United States Department of the Interior

NATIONAL PARK SERVICE
PO Box 168
Yellowstone National Park
Wyoming 82190

IN REPLY REFER TO:

YELL 282a
7/06

Dear Student of Geology:

Enclosed is the information you requested on the geology of Yellowstone National Park. We hope you find the information useful in learning about the dynamic and fascinating geology of Yellowstone, the world's first national park.

Please visit our official Website at www.nps.gov/yell for further information and current conditions at the park.

Division of Interpretation
Yellowstone National Park

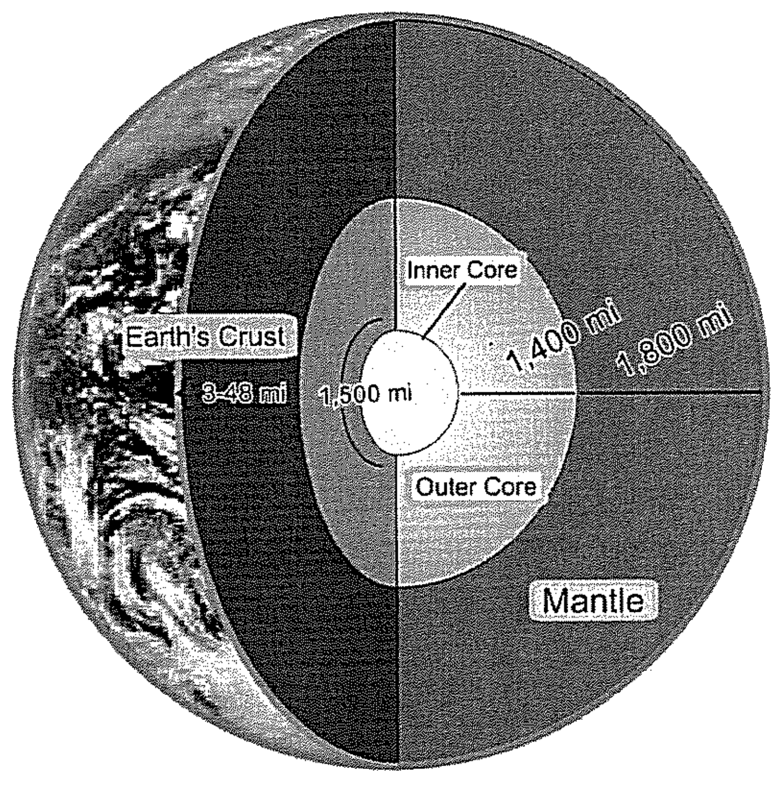
Geology

3

Yellowstone National Park's unique physical landscape has been and is being created by many geological forces. Here, 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, and other geologic wonders such as the Grand Canyon of the Yellowstone River.

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 more than 300 geysers.
- The largest concentration of active geysers in the world—approximately half of the world's total.
- Most of the undisturbed geyser basins left in the world (Kamchatka Peninsula has the others; the rest have been modified or destroyed by human development.)
- One of the few places in the world where active travertine terraces are found, at Mammoth Hot Springs.
- Site of many petrified trees resulting from repeated volcanic eruptions over the ages.



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 gives rise to forces that shape 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 *(see at right).* The distance from the Earth's surface to its center or core is approximately 4,000 miles. The core may once have been entirely molten, but, as the planet cooled, the inner core (about 1,500 miles thick) solidified. The outer core (about 1,400 miles thick) remains molten and is surrounded by a 1,800 mile thick mantle of dense, mostly solid rock. Above this layer is the relatively thin crust, three to forty-eight miles thick, on which the continents and ocean floors are found.

The Earth's lithosphere (crust and upper mantle) is divided into many plates, which are in constant motion. Where plate edges meet, one plate may slide past another, one plate may be driven beneath another (subduction), or upwelling volcanic material pushes the plates apart at mid-ocean ridges. Continental plates are made of less dense rocks (granites) than oceanic plates (basalts) and thus, "ride" higher than oceanic plates. Many theories have been proposed to explain crustal plate movement. Currently, most 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, as described on the next pages.

3 Ancient Yellowstone

Illustrations on pages 38, 39, 40, and 46 adapted with permission from Windows Into the Earth, *Dr. Robert Smith and Lee J. Siegel, 2000.*

See Chapter 10 for more information about geology in the park's major areas.

This chapter focuses on events and processes of the last 20 million years that have created the park we see today— a tiny fraction of the 4.6 billion years of the planet's existence.

Most of Earth's history (from the beginning to approximately 570 million years ago) is known as the Precambrian era. Rocks of this age are found in northern Yellowstone and in the hearts of the Teton, Beartooth, Wind River, and Gros Ventre ranges. Throughout much of this era, the West was repeatedly flooded by ancient seas. During the Paleozoic and Mesozoic eras (570 to 66 million years ago), this area was covered at times by ocean. At other times it was a land of sand dunes, tidal flats, and vast plains. Near the end of this era, mountain building processes created 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. Volcanic debris buried trees that are seen today as fossilized remnants along Specimen Ridge in northern Yellowstone. This period of volcanism is not related to the present Yellowstone volcano.

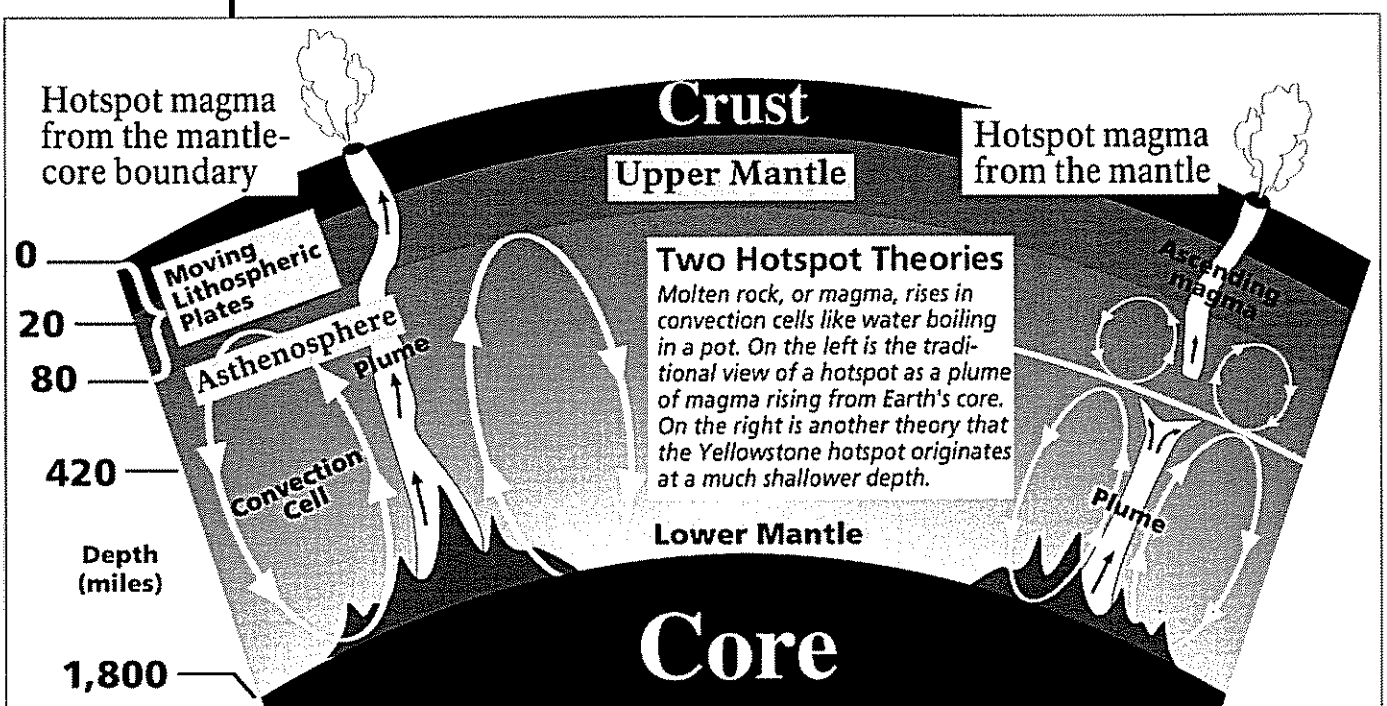
Approximately 30 million years ago, vast expanses of the West began stretching apart along an east-west axis. This stretching process increased about 17 million years ago and continues today, creating the modern basin and range topography (north-south mountain ranges interspersed with long north-south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

About 16.5 million years ago, a great period of volcanism appeared near the area now marked by the convergence of the Nevada, Oregon, and Idaho state lines. Repeated volcanic eruptions can be traced across southern Idaho into Yellowstone National Park. This volcanism remains a driving force in Yellowstone today.

Magma & Hotspots

Magma (molten rock from Earth's mantle) rises to within a few miles of the surface in Yellowstone. This heat fuels the Yellowstone volcano and its associated hydrothermal areas. How it rises and whether or not a hotspot is involved remain the subject of much scientific research and discussion. *(See illustration below.)*

Traditional hotspot theory holds that a plume of molten rock rises all the way from Earth's core-mantle boundary to trigger volcanic



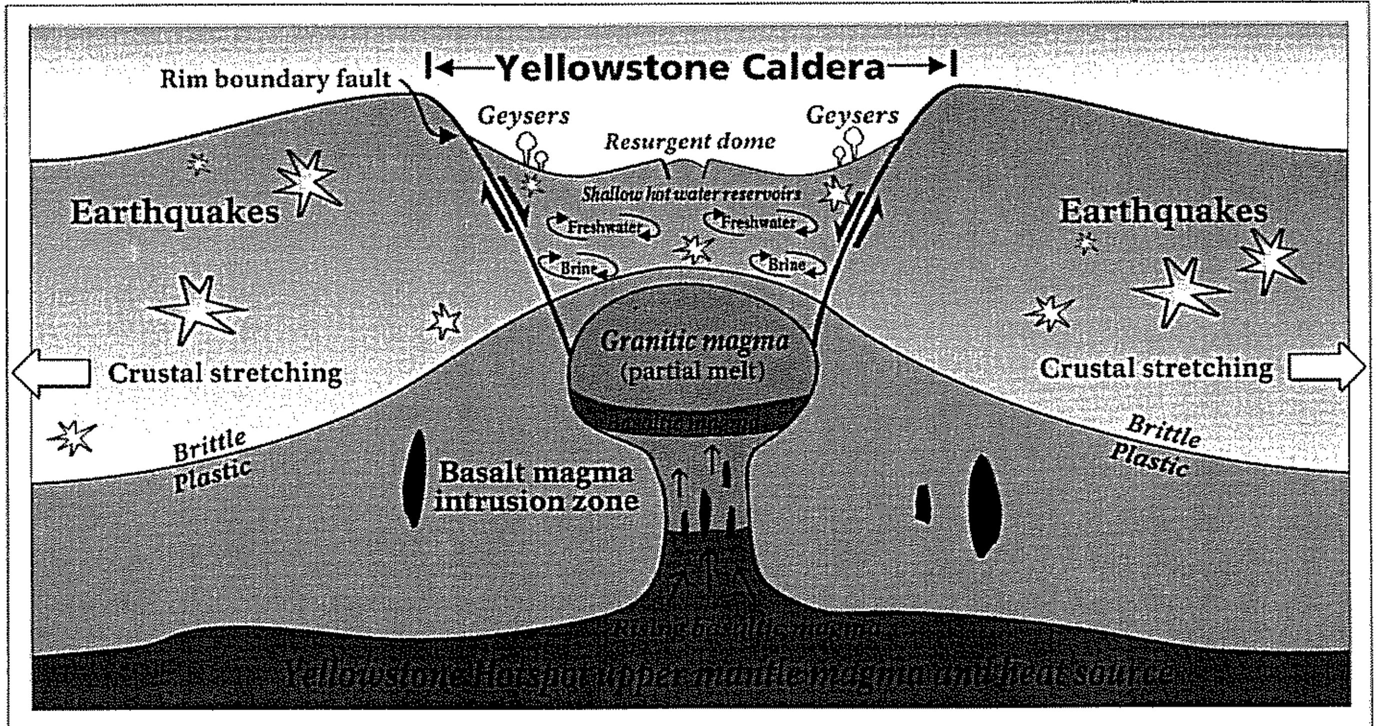
Two Hotspot Theories
Molten rock, or magma, rises in convection cells like water boiling in a pot. On the left is the traditional view of a hotspot as a plume of magma rising from Earth's core. On the right is another theory that the Yellowstone hotspot originates at a much shallower depth.

eruptions at the surface. Newer theories relate the rise of molten rock to areas in Earth's crust weakened by stretching and thinning such as that which is ongoing throughout the interior West. Some of these theories also propose a shallower mantle origin for hotspots. Still other theories place Yellowstone's hotspot on the surface as a manifestation of longlived volcanism.

