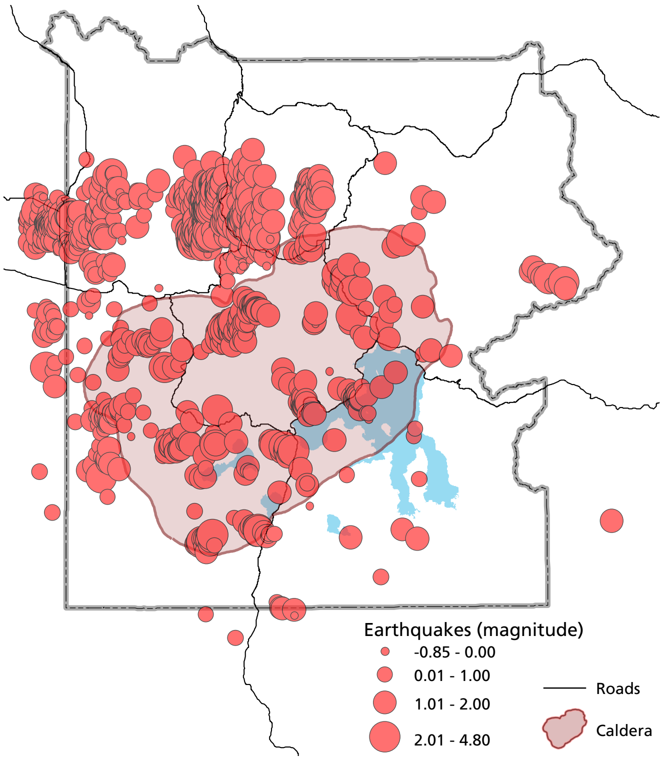
Earthquakes occur along fractures in the crust where stress from crustal plate movement and volcanic activity build to a significant level. The rock along these faults becomes so strained that eventually it slips or breaks. Energy is then released as shock waves (seismic waves) that reverberate throughout the surrounding rock. Once a seismic wave reaches the surface of the Earth, it may be felt. Surface waves affect the ground, which can roll, crack open, or be vertically and/or laterally displaced. Structures are susceptible to earthquake damage because the ground motion is dominantly horizontal.

In Yellowstone, earthquakes help to maintain hydrothermal activity by keeping the "plumbing" system open. Without periodic disturbance of relatively small earthquakes, the small fractures and conduits that supply hot water to geysers and hot springs might be sealed by mineral deposition. Some earthquakes generate changes in Yellowstone's hydrothermal systems. For example, the 1959 Hebgen Lake and 1983 Borah Peak earthquakes of magnitude 7.3 and 6.9, respectively, caused measurable changes in Old Faithful Geyser and other hydrothermal features.

Yellowstone commonly experiences "earthquake swarms"—a series of earthquakes over a short period of time in a localized area. The largest swarm occurred in 1985, with more than 3,000 earthquakes recorded during three months on the northwest side of the park. Hundreds of quakes were recorded during swarms in 2009 (near Lake Village) and 2010 (between Old Faithful area and West Yellowstone). Scientists interpret these swarms as due to shifting and changing pressures in the Earth's crust that are caused by migration of hydrothermal fluids, a natural occurrence of volcanoes.

Earthquakes help us to map and to understand the sub-surface geology around and beneath Yellowstone. The energy from earthquakes travels through hard and molten rock at different rates. Scientists can "see" the subsurface and make images of the magma chamber and the caldera by "reading" the seismic waves emitted during earthquakes. An extensive geological monitoring system is in place to aid in that interpretation.

On March 30, 2014 at 6:34 am Mountain Daylight Time, an earthquake of magnitude 4.8 occurred four



Approximately 2,000 earthquakes occurred in Yellowstone in 2014. Red dots = earthquakes. Earthquake data provided courtesy University of Utah.

miles north-northeast of Norris Geyser Basin. The M4.8 earthquake was reported felt in Yellowstone National Park, in the towns of Gardiner and West Yellowstone, Montana and throughout the region. This is the largest earthquake at Yellowstone since the early 1980s and was part of a notable GPS-determined uplift episode of 3 cm at Norris that built up in the 4 months prior to the quake. The area returned to subsidence in the following 4 months. Analysis of the earthquake indicated a tectonic origin and was part of a sequence of earthquake swarms located north and northwest of Norris that began in Sept. 2013. Notably, the M4.8 event occurred at the same time that the Yellowstone caldera began to experience increased uplift rates up to +6 cm/yr, among the highest of the Yellowstone caldera uplift in modern history.