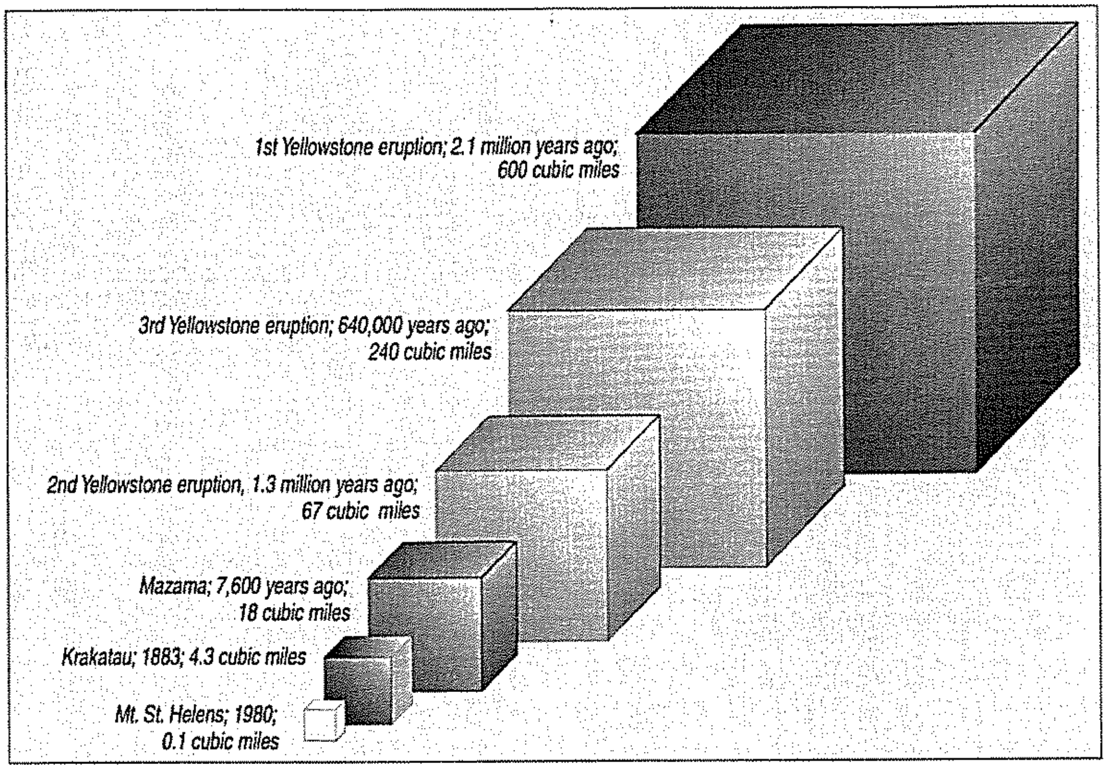
Regardless of its origins and subsurface behavior, the magma chamber feeding Yellowstone's volcano has been close to the surface for some 16.5 million years, erupting repeatedly and leaving a track of 100 gigantic calderas (craters) across 500 miles from the Nevada-Oregon border northeast up Idaho's Snake River Plain and into central Yellowstone. This trail of evidence was created as the North American plate moved in a southwestern direction over the shallow magma. Earth's surface bulges above it, notable in the Yellowstone area where the average elevation is 1,700 feet higher than surrounding regions.

About 2.1 million years ago, the movement of the North American plate brought the Yellowstone area into proximity with the shallow magma. The heat melted rocks in the crust, creating a magma chamber of partially molten, partially solid rock (see below). Upward pressure from the shallow magma chamber cause overlying rocks 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 eruption then occurred, spewing volcanic ash and gas high into the atmosphere and causing fast-moving superhot pyroclastic flows on the ground. As the underground magma chamber emptied, the ground above it sunk, creating a huge crater known as the Huckleberry Ridge Caldera. Smaller lava flows eventually filled in the caldera over tens to hundreds of thousands of years.

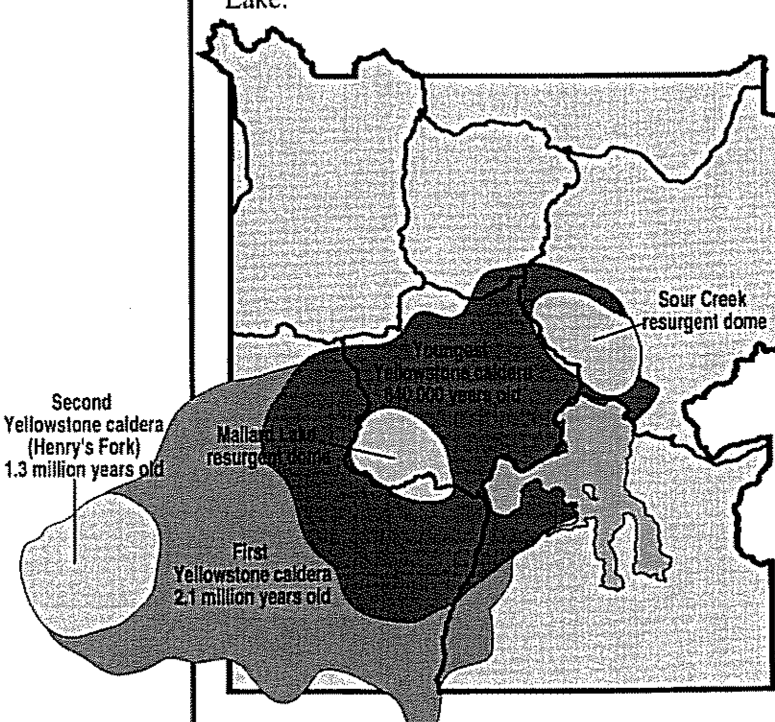
The volume of material ejected during this eruption is estimated to have been 2,400 times the size of the 1980 eruption of Mt. St. Helens in Washington *(see illustration next page)*, and ash has been found as far away as Missouri. Approximately 800,000 years later, a second, smaller volcanic eruption occurred on the western edge of the Huckleberry



At Yellowstone and some other volcanoes, some scientists theorize that Earth's crust fractures and cracks in a concentric or ring-fracture pattern. At some point these cracks reach the magma "reservoir," release the pressure, and the volcano explodes. The huge amount of material released causes the volcano to collapse into a huge steaming crater—a caldera.



Ridge Caldera and created the Henry's Fork Caldera. Then 640,000 years ago, the third massive volcanic eruption in central Yellowstone created the Yellowstone Caldera, 30 by 45 miles in size. About 162,000 years ago, a volcanic eruption created a smaller caldera now filled by the West Thumb of Yellowstone Lake.



Yellowstone remains atop the shallow magma. The pressure and movement of the underlying heat, magma, and fluids cause the entire caldera floor to inflate and deflate rapidly (compared to more typical geologic processes). Rising magma has created two large bulges in the Earth called resurgent domes (Sour Creek and Mallard Lake), which we see as large hills.

From the summit of Mt. Washburn, one can look south into much of this vast volcanic feature. The caldera rim is also visible along the park road system at Gibbon Falls, Lewis Falls, and Lake Butte.

Future Volcanic Activity

Will Yellowstone's volcano have another catastrophic eruption? Over the next thousands to millions of years, probably. In the next few hundred years? Not likely.

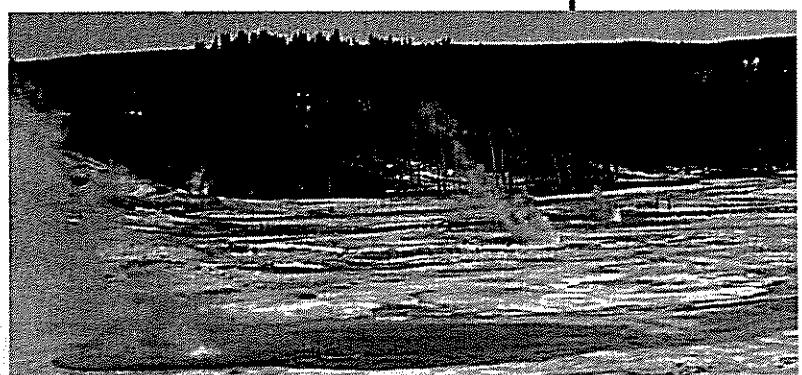
More likely activity would be lava flows, such as those that occurred after the last major eruption. Such a lava flow would ooze slowly over months and years, allowing plenty of time for park managers to evaluate the situation and protect people. There is no scientific evidence indicating such a lava flow will occur soon.

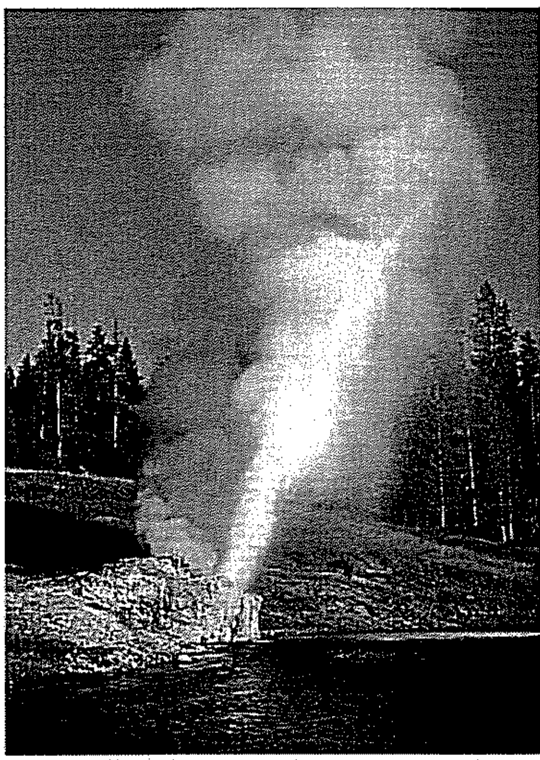
Geyser Basin Systems

Yellowstone's hydrothermal features would not exist without the underlying magma body that releases tremendous heat. They also depend on sources of water, such as in the mountains surrounding the Yellowstone Plateau. There, snow and rain slowly percolate through layers of porous rock riddled with cracks and fissures. Some of this cold water meets hot saline 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 rock and water. The result is superheated water with temperatures exceeding 400°F.

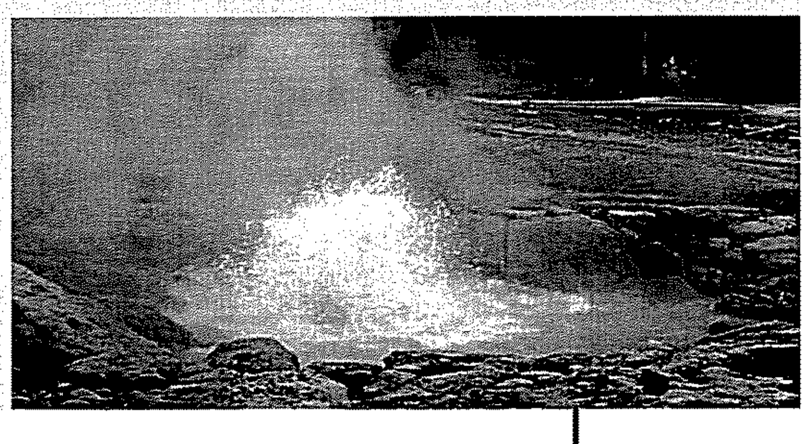
The superheated water is less dense than the colder, heavier water sinking around it. This creates convection currents that allow the lighter, more buoyant, superheated water to begin its slow journey back to the surface following the cracks, fissures, and weak areas through rhyolitic lava flows. As hot water travels through this rock, high temperatures dissolve some silica in the rhyolite.

While in solution underground, some silica coats the walls of the cracks and fissures to form a nearly pressure-tight seal. This locks in the hot water and creates a "plumbing" system that can withstand the great pressure needed to produce a geyser. At the surface, silica precipitates to form either geyserite or sinter, creating the massive geyser cones, the scalloped edges of hot springs, and the seemingly barren landscape of geyser basins.





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, much as it does with depth in the ocean. Increased pressure exerted by the enormous weight of the overlying rock and 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 until the bubbles are too large and numerous to pass freely through the tight spots. 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.

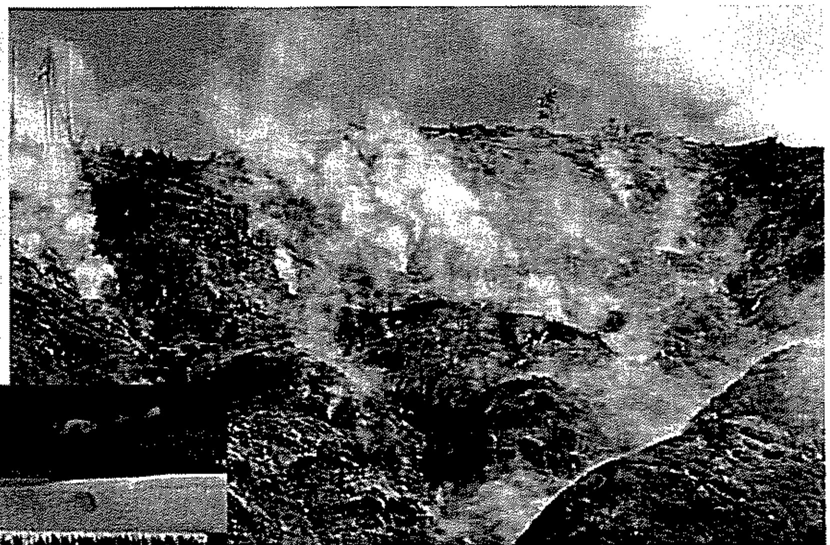


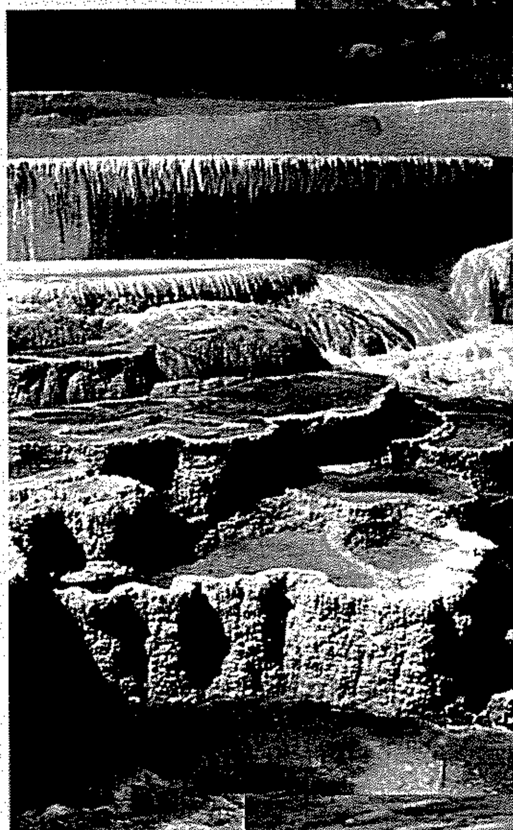
***Geyser basin landscapes**, as at Norris (above right), owe their light, barren appearance to a rock called sinter. **Cone geysers**, such as Riverside in Upper Geyser Basin (above) erupt in a narrow jet of water, usually from a cone. **Fountain geysers**, such as Echinus in Norris Geyser Basin (right) shoot water in various directions, typically from a pool.*

3

Hydrothermal Features

Fumaroles *or steam vents, are the hottest hydrothermal features in the park. They have so little water that it all flashes into steam before reaching the surface. At places like Roaring Mountain (right), the result is a loud hissing of steam and gases.*

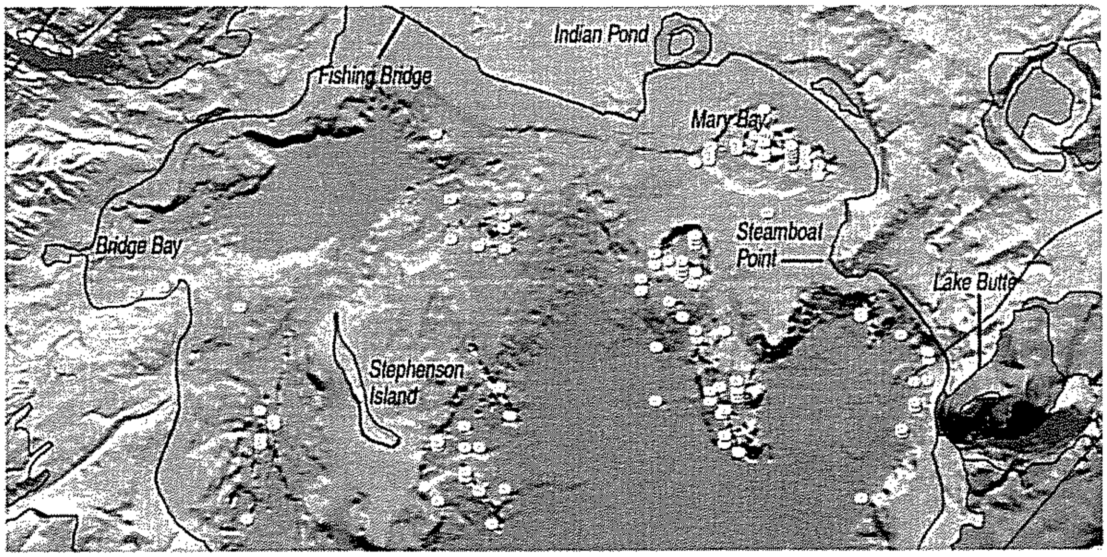




Travertine terraces, *found at Mammoth Hot Springs (right), are formed from limestone (calcium carbonate). Thermal waters rise through the limestone, carrying high amounts of dissolved carbonate. At the surface, carbon dioxide is released and calcium carbonate is deposited as travertine, the chalky white rock of the terraces. Due to the rapid rate of deposition, these features constantly and quickly change.*

Mudpots *such as Fountain Paint Pot (center, right) are acidic hot springs 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. Various gases escape through the wet clay mud, causing it to bubble. Mudpot consistency and activity vary with the seasons and precipitation.*

Hot Springs *such as this one at West Thumb (right) 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 circulation, called convection, prevents water from reaching the temperature needed to set off an eruption.*



Hydrothermal vents in northern Yellowstone Lake (above) were mapped as part of a five-year project. Scientists also are studying spires from Bridge Bay (below) that no one knew existed a decade ago. Scientists think they may be very old hydrothermal vents.

Beneath Yellowstone Lake

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 in the results of single-channel 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 when suddenly very large, spire-like structures appeared in the photographic field of view (photo at right). These structures looked similar to hydrothermal structures found in deep ocean areas, such as the Mid-Atlantic Ridge and the Juan de Fuca Ridge. They also provided habitat for aquatic species such as fresh water sponges and algae.

Lake-bottom Surveys

From 1999 to 2003, scientists from the U.S. 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 showed the northern half of the lake to be 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, active fissures, and domal features containing gas pockets and deformed sediments. Also mapped were young previously unmapped faults, landslide deposits, and submerged older lake shorelines. These features are part of an undulating landscape shaped by old 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.

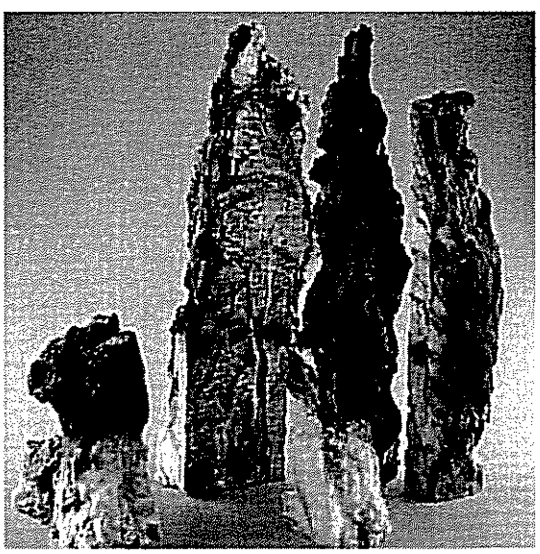
These new surveys give an accurate picture of the geologic forces shaping Yellowstone Lake and determine geologic influences affecting the present-day aquatic biosphere. For example, craters result from hydrothermal explosions caused by water flashing to steam which is often accompanied by failure and fragmentation of overlying caprock. Spires may be formed in a way similar to black smoker chimneys, which are hydrothermal features associated with oceanic plate boundaries.

Spire Analysis

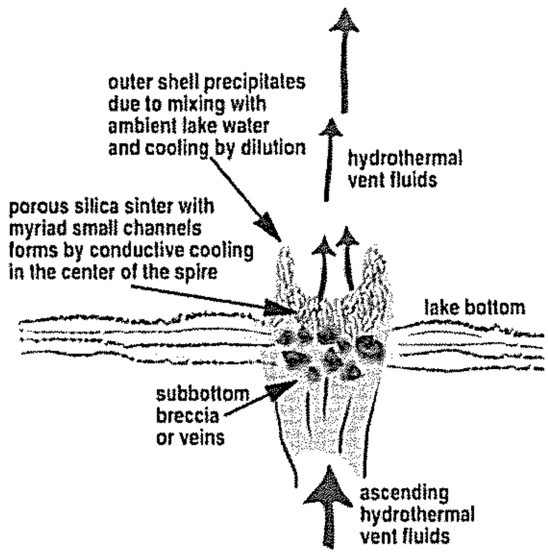
With the cooperation of the National Park Service, scientists from the University of Wisconsin–Milwaukee collected a small spire for study by several teams. They conducted a CAT scan of the spire, which showed structures seeming to be conduits, perhaps for hydrothermal circulation. When they cut open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

Early tests by the U.S. Geological Survey show that the spire may be more than 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. Ongoing investigations include confirming the spire's age and composition.

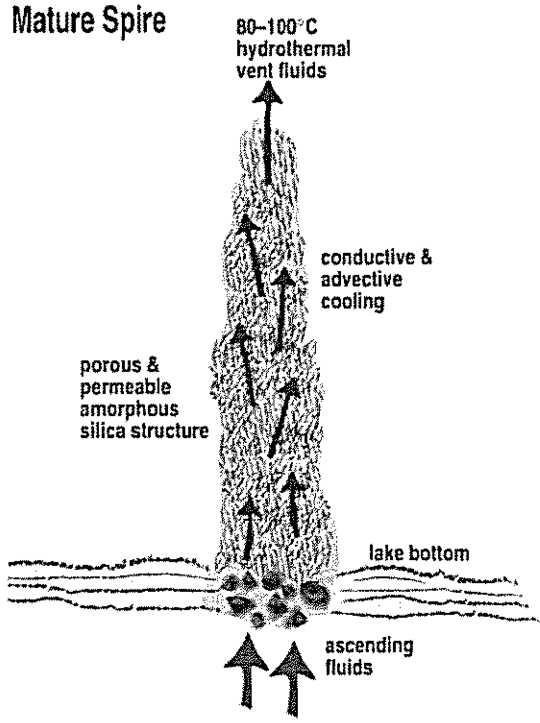
Both research projects have already expanded our understanding of the geological forces at work beneath Yellowstone Lake. Additional study of the spires and other underwater features will continue to contribute to our understanding of the relationship between these features and the aquatic ecosystem.