More Information

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Much of Yellowstone was shaped by glaciers. Glacial erratics are scattered across Yellowstone's landscape, shown here with a kettle pond in the Lamar Valley.

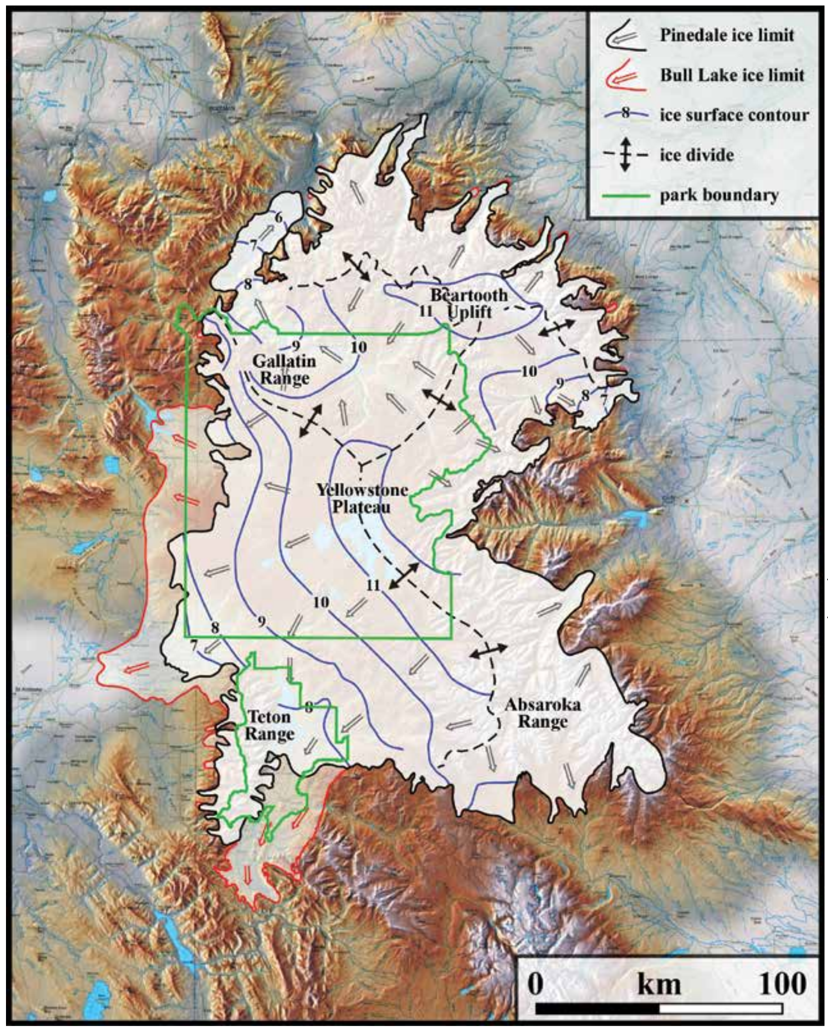
Glaciers

Glaciers result when, for a period of years, more snow falls in an area than melts. Once the snow reaches a certain depth, it turns into ice and begins to move under the force of gravity or the pressure of its own weight. During this movement, rocks are picked up and carried in the ice, and these rocks grind Earth's surface. Ice and water erode and transport earth materials as well as rocks and sediments. Glaciers also deposit materials. Large U-shaped valleys, ridges of debris (moraines), and out-of-place boulders (erratics) are evidence of a glacier's passing.

Yellowstone and much of North America have experienced numerous periods of glaciation during the last 2.6 million years. Succeeding periods of glaciation have destroyed most surface evidence of previous glacial periods, but scientists have found evidence of them in sediment cores taken on land and in the ocean. In Yellowstone, a glacial deposit near Tower Fall dates back 1.3 million years. Evidence of such ancient glaciers is rare.