Initial Spire Growth



Mature Spire



Illustrations on this page adapted from originals by Dr. Lisa A. Morgan, U.S.G.S. Research Geologist

Earthquakes

Earthquakes occur along fault zones in the crust where forces from crustal plate movement build to a significant level. The rock along these faults becomes so stressed that eventually it slips or breaks. Energy is then released as shock waves (seismic waves) that reverberate throughout the surrounding rock.

Different kinds of seismic waves are released inside the earth during an earthquake. Primary waves ("P-waves") move quickly in the direction of travel, compressing and stretching the rock. Secondary waves ("S-waves") move up, down, and sideways through rock in a rolling motion. 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 usually horizontal.

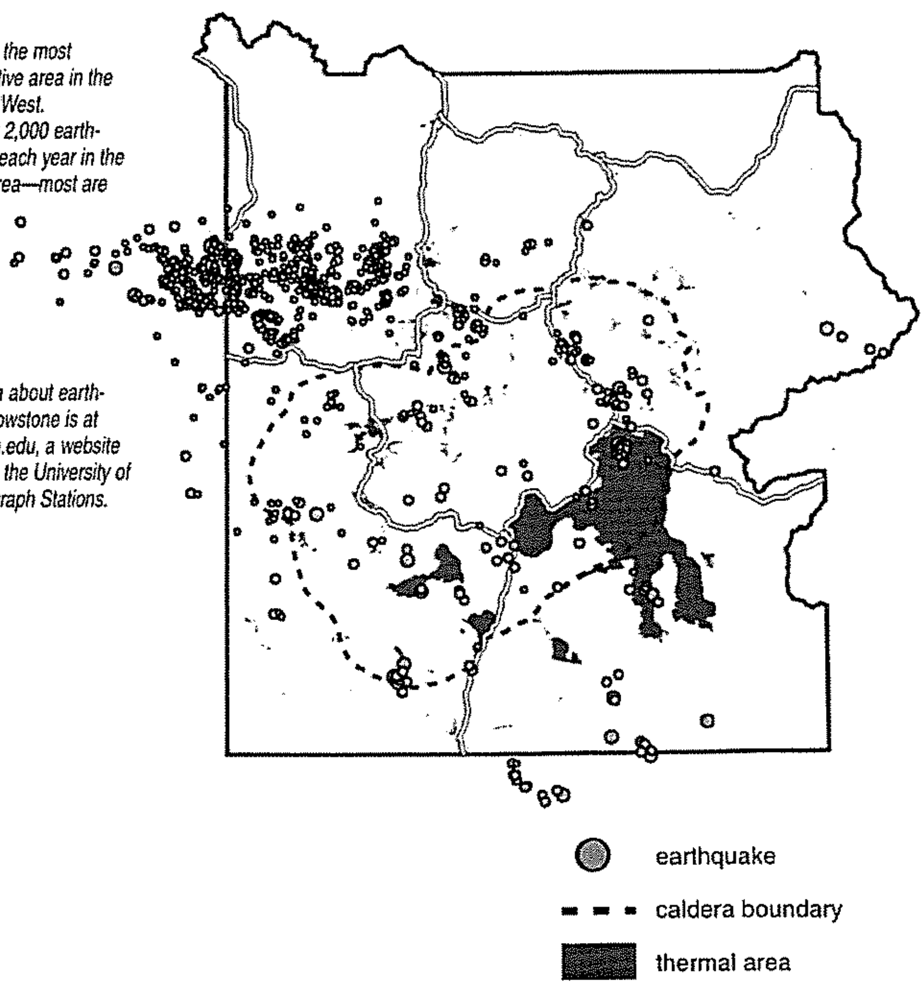
Earthquakes in Yellowstone help to maintain hydrothermal activity by keeping the "plumbing" system open. Without the periodic disturbance of relatively small earthquakes, the small fractures and conduits that supply hot water to geysers and hot springs might be sealed by mineral deposition. Some earthquakes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

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

1,293 Earthquakes in 2004, Yellowstone Area

Yellowstone is the most seismically active area in the Intermountain West. Approximately 2,000 earthquakes occur each year in the Yellowstone area—most are not felt.

Real-time data about earthquakes in Yellowstone is at www.seis.utah.edu, a website maintained by the University of Utah Seismograph Stations.



Scales of Magnitude

The size of an earthquake is given by its magnitude, which is often referred to as Richter Magnitude. On this scale, the amplitude of shaking goes up by a factor of 10 for each unit on the scale. Thus, at the same distance from the earthquake, the shaking will be 10 times as large during a magnitude 5 earthquake as during a magnitude 4 earthquake. The total amount of energy released by the earthquake, however, goes up by a factor of 32. There are many different ways that magnitude is measured from seismograms, partially because each method only works over a limited range of magnitudes and with different types of seismometers. But, all of the methods are designed to agree well over the range where they overlap.

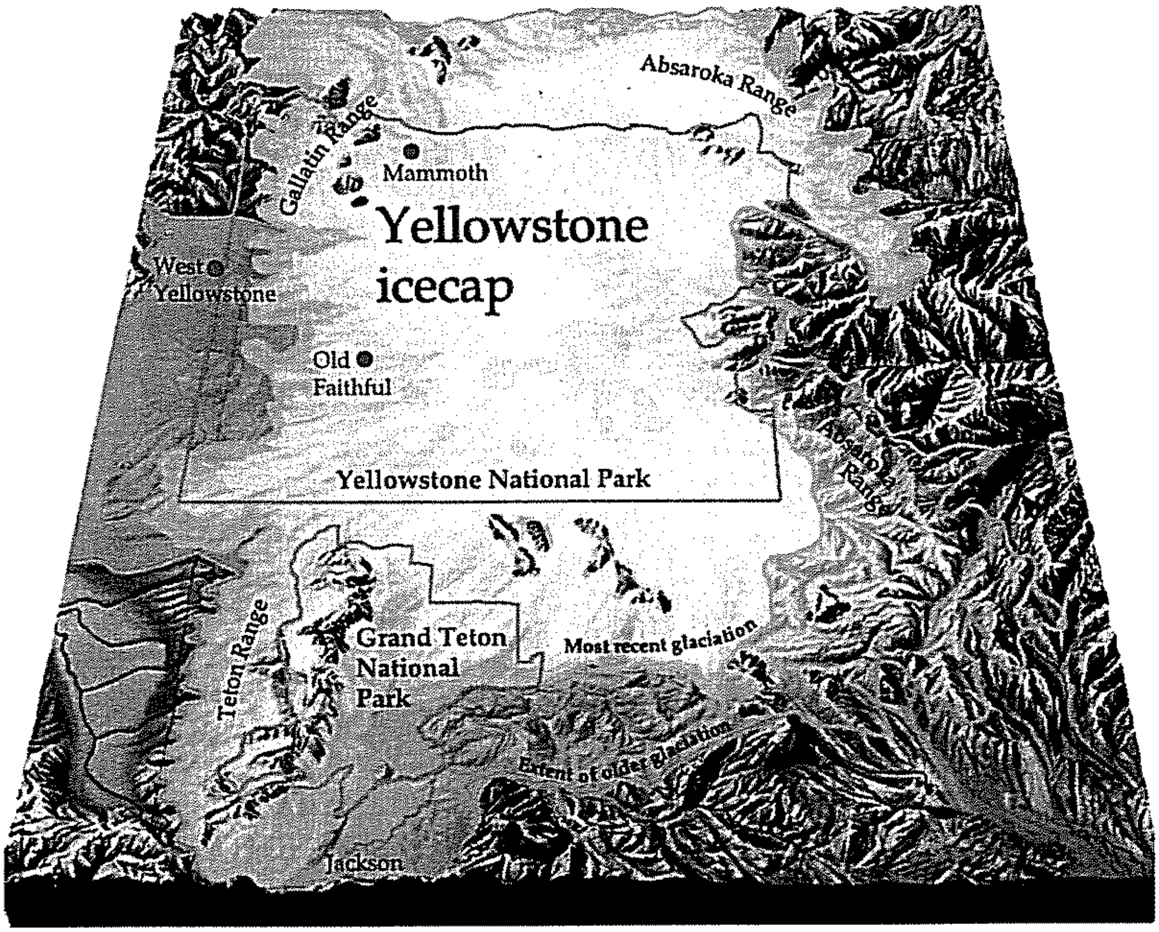
The methods used in University of Utah earthquake listings include:

ML—local magnitude, the original scale defined by Richter and Gutenberg based on the maximum amplitude of the waves. This is the preferred magnitude, when available.

MC—coda magnitude, based on measurements of the duration of the seismic waves for earthquakes up to about magnitude 5.

3

Glaciers



The extent of two major glaciations are shown on this map:
Bull Lake—orange outline
Pinedale—blue outline

Scientific understanding of glacier dates, sequence, and extent continues to evolve, and varying information appears in different references (including previous editions of this book). The information here is considered current by Yellowstone's geologist as of March 2006.

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 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, eroding and carrying material away. 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 two 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.

The Bull Lake Period glaciers covered the region about 140,000 years ago. Evidence exists that this glacial episode extended farther south and west of Yellowstone than the subsequent Pinedale Glaciation *(described in the next paragraph)*, but no evidence of it is found to the north and east. This indicates that the Pinedale Glaciation destroyed surface evidence of Bull Lake Glaciation in these areas.

In the Yellowstone region, the last (and most studied) major glaciation, the Pinedale, may have begun as early as 70,000 years ago. It ended more than 14,000 years ago. At the peak of the Pinedale Glaciation—25,000 years ago—nearly all of today's Yellowstone National Park was covered by a huge ice cap 4,000 feet thick (at a point above present-day Yellowstone Lake, *see above)*. Mount Washburn and Mount Sheridan were both completely covered by ice. This ice field was not part of the continental ice sheet extending south from Canada. The ice field occurred here, in part, because the hotspot beneath Yellowstone had pushed up the area to a higher elevation with colder temperatures and more precipitation than the surrounding land.

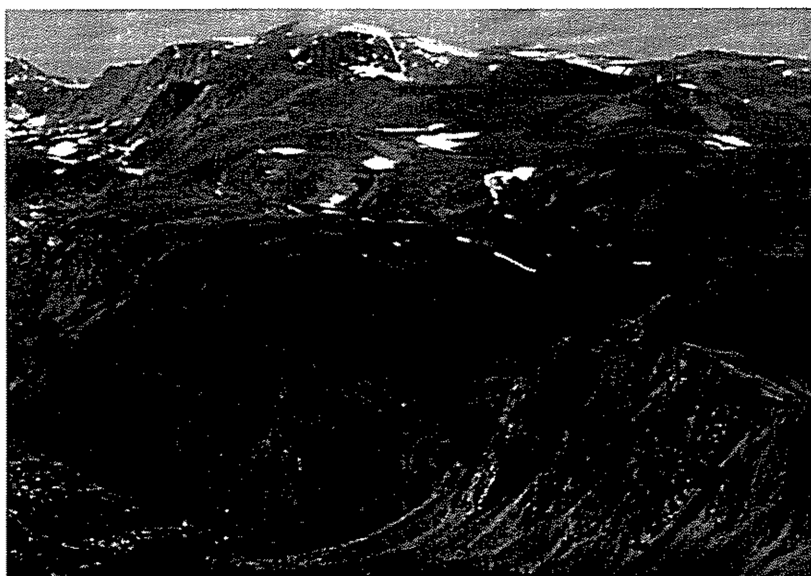
Sedimentation & Erosion

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 Mountains 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 (570 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 *(see next page)*.