The Bull Lake glaciers covered the region about 151,000 to 160,000 years ago. Evidence exists that this glacial episode extended farther south and west of Yellowstone than the subsequent Pinedale Glaciation, but little surface evidence of it is found to the north and east. This indicates that the Pinedale Glaciation covered or eroded surface evidence of Bull Lake Glaciation in these areas.

The Yellowstone region's last major glaciation, the Pinedale, is the most studied. Its beginning has been hard to pin down because field evidence is missing or inconclusive and dating techniques are inadequate.



MODIFIED BY J. LICCIARDI IN DECEMBER 2015 FROM LICCIARDI AND PIERCE (2008)

Light shaded areas bounded by black and red lines indicate the areas covered during the Pinedale and Bull Lake glaciations, respectively. Blue lines are contours in thousands of feet on the reconstructed Pinedale glacier surface. Black dashed lines with double-pointed arrows indicate main ice divides. Yellowstone and Grand Teton National Park boundaries are shown by green outlines.

Ages of Pinedale maximum vary around the Yellowstone Ice Cap from 21,000 years ago on the east to 20,000 years ago on the north and possibly as young as 15,000–16,000 years ago on the south. Most of the Yellowstone Plateau was ice free between 13,000 to 14,000 years ago.

During the Pinedale glaciation, glaciers advanced and retreated from the Beartooth Plateau, altering the present-day northern range and other grassy landscapes. During glacial retreat, water flowed differently over Hayden Valley and deposited various sediments. Glacial dams also backed up water over Lamar Valley; when the dams lifted, catastrophic floods helped to form the modern landscape around the North Entrance of the park.

During the Pinedale's peak, nearly all of Yellowstone was covered by an ice cap up to 4,000 feet thick. Mount Washburn was completely covered by ice. This ice cap was not part of the continental ice sheet extending south from Canada. The ice cap occurred here, in part, because Yellowstone's higher elevation volcanic plateau allowed snow to accumulate.

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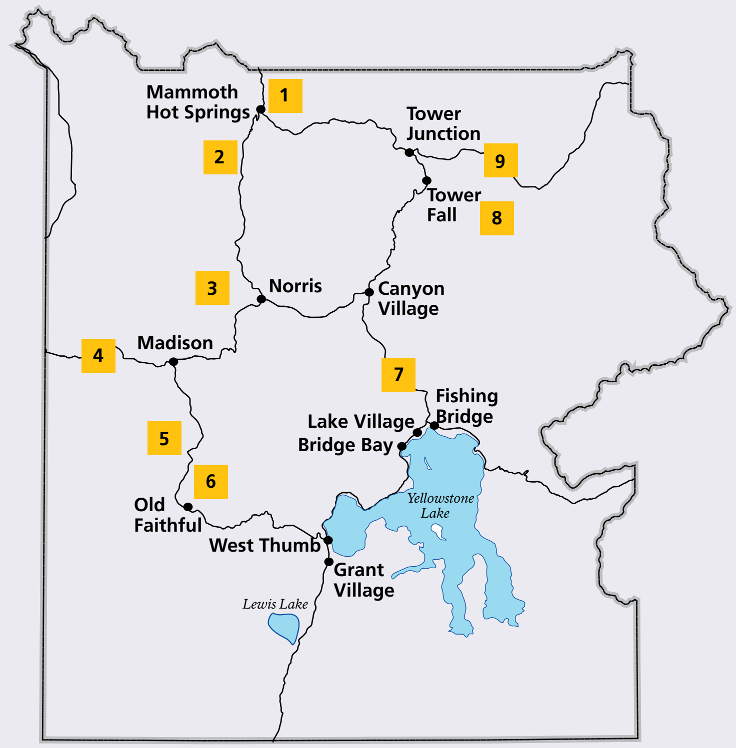
Where to See Evidence of Glaciers



1. Mammoth Hot Springs: Thermal kames exist in this area. Mount Everts and Bunsen Peak were both overridden by ice. The top of Sepulcher peeked above the Pinedale ice.
2. Swan Lake Flat: These meadows and wetlands formed after the glaciers retreated. Electric Peak, to the northwest, was also carved by glaciers.
3. Norris Geyser Basin: Several high peaks in the Gallatin Mountains were above the Pinedale ice cap.
4. Madison Valley, west of Seven Mile Bridge: Glacial moraines, glacial outwash, and recent Madison River deposits can be seen.
5. Fountain Flats: The Porcupine Hills and Twin Buttes are thermal kames.
6. Upper Geyser Basin: Volcanic rocks and ice-water contact deposits. Deposits underlying this and other area geyser basins store the water necessary for geysers to occur and allow the water to percolate up from depth.
7. Hayden Valley: The valley is covered with glacial till left from the most recent glacial retreat. It also has a variety of glacial and ice-water contact deposits. This glacial till contains many different grain sizes, including clay and a thin layer of lake sediments that do not allow water to percolate quickly into the ground. Thus, Hayden Valley is marshy.
8. Tower Fall area: North of Tower Fall, sediments between layers of basalts may show evidence of the oldest known glaciation in Yellowstone. Plus, huge boulders (known as erratics) from the last major glaciation rest atop the youngest basalt.
9. Lamar Valley: Huge boulders and ponds between the Lamar and Yellowstone rivers were left by melting glaciers, as were several moraines. Other ponds are within post glacial landslides.

Sedimentation and erosion actively shape Yellowstone's landscape. Here, the Lamar River erodes its banks, depositing the sediment elsewhere.

Sedimentation and Erosion

Not all the rocks in Yellowstone are of "recent" volcanic origin. Precambrian igneous and metamorphic rock in the northeastern portion of the park and Beartooth Plateau are at least 2.7 billion years old. These rocks are very hard and erode slowly.

Sedimentary sandstones and shales, deposited by seas during the Paleozoic and Mesozoic eras (approximately 540 million to 66 million years ago) can be seen in the Gallatin Range and Mount Everts. Sedimentary rocks in Yellowstone tend to erode more easily than the Precambrian rocks.

Weathering breaks down earth materials from large sizes to small particles, and happens in place. The freeze/thaw action of ice is one type of weathering common in Yellowstone. Agents of erosion—wind, water, ice, and waves—move weathered materials from one place to another.

When erosion takes place, sedimentation—the deposition of material—also eventually occurs. Through time, sediments are buried by more sediments and the material hardens into rock. This rock is eventually exposed (through erosion, uplift, and/or faulting), and the cycle repeats itself. Sedimentation and erosion are "reshapers" and "refiners" of the landscape—and they also expose Yellowstone's past life as seen in fossils like the petrified trees.

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Left: The Beartooth Mountains northeast of Yellowstone are actually an uplifted block of Precambrian rock. Right: Mt. Everts, near Mammoth, exposes sedimentary rock, which erodes easily and often tumbles or slides into Gardner Canyon.

Petrified trees in Yellowstone are the result of volcanic debris flows that occurred about 50 million years ago. This piece of petrified wood shows annual rings.

Fossils

The fossil record of Yellowstone is one of the most diverse in the NPS. Fossil of plants, invertebrates, vertebrates, and trace fossils have been identified in Yellowstone National Park from more than 40 stratigraphic units (rock layers of known age and origin) spanning more than 540 million years from the Cambrian to the Cenozoic eras.

Paleontological resources, or fossils, are any remains of past life preserved in geologic context. Yellowstone holds the two main types of fossils: body fossils and trace fossils. Body fossils are the physical remains of an actual organism (shells, bones, teeth, plant leaves, etc.), while trace fossils (burrows, coprolites, footprints, trackways, etc.) preserve evidence of an organism's activity or behavior. Best known in Yellowstone are the fossil forests of Specimen Ridge, where the remains of hundreds of 50-million-year-old trees stand exposed on a steep hillside, with trunks up to eight feet in diameter and some more than 20 feet tall.

Although the park's paleontologic resources are extensive and scientifically valuable, it is estimated that only 3% of the park's potentially fossil-bearing units have been assessed. Erosion is the key to discovery of nearly all paleontological specimens; however, once exposed, fossils are subjected to physical and chemical forces that can quickly become destructive to them.