The Beartooth Mountains northeast of Yellowstone (left) are actually an uplifted block of Precambrian rock.

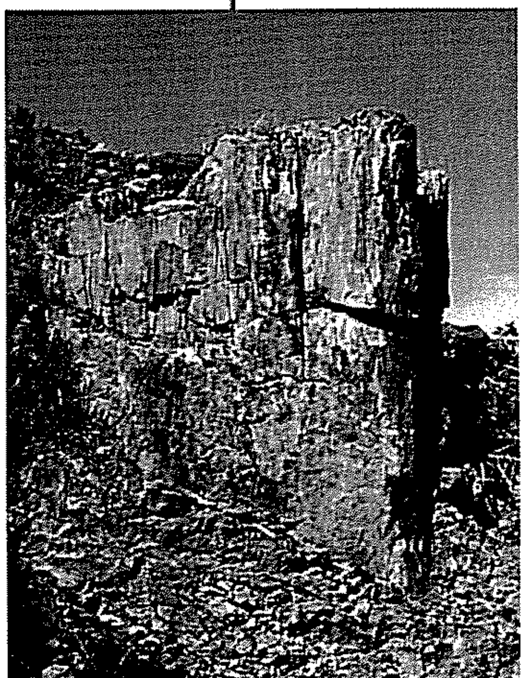
Mt. Everts, near Mammoth, (below) exposes sedimentary rock, which erodes easily and often tumbles into Gardner Canyon.

3 Fossils

Fossils

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.



In Yellowstone, many petrified trees can be seen. Resulting from volcanic eruptions about 50 million years ago, they present questions that scientists continue to ponder: Were the trees petrified in place and thus represent layers of forest? Or were they scattered before and after petrification, which means the number of forests cannot be determined?

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, including the Gallatin Range, Specimen Creek, Tower, Crescent Hill, Elk Creek, Specimen Ridge, Bison Peak, Barronette Peak, Abiathar Peak, Mount Norris, Cache Creek, and Miller Creek. Petrified wood is also found along streams in areas east of Yellowstone Lake. The most accessible petrified tree site is on Specimen Ridge.

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." The report identified the petrified trees on the north slope of Amethyst Mountain opposite the mouth of Soda Butte Creek, about eight miles southeast of Junction Butte.

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.

Another theory proposes that the trees were uprooted by volcanic debris flows and transported to lower elevations. The 1980 eruption of Mount St. Helens supported this idea. Mud flows not only transported trees to lower elevations, they also deposited the trees upright.

Cretaceous marine and nonmarine sediments are exposed on Mount Everts. The area is under study; 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.

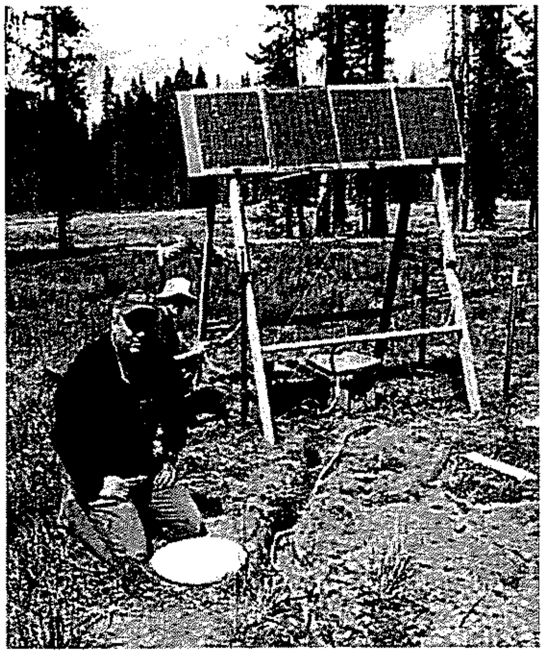
Fossil Invertebrates

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 rhinocerus) tooth and mandible found on Mt. Hornaday in 1999.



Dr. Robert Smith and assistant set up a temporary seismographic station. It is one of dozens throughout the Greater Yellowstone Ecosystem sending seismic data to researchers at the University of Utah.

Yellowstone As a Geologic Laboratory

Yellowstone is a unique outdoor laboratory for research scientists. Many of these scientific studies have ramifications far beyond Yellowstone National Park. Current research examples:

- Earthquake monitoring stations detect the numerous daily tremors occurring in the Yellowstone region, and the patterns are studied to develop an understanding of the geodynamics of Yellowstone's hotspot.
- Studies on the location of previously unmapped geologic structures should help us understand what controls subsurface fluid flow and recharge in geothermal systems.
- Baseline geochemical studies help distinguish between human and natural influences on the underground water network in the region.
- Underwater studies in Yellowstone Lake have identified hydrothermal vents where organisms have been found that survive on sulphur emissions and that resemble life found under the ocean near similar hydrothermal vents; comparison studies continue.
- The deposition of sinter around hydrothermal springs is being studied to understand how early life developed on Earth and to look for similarities on other planets, particularly Mars.
- Thermophiles—microorganisms that can live in extreme environments—are being collected from the park's hydrothermal features, identified, and their heat-resistant enzymes are being studied. Some already are being used in a variety of medical and forensic processes. *(See Chapters 4 & 9.)*

All scientists in Yellowstone work under special permits and are closely supervised by National Park Service staff.

THE YELLOWSTONE VOLCANO OBSERVATORY

Increased scientific surveillance of Yellowstone in the past 30 years has detected unmistakable changes in its vast underground volcanic system, similar to historical changes observed at many other large calderas (volcanic depressions) in the world. To strengthen the capabilities of scientists to track and respond to changes in Yellowstone's activity, a fifth U.S. volcano observatory was created in 2001, complementing existing ones for Hawaii, Alaska, the Cascades, and Long Valley, California. The Yellowstone Volcano Observatory (YVO) is supported jointly by the U.S. Geological Survey, the University of Utah, and Yellowstone National Park.

The principal goals of YVO include:

* *Strengthening the monitoring system for tracking earthquake activity, uplift and subsidence, and changes in the hydrothermal (hot water) system;*

* *Assessing the long-term potential hazards of volcanism, earthquakes, and explosive hydrothermal activity in the Yellowstone region;*

* *Enhancing scientific understanding of active geologic and hydrologic processes occurring beneath Yellowstone and in the surrounding region of the Earth's crust; and*

* *Communicating new scientific results, the current status of Yellowstone's activity, and forecasts of potential hazardous hydrothermal explosions or volcanic eruptions to Yellowstone National Park staff, the public, and local, State, and Federal officials.*

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

This text from a YVO pamphlet, "Steam Explosions, Earthquakes, and Volcanic Eruptions—What's in Yellowstone's Future?," sold by the Yellowstone Association.

Table 39.1 Generalized Geologic Column, Yellowstone National Park.

Time Units				Rock Units	Geologic Events
Era	Period		Epoch		
Cenozoic	Quaternary		Holocene	Alluvial, landslide, glacial, and hot spring deposits	Earthquakes; landsliding Geothermal activity, hot springs, geysers Neoglaciation Regional uplift; doming in center of Yellowstone Plateau Erosion of Grand Canyon of Yellowstone River Pinedale glaciation Post-caldera lava flows; Obsidian Cliff Bull Lake glaciation Pre-Bull Lake glaciation Climactic eruptions and caldera collapse of third volcanic cycle; rhyolitic ash falls, mudflows, welded tuff, breccias, etc. Second volcanic cycle; Island Park caldera and western part of Yellowstone Plateau First volcanic cycle; caldera collapse in Island Park area, ash falls, pyroclastics, breccias, etc ; rhyolitic eruptions
			Pleistocene	*Yellowstone Group (about 20 formations and members) { (Plateau rhyolites and basalts) (Lava Creek Tuff) (Mesa Falls Tuff not exposed in park) (Huckleberry Ridge Tuff)	
	Tertiary	Neo-gene	Pliocene Miocene		Erosion of ranges, canyon cutting, sedimentation in basins
		Paleogene	Oligocene		Regional uplift; block-faulting
			Eocene	*Absaroka Volcanic Supergroup (9 formations)	Repeated eruptions of andesitic pyroclastics and lavas; burial of fossil forests Basaltic breccias and flows Post-orogenic faulting, uplift and erosion
			Paleocene		
Paleozoic/ Mesozoic	(Cretaceous)			*Over 40 formations, some in northern and some in southern sections of park	Laramide orogeny; intense folding and thrust faulting, uplifting of Rocky Mountains
					Extensive deposition of marine and nonmarine sedimentary rocks as seas advanced and retreated over downwarped area
					Major angular unconformity
Precambrian				Gneisses and schists	Orogenic cycles, intrusions, metamorphism, sedimentation and erosion

*For details of the stratigraphic record, see Keefer (1971, pp. 9–11), Parsons (1978, p. 214), Christiansen and Blank (1972, p. B6), Love and Keefer (1975, p. D9), Ruppel (1972, p. A8), Smedes and Prostka (1972, p. C7).

VOLCANO HAZARDS FACT SHEET

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

Yellowstone: Restless Volcanic Giant

Three million visitors each year marvel at Yellowstone's Rocky Mountain splendor, including its thousands of steaming geysers, shimmering thermal pools, and bubbling mudpots. But the greatest wonder of all goes mostly unnoticed. Hidden underground, powerful volcanic, tectonic, and hydrothermal forces are continually reshaping the landscape of America's first and foremost national park. Symptoms of the underground turmoil include numerous earthquakes (most too small to be felt), uplift and subsidence of the ground surface, and persistent but ever-changing hydrothermal activity. Eventually, the unrest will culminate in another large earthquake or volcanic eruption, both of which have occurred many times before in Yellowstone's geologic past. Scientists from the U.S. Geological Survey and the University of Utah are studying the Yellowstone region to assess the potential hazards from future earthquakes and eruptions and to provide warning if the current level of unrest should intensify.

YELLOWSTONE'S ROOTS

Scientists have traced Yellowstone's origin to a *hot spot* in the mantle, one of a few dozen such hot spots on Earth. Buoyant material from a hot spot rises through the upper mantle, bringing heat from the Earth's interior closer to the surface. The Yellowstone hot spot impinges on the base of the North American plate, one of several rigid plates that make up the Earth's crust. These plates move a few inches per year with respect to the stationary hot spots and each other, sometimes causing great earthquakes as the plates collide, grind past one another, or split apart.

The Yellowstone hot spot has interacted with the North American plate for perhaps as long as 17 million years, causing widespread outpourings of basalt that bury about 200,000 square miles in Washington, Oregon, California, Nevada, and Idaho under stacks of lava flows half a mile or more thick. Some of the basaltic melt, or *magma*, produced by the hot spot accumulates near the base of the plate, where its heat melts rocks from the Earth's lower crust. These melts, in turn, rise closer to the surface to form large reservoirs of potentially explosive rhyolite magma. Catastrophic eruptions have partly emptied some of these reservoirs, causing their roofs to collapse. The resulting craters, some of which are more than 30 miles (50 kilometers) across, are known as volcanic *calderas*. Because the plate was moving an inch or so per year southwestward over the hot spot for millions of years as the calderas formed, groups of calderas are strung out like beads on a string across parts of Idaho and Wyoming (fig. 1).