Yellowstone's petrified trees occur within volcanic rocks approximately 50 million years old. They are the result of rapid burial and silicification, not volcanic eruptions.

Collecting any natural resources, including rocks and fossils, is illegal in Yellowstone.

Fossils are a non-renewable resource. Road construction, other infrastructure development, and illegal collecting can also impact fossil-bearing units. Due to the fragility of most fossils, it is necessary to inventory and document fossil localities to evaluate existing fossil material and obtain baseline information so that appropriate management decisions can be made about these areas.

The fossils of Yellowstone have long been studied and have already contributed to important scientific findings. Research in the park by Charles Walcott on trilobites in the late 1800s provided the foundation for his theory of the "Cambrian Explosion," a term he used to describe the relatively sudden appearance of complex multi-cellular life possessing "hard parts" such as phosphatic or calcitic exoskeletons.

Sediment cores from the bottom of Yellowstone's lakes contain fossils of pollen deposited during the Late Pleistocene. These pollen records show which plants were present at that time and allow researchers to infer climate conditions. The pollen in sediment layers illustrates the changes in vegetation and climate over time, providing a model of regional reforestation and climate history.

Paleontologists have also devoted much attention to the Eocene fossil plant material in the park, using it to inform regional studies of the paleoclimate and paleoecology of that period. Much could be gained in understanding current global climate change by studying Eocene times, an episode of rapid and intense warming when our planet was at its hottest.

Paleobotany

Nearly 150 species of fossil plants (exclusive of fossil pollen specimens) from Yellowstone have been described, including ferns, horsetail rushes, conifers, and deciduous plants such as sycamores, walnuts, oaks, chestnuts, maples, and hickories. Sequoia is abundant, and other species such as spruce and fir are also present.

Most petrified wood and other plant fossils come from Eocene deposits about 50 million years old, which occur in many northern parts of the park.

The first fossil plants from Yellowstone were collected by the early Hayden Survey parties. In his 1878 report, Holmes made the first reference to Yellowstone's fossil "forests."

Around 1900, F. H. Knowlton identified 147 species of fossil plants from Yellowstone, 81 of them new to science. He also proposed the theory that the petrified trees on the northwest end of Specimen Ridge were forests petrified in place.

Additional studies and observations informed a modification of Knowlton's original hypothesis. Andesitic volcanic eruptions such as the 1980 eruption of Mount St. Helens showed that trees are uprooted by rapidly flowing volcanic debris flows. The volcanic debris flows not only transported the trees to lower elevations, the trees were also deposited upright. Thus, with increased scientific knowledge, our understanding of Yellowstone's fossil forests has changed.

Cretaceous marine and nonmarine sediments are exposed on Mount Everts and other areas in Yellowstone. Similar to Cretaceous rocks throughout the Rocky Mountains, fossil leaves, ferns, clam-like fossils, shark teeth, and several species of vertebrates have been found. In 1994 fossil plants were discovered in Yellowstone during the East Entrance road construction project, which uncovered areas containing fossil sycamore leaves and petrified wood.

Fossil Invertebrates

Fossil invertebrates are abundant in Paleozoic rocks, especially the limestones associated with the Madison Group in the northern and south-central parts of the park. They include corals, bryozoans, brachiopods, trilobites, gastropods, and crinoids. Trace fossils, such as channeling and burrowing of worms, are found in some petrified tree bark.

Fossil Vertebrates

Fossil remains of vertebrates are rare, but perhaps only because of insufficient field research. A one-day survey led by paleontologist Jack Horner, of the Museum of the Rockies, Bozeman, Montana, resulted in the discovery of the skeleton of a Cretaceous vertebrate. Other vertebrate fossils found in Yellowstone include:

- Fish: crushing tooth plate; phosphatized fish bones; fish scales; fish teeth.
- Horse: possible Pleistocene horse, *Equus nebraskensis*, reported in 1939.
- Other mammals: Holocene mammals recovered from Lamar Cave; Titanothere (type of rhinoceros) tooth and mandible found on Mt. Hornaday in 1999.

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