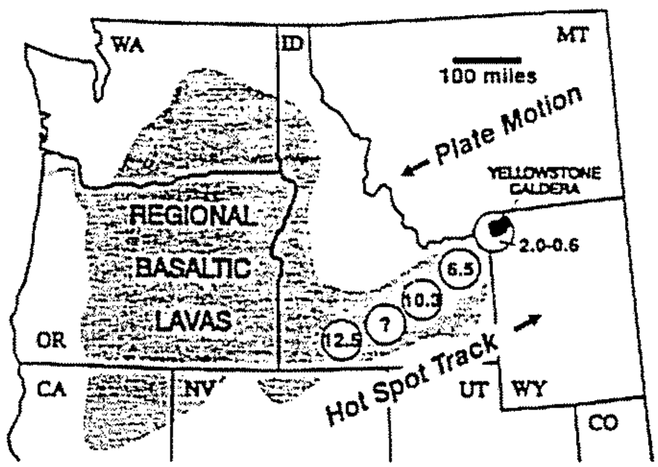


Figure 1. Regional basaltic lavas (stippling) and chain of rhyolitic caldera groups (circles), with ages in millions of years, along track of Yellowstone hot spot.

THE YELLOWSTONE CALDERA

The most recent caldera-forming eruption about 650,000 years ago produced a caldera 53 x 28 miles (85 x 45 kilometers) across in what is now Yellowstone National Park (fig. 2). During that eruption, ground-hugging flows of hot volcanic ash, pumice, and gases swept across an area of more than 3,000 square miles. When these enormous *pyroclastic flows* finally stopped, they solidified to form a layer of rock called the *Lava Creek Tuff*. Its volume was about 240 cubic miles (1,000 cubic kilometers), enough material to cover Wyoming with a layer 13 feet thick or the entire conterminous United States with a layer 5 inches thick. The Lava Creek Tuff has been exposed by erosion at Tuff Cliff, a popular Yellowstone attraction along the lower Gibbon River.

The eruption also shot a column of volcanic ash and gases high into Earth's stratosphere. This volcanic cloud circled the globe many times and affected Earth's climate by reducing the intensity of solar radiation reaching the lower atmosphere and surface. Fine volcanic ash that fell downwind from the eruption site blanketed much of North America. This ash layer is still preserved in deposits as far away as Iowa, where it is a few inches thick, and the Gulf of Mexico, where it is recognizable in drill cores from the sea floor.

Lava flows have since buried and obscured most of the caldera, but the underlying processes responsible for Yellow-

stone's tremendous volcanic eruptions are still at work. Eventually, another "bead" may be added to Yellowstone's 300-mile-long string of calderas, with global consequences that are beyond human experience and impossible to anticipate fully.

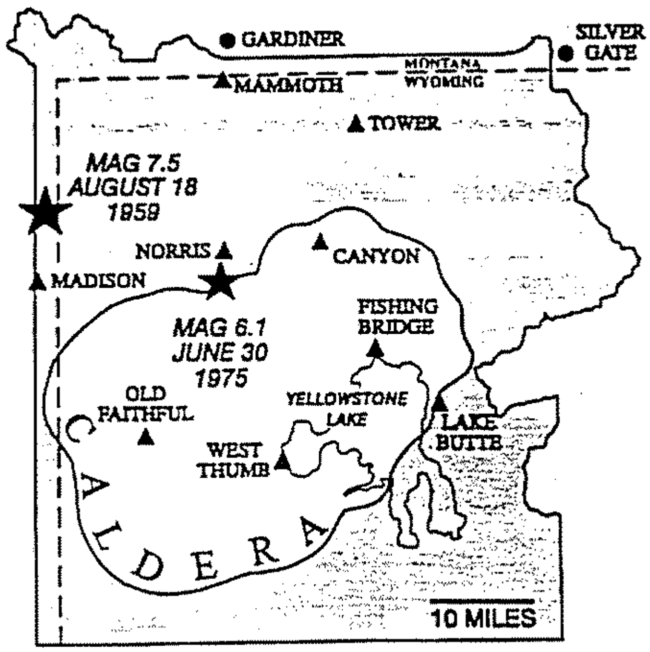


Figure 2. Yellowstone National Park and the 630,000-year-old Yellowstone caldera, with locations of two recent large earthquakes (stars).

CONTEMPORARY UNREST

In the meantime, the giant is restless. Thousands of small earthquakes rattle the Yellowstone region each year. Most of these are too small to be noticed except by sensitive seismometers, but a few are large enough to cause substantial damage. At least eight magnitude-6 or greater earthquakes have occurred in the Yellowstone region during historical time. The largest of these was the magnitude-7.5 Hebgen Lake earthquake on August 18, 1959, which cost 28 lives and $11 million in damage. The most recent was a magnitude-6.1 earthquake near the Norris geyser basin on June 30, 1975.

Earthquakes are not the only symptom of unrest. Yellowstone's famous hydrothermal system releases heat energy at an average rate of about 4,500 megawatts — about 50 times the planetary average. In addition, repeated surveys show that the ground surface near the center of the Yellowstone caldera rose more than 3 feet from 1923 to 1985, then subsided about 6 inches from 1985 to 1992 (fig. 3). Studies of shorelines near the outlet of Yellowstone Lake show that the caldera's center has risen and fallen 3 times during the past 10,000 years. The total vertical change during each "breath" of the caldera is estimated to be about 65 feet (20 meters).

REASON TO WORRY?

The current rates of seismicity, ground deformation, and hydrothermal activity at Yellowstone, although high by most geologic standards, are probably typical of long time periods between eruptions and therefore not a reason for immediate concern. Potentially damaging earthquakes are likely to continue occurring every few decades, as they have in the recent past. Eventually Yellowstone will erupt again, but there is no indication that an eruption is imminent or what kind of eruption may come next. For the foreseeable future, the same powerful forces that created Yellowstone will continue to animate this slumbering, but restless, volcanic giant.

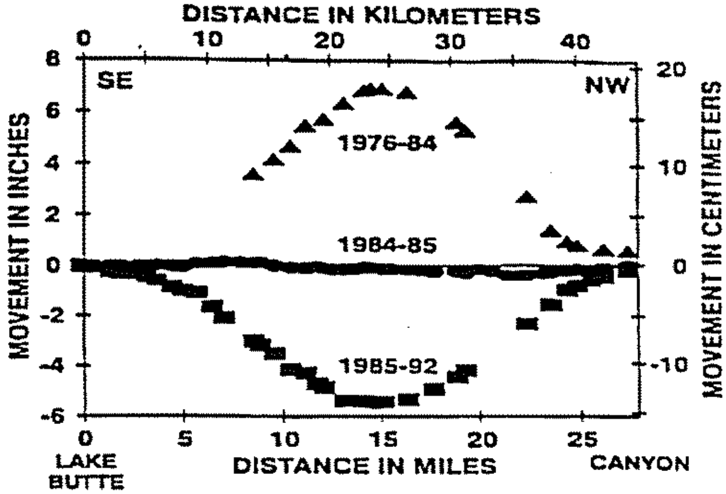


Figure 3. Ground movements between Lake Butte and Canyon (see fig. 2) for the periods 1976-84 (uplift), 1984-85 (quiescence), and 1985-92 (subsidence).

ADDITIONAL READING

Brantley, S.R., 1994, Volcanoes of the United States: General Interest Publications of the U.S. Geological Survey, U.S. Government Printing Office, Jacket 376-846, 44 pages.

Pierce, K.L., and Morgan, L.A., 1992, The track of the Yellowstone hotspot: volcanism, faulting, and uplift: Geological Society of America Memoir 179, pages 1-53.

Smith, R.B., and Christiansen, R.L., 1980, Yellowstone Park as a window on the Earth's interior: Scientific American, volume 242, pages 104-117.

Smith, R.B., and Braile, L.W., 1994, The Yellowstone hotspot: Journal of Volcanology and Geothermal Research, v. 61, pages 121-187.

Daniel Dzurisin, Robert L. Christiansen, and Kenneth L. Pierce

For additional information, contact:

U.S. Geological Survey
Cascades Volcano Observatory
5400 MacArthur Blvd.
Vancouver, Washington 98661

Tel: (360) 696-7693 e-mail: cvo@pwavan.wr.usgs.gov
fax: (360) 696-7866 URL: http://vulcan.wr.usgs.gov/

YELL 264

A GEOLOGY OUTLINE OF YELLOWSTONE NATIONAL PARK

Many events have shaped the Yellowstone we see today, and the land is still changing. The following is an outline of some of the significant geological events which have occurred in the area known as Yellowstone National Park. This will help you to understand what forces have shaped the park's landscape and why there is such an abundance of geothermal activity here.

2.7 BILLION YEARS AGO: The oldest rocks known in Yellowstone were formed. These Precambrian gneisses and schists are exposed in parts of the Gallatin Mountain Range.

570 MILLION YEARS AGO: A 2.1 billion year gap exists between the Precambrian rocks and this time. Probably some uplifting occurred during this period, and a great deal of erosion took place. At this time, the area that is Yellowstone was basically a featureless plain. What rocks are known from this time period may be found on Buffalo Plateau in the north central part of the park.

570 TO 75 MILLION YEARS AGO: For about 500 million years (from Cambrian to the Cretaceous periods), Yellowstone was periodically flooded by shallow seas that covered much of what is the western United States. Many sedimentary rocks found in Yellowstone were formed as deposits in these seas (sandstone, shale, limestone, dolomite, and various "formations" which combine types of rocks). Based on the fossil record, it appears that seas advanced and retreated at least one dozen times in the Yellowstone area. Rocks from this time may be found on Mount Everts, the Gallatin Mountains, and around the Snake River.

75 MILLION YEARS AGO: Tha Laramide Orogeny began about this time, lasting about 20 million years. Major crustal movements took place in Yellowstone and throughout the Rocky Mountain area as mountain building occurred. Anticlines, synclines, and various faults date from this period. The crustal movements probably helped to lead to the volcanic events which came later. Uplifting movements during the orogeny changed stream courses and increased erosion.

55 to 50 MILLION YEARS AGO: Several large volcanoes erupted in and near Yellowstone. Volcanic rocks from eruptions of the Absaroka and Washburn ranges now cover part of the Gallatin Mountains as well as other areas of Yellowstone. Both intrusive and extrusive rocks date from this time, including lava, ash, pumice, rhyolite, andesite, basalt, and breccia. Some eruptions were "quiet" lava flows; others were violent. Heavy rainfall at this time also caused some known mudflows and landslides. The timing of these varied eruptions resulted in the petrified tree specimens found in the park on Specimen Ridge and the Gallatin Mountains. Probably several hundred years passed between eruptions.

50 TO 40 MILLION YEARS AGO: Erupting Absaroka volcanoes buried most of Yellowstone under thousands of feet of lava, breccia, and ash. This extensive deposition turned Yellowstone into a plateau with just a few volcanic peaks towering above it and sluggish streams cutting through it. Yellowstone was probably not as high above sea level then as it is today. Based on the fossil record, Yellowstone's climate was warm, almost subtropical.

40 TO 10 MILLION YEARS AGO: There are no examples in the park from the period between the Absaroka volcanoes and this time. Some rocks dating from this gap can be found south of the park. In Yellowstone, rocks from this time period were probably eroded away.

10 MILLION YEARS AGO: Another period of uplift occurred. The Teton and Gallatin mountain ranges were uplifted thousands of feet, increasing drainage and erosion throughout this area. As the uplift went on, Yellowstone was characterized by sharply defined canyons, mountains, and tablelands.

3 TO 2 MILLION YEARS AGO: Magma had been building up for some time in two chambers under Yellowstone. About two million years ago a first eruption from these chambers occurred. Much of the huge caldera caused by this eruption was obliterated by a later eruption that occurred 600,000 years ago. The removal of so much magma caused the two chambers to collapse around a ring fracture zone, leaving the second caldera several thousand feet deep and many miles in diameter. This caldera was roughly bounded by the Washburn Range, Absaroka Range, Flat Mountain, the Red Mountains, and the Madison Junction bluffs. A third caldera eruption took place between 200,000 and 125,000 years ago in what is now the West Thumb of Yellowstone Lake. This caldera within a caldera measures four miles wide and six miles long. Dust and ash from the caldera eruptions filled Yellowstone's lowlands. Only peaks as high as Bunsen Peak stood above the ash (which settled into a "welded tuff").

Molten lava continued to flow from the two magma chambers, with much of the lava filling in the caldera but some running over the rim. Lava flows of rhyolite now compose some park plateaus, such as the Madison Plateau; a few lava flows were basaltic, such as the columns found along the Yellowstone River near Tower Fall. Obsidian Cliff was also formed at this time, but it derived from a lava flow outside the caldera area. The last of the lava flows took place about 60,000 years ago.

300,000 TO 8,000 YEARS AGO: Three periods of glaciation took place in Yellowstone. The "Pre-Bull Lake" glaciation lasted from about 300,000 to 180,000 years ago; the "Bull Lake" glaciation lasted from 125,000 to 45,000 years ago. As the previous entry indicates, these glaciers were in Yellowstone at the same time lava was flowing in parts of the park.

The "Pinedale" glaciation lasted from 25,000 to about 8,000 years ago. This glacial period is better known than the previous two. In fact, it obscured much of the change that the previous two had caused. Icefields from the Absaroka and Gallatin ranges as well as from mountains north of the park contributed to the Pinedale glaciers covering Yellowstone. Glacier ice built up to as much as 3,000 feet thick (over the Lake Basin) within the park. Only the west edge of the park and the highest ridges escaped being glaciated. As ice and rock, the glaciers gouged and smoothed the topography. As they melted, glaciers left behind moraines and boulder erratics, especially in the lower Lamar Valley. Streams and lakes developed from glacial meltwater, causing erosion and redistribution of sediments. Although some snowfields exist year-round in the park, there are presently no glaciers in Yellowstone. A few glaciers can still be found in the Teton and Wind River ranges.

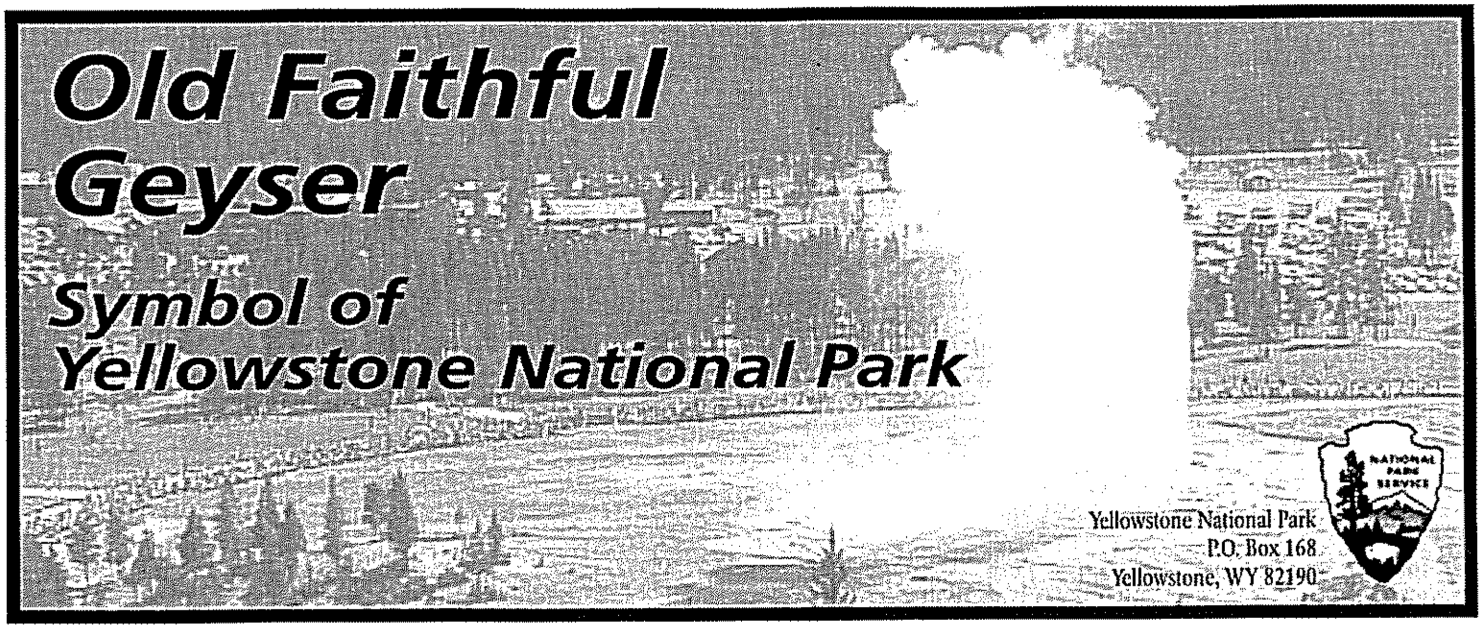
THE PRESENT TIME: Features which probably attract some visitors to Yellowstone-the Grand Canyon of the Yellowstone River, geothermal features, waterfalls, rivers, and lakes-resulted from geological processes still happening today. Yellowstone has more geysers, mud pots, hot springs, and fumaroles than any other place in the world. Long-term erosion is exemplified on a grand scale by the Grand Canyon of the Yellowstone and the park's numerous waterfalls. Because many faults are located in Yellowstone, earthquakes regularly occur here. Most earthquakes are not readily noticeable. However, in 1959 a powerful earthquake (7.8 on the Richter Scale) was centered just outside the park to the west; it triggered landslides and caused radical behavior in geysers within the park.

Suggested reading:

<u>The Roadside Geology of Yellowstone Country</u> by William Fritz

<u>Interpreting the Landscape of Grand Teton and Yellowstone National Parks</u> by John Good and Kenneth Pierce

<u>The Geologic Story of Yellowstone National Park</u> by W.R. Keefer



About Old Faithful Geyser

Soon, a towering column of water will surge out of the earth as Old Faithful continues its unbroken series of eruptions. Eruptions occur an average of 17 times per day, every day. Because of changes in circulation that resulted from the 1959 Hebgen Lake and 1983 Borah Peak earthquakes, as well as other local and smaller earthquakes, the average interval between eruptions has been lengthening during the last several decades. In the past, Old Faithful displayed two eruptive modes: short duration eruptions followed by a short interval, and a long duration eruption followed by a long interval. However, after a local earthquake in 1998, Old Faithful's eruptions are more often of the long duration, long interval type.

Other great geysers are dormant for months or years between their periods of activity, yet Old Faithful has not stopped in historic times. Other geysers erupt to greater heights, and a few are more predictable. However, careful observations of each Old Faithful eruption enable interpretive rangers to predict the next eruption.

Old Faithful— Vital Statistics

as of 2004

Height of eruption	106–184 feet (32–56 m) Average = 130 feet (40 m)
Duration of eruption	1.5–5 minutes
Interval between eruptions If eruption lasts less than 2.5 minutes If eruption lasts more than 2.5 minutes	 65 minute interval 92 minute interval
Temperature	203°F (95°C) just prior to an eruption (water boils at 199°F/93°C at this altitude [7,366 ft/2,245 m])
Volume of water in an eruption	3,700–8,400 gallons (14,000–32,000 liters)

Geyser Essentials

In order to exist, geysers need:

Heat

Magma (partially melted rock) is the source of heat for geysers and hot springs. The heat is transmitted through solid rock and fluid substances to water that has seeped to depths as great as 10,000 feet (3 km) below the surface. The water temperature can exceed 400°F (204°C).

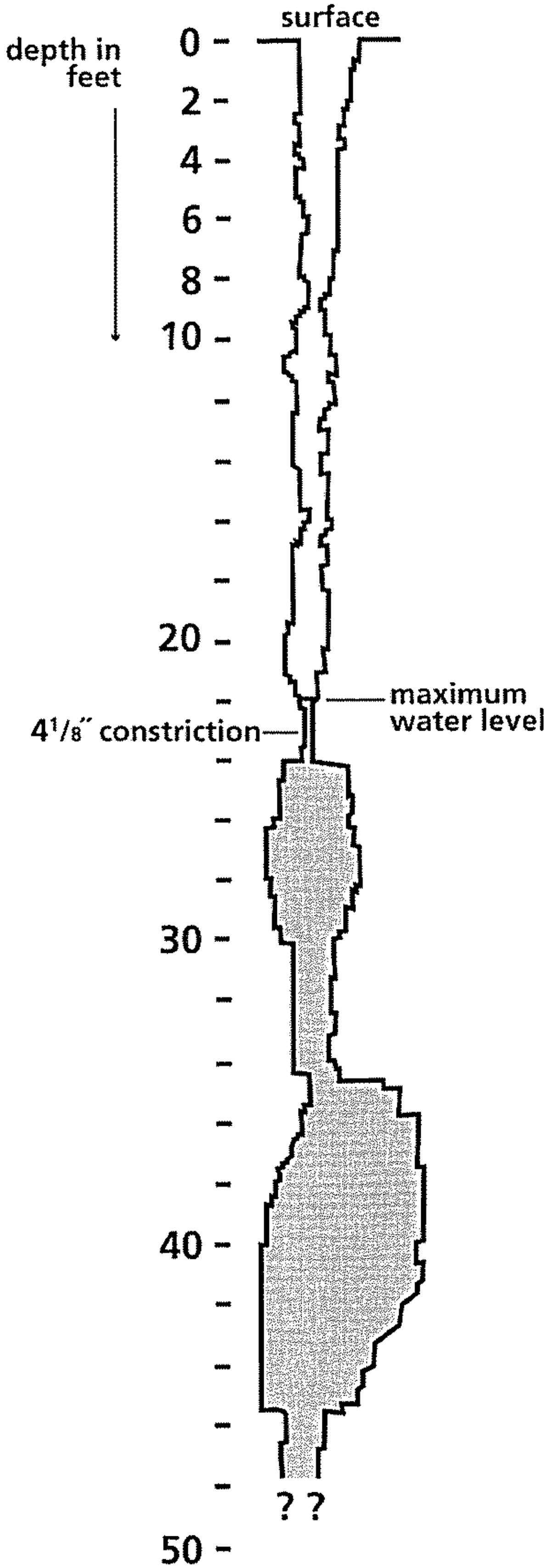
Water

The tremendous amounts of water that erupt from Old Faithful, Giantess, Grand, Echinus, and other major geysers show that large volumes of water move rapidly throughout a geyser's natural "plumbing." The water comes from one or more porous, permeable beds of rock, called aquifers. It is believed that almost all of the water in geysers and hot springs comes from surface water such as rain and snow.

A constricted "plumbing system"

In Yellowstone's hydrothermal areas, the under-lying rocks contain fissures and fractures through which water circulates from deep within the earth. High temperatures dissolve silica and other minerals in the water, which coat the plumbing. If a constriction develops in plumbing, a geyser may result.

Old Faithful's Plumbing



Geyser tubes or "plumbing systems" are not uniform in shape. They are usually crooked or constricted in many places. Measurements of Old Faithful's conduit reveal a constriction at about 22 feet (6.7 m).

No two geysers erupt alike because of variations in heat flow, water movement, and plumbing systems.

Notice the size of the constriction in Old Faithful's plumbing—rocks, sticks, and other objects could easily clog it, thus altering or stopping its eruptions.

It is illegal to throw anything in Yellowstone's hydrothermal features.

Geysers are rare and beautiful. Treasure and preserve them!

Yellowstone

Yellowstone National Park
P.O. Box 168
Yellowstone, WY 82190

Steamboat Geyser—
Tallest Active Geyser in the World

Tucked away in the Norris Geyser Basin is Steamboat Geyser, the world's tallest active geyser—its major eruptions shoot water more than 300 feet (91 m).

Only Waimangu Geyser in New Zealand rocketed to greater heights—and it did so for only four years, ending in 1904. In Yellowstone National Park's recorded history, only two other geysers—Excelsior Geyser in Midway Geyser Basin and Sapphire Pool in Biscuit Basin—have exceeded Steamboat in massiveness. Excelsior was very active for about 10 years, ending in 1888, and had one major eruption in 1985. Sapphire Pool was active for several years after the Hebgen Lake Earthquake of August 1959.

Steamboat's minor and major eruptions, described on the back of this page, are entirely unpredictable.

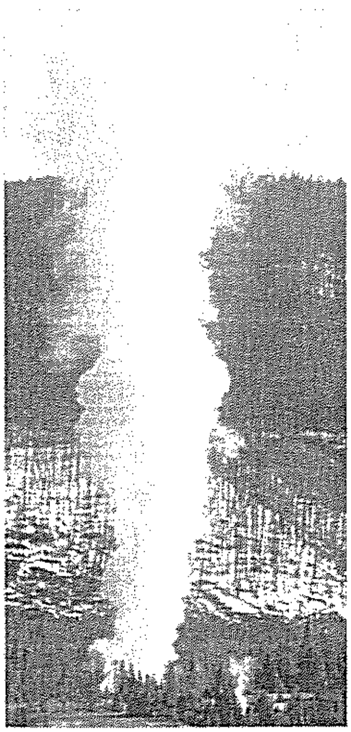
Steamboat's Major Eruptions

All known major eruptions are listed below. During Steamboat's early years, other major eruptions probably occurred but were not seen because most of each year passed with no observers in Norris Geyser Basin.

YEAR	NUMBER OF ERUPTIONS	INTERVALS
1878	At least 2	
1890	At least 1	12 years
1891	At least 1	Less than 1 year
1892	At least 1	Less than 1 year
1894	At least 1	2 years
1902	At least 1	8 years
1911	At least 1	9 years
1961	At least 1	50 years
1962	At least 7	8–360 days
1963	26	6–32 days
1964	29	5–45 days
1965	22	7–50 days
1966	At least 10	11–77 days
1967	At least 3	15–310 days
1968	At least 3	42–150 days
1969	2	45 days
1978	2	9 years & 148 days
1979	1	199 days
1982	23	4–43 days
1983	12	4–107 days
1984	5	19–93 days
1989	3	107 days to 4.3 years
1990	1	238 days
1991	1 (October 2)	
2000	1 (May 2)	8 years & 212 days
2002	2 (April 26, September 13)	1 year & 359 days, 140 days
2003	3 (March 26, April 27, Oct. 22)	194 days, 30 days, 178 days
2005	1 (May 23)	1 year & 172 days

This is a total of 166 recorded eruptions, with intervals ranging from 4 days to 50 years.

Major Eruptions—Rare & Spectacular



Steamboat Geyser, May 2000

The magnitude and destructive force of a major eruption of Steamboat Geyser are unforgettable. Water intermittently surges from two vents to varying heights. Suddenly water explodes from the larger north vent more than 300 feet (91 m) high. Curtains of water fall to the slope above the geyser and collect in torrents rushing back into the vent, carrying huge amounts of mud, sand, and rock that are shot skyward again and again. Water coats everything with a glistening layer of silica. Trees and cars in the parking lot are often covered with eruption debris. An eruption in February 21, 1982, blanketed the snow upslope from the geyser's vent with an estimated 700 cubic feet (20 cubic m) of debris. Mature lodgepole pines have been broken by the blast, stripped of their limbs by the weight of ice from the water and steam of winter activity, and undermined and then washed away by the geyser's massive discharge. Commonly, the boardwalk at the base of the hill has been covered by the geyser's outwash.

The water phase of a major eruption lasts from 3 to more than 40 minutes. Once the water supply is exhausted, the geyser continues with a powerful steam phase lasting from several hours to a day and a half. Its roar is so great that conversation near the geyser is difficult, and visitors in the Norris Campground, a mile to the north, have been awakened by the noise.

Not-so-minor Eruptions

Steamboat's minor eruptions—the most typical display—reach 6–40 ft (2–12 m) and last 1–4 minutes. Intervals may be as short as 2–5 minutes. The higher and longer minors often excite viewers because a major eruption seems imminent. Usually the geyser calms down again.

Inquire at the Norris Information Station about Steamboat's current activity—is it having a quiet year, emitting only steam, or is it having frequent, high minor eruptions?

Dormancy & Rejuvenation

On September 2, 1961, Steamboat had its first major eruption since 1911. No one knows what caused the long dormancy, but the rejuvenation might have been a delayed response to the Hebgen Lake Earthquake of August 1959.

The Hebgen Lake Earthquake, measuring 7.5 on the Richter Scale, had its epicenter a few miles outside the western boundary of Yellowstone National Park. It caused widespread and spectacular changes in the hydrothermal features along the Firehole River.

Two years later, Steamboat Geyser erupted for the first time in 50 years. Some scientists believe this rejuvenation was a direct result of the shifts in thermal energy caused by the 1959 earthquake; others say it was coincidental.

Steamboat remained active through the 1960s, then was dormant for nine years. In March 1978, swarms of tremors hit the Old Faithful area. Later that month, observers noted Steamboat's minor eruptions had increased volume and were reaching 90 feet (27 m). On March 28, Steamboat had a major eruption. Again, some scientists think it was a response to the earlier earthquake activity, some say it was coincidental.

In the last decade of the 20th century, Steamboat quieted again. Then, on May 2, 2000, a major eruption occurred. No major earthquake activity preceded this eruption nor eruptions in 2002 and 2003. Nevertheless, scientists continue to study Steamboat to find out if it is among the seismically-sensitive geysers.

The Cistern Spring Connection

Cistern Spring, at the base of the hill, exhibits changes related to its gigantic neighbor.

After 1959, Cistern Spring's temperature gradual rose, possibly receiving some of this heat from Steamboat. Cistern began increasing discharge in 1965 when Steamboat's frequency of major eruptions was beginning to decrease. This surge in heat and water was so great that all vegetation immediately south of Cistern was killed and a colorful silica terrace rapidly grew several feet high. This terrace continues to rise and expand.

Since that time, Cistern has also drained during and/or after a major Steamboat eruption.

Steamboat's Future

Steamboat Geyser's future is unpredictable. Fifty years with no major eruptions occurred in the past, and it is just as likely that 50 or more years will pass as quietly as before. The dynamic nature so characteristic of this geyser basin, and of the geology of Yellowstone as a whole, will determine the answer.

For more information

www.nps.gov/yell
volcanoes.usgs.gov/yvo/steamboat.html

YELL 261
Rev. 9/99

GEOLOGICAL HISTORY OF THE GRAND CANYON OF THE YELLOWSTONE

Visitors to the Grand Canyon of the Yellowstone River witness an inspiring display of depth, color, and ruggedness. Rangers are often asked three questions: Why is there a canyon? Why are the walls of the Canyon so colorful? Why are there waterfalls here? Answers lie in understanding the geological events responsible for this amazing landscape.

The Big Picture

The story begins about 16 million years ago, when hot material rising through Earth's mantle reached the surface. This so-called ***hotspot*** is responsible for many features seen in Yellowstone National Park, including the Canyon and its colorful rocks. The hotspot initially lifted the landscape and spewed volcanic material onto the surface near the juncture of Nevada, Idaho, and Oregon, about 300 miles southwest of Yellowstone. But Earth's outer shell is not fixed; it consists of plates that move a fraction of an inch to a few inches per year (the same rate your fingernails grow!). Moving southwestward about 1 inch per year, the ***North American Plate*** thus drifted 300 miles over the fixed hotspot in the last 16 million years. Like a candle burning through a moving sheet of waxed paper, a line of volcanoes formed across southern Idaho to Yellowstone. The Hawaiian Islands are a similar chain of volcanoes, formed as the Pacific Plate moves over another hotspot. Lying directly over a hotspot, the Yellowstone region is thus similar to the Big Island of Hawaii, with its high elevation and young volcanic rocks.

Three factors, each related to the hotspot, conspire to form the Grand Canyon of the Yellowstone.

A) Like a hot-air balloon rising, ***the hotspot elevates the Yellowstone Plateau***. At 8,000 feet elevation, this broad region is 2,000 to 3,000 feet higher than most of the surrounding land.
B) The hotspot melts some of the rock of Earth's crust, forming a ***magma chamber*** about 3 miles below the surface. Magma periodically flows out on the surface and hardens into lava flows.
C) Water from rain and snow seeps into the ground where it encounters hot rocks above the magma chamber. The hot water expands and rises, returning to the surface as the ***geysers, hot springs, mudpots,*** and ***steam vents*** seen in the park.

These factors help us answer the three questions posed above.

Why is there a Canyon?

Deep canyons form not just because a river cuts deeply into the ground, but also because the land moves slowly upward. The Grand Canyon in Arizona is a good example. There are two ways we can envision the Colorado River carving that canyon. Think of the land as a giant layer cake. You could take a sharp knife and carve downward through the soft layers. Another way is to hold the knife steady and lift the cake. That is what has been happening for the past 6 million years in northern Arizona – the Colorado Plateau has slowly moved upward, but the Colorado River erodes to stay at about 2,000 to 3,000 feet elevation. So, too, is this occurring with the Grand Canyon of the Yellowstone. The Yellowstone River wants to stay at low elevation, but the hotspot gradually uplifts the Yellowstone Plateau. So to keep up, the river continuously cuts downward, forming the Canyon.

Why are there such fantastic colors on the walls of the Canyon?

From the rim of the Grand Canyon of the Yellowstone, artist Thomas Moran first painted his wonderful images of Yellowstone in 1871. These paintings, and those of countless artists since, were inspired by the wonderful red, orange, and yellow colors along the Canyon walls. Most of the rocks in the Canyon area are ***rhyolite***, light-colored lava flows that contain some iron. There is a fair-sized thermal area in the Canyon area, much like the better known one around Old Faithful. Looking down into

the Canyon you may see steam vents; near Clear Lake, a short hike south of the Canyon, there are active mudpots. When iron is subjected to hot water, it turns into iron-oxide, which is ***rust***. All those reds, yellows, and oranges on the Canyon walls are beautiful examples of rust and other iron compounds, formed as the rising thermal waters interacted with the rhyolite.

Why are there waterfalls here?

There are two prominent waterfalls in the upper part of the Grand Canyon of the Yellowstone. The ***Upper Falls*** are 109 feet high; the ***Lower Falls*** drop 308 feet (nearly twice the height of Niagara Falls). Like many prominent waterfalls, the falls of the Yellowstone River exist because ***rock layers change laterally from soft to hard***. Consider two potatoes, one raw and one that has been boiled for half an hour. The raw potato is hard; if you tried to stab it with a fork, it might bend the fork; but the boiled potato is so soft that the fork would easily break it apart. Remember that the brilliant colors of the Canyon are due to hydrothermal alteration. The hot water also weakened the rhyolite layers, much like boiling the potato softened it. The Yellowstone River thus had a relatively easy time cutting through the weak layers downstream from the falls. At the Lower Falls, however, the rock is dull gray, indicating that the rhyolite has not been altered by hot water. The Yellowstone River is therefore having trouble cutting through these harder rocks, and so remains high and must take the big plunge over the falls.

Deposition of Layers

About 600,000 years ago volcanic eruptions occurred in what is now the central part of Yellowstone National Park. So much material came out that it emptied a large part of the magma chamber that lies 3 to 4 miles beneath the Earth's surface. The roof of the Yellowstone Plateau collapsed into the void, forming a deep hole, the ***Yellowstone Caldera***. Later eruptions, from 600,000 to about 70,000 years ago, periodically coated the bottom of the caldera with a sequence of lava flows. Most of the rocks you see today in the Grand Canyon of the Yellowstone are rhyolite layers at the top of this sequence. During winters, 5 to 10 feet of snow accumulates over the higher parts of Yellowstone National Park. Virtually all of that snow melts by August. But imagine what would happen if Earth's average temperature were about 20° F colder - not all of the snow would melt during the summer. Snow would accumulate year after year, developing an ice-cap similar to those today over Antarctica, Greenland, and part of Iceland. It is estimated that ice sheets covering the Yellowstone Plateau during recent ice ages were about 3,000 feet thick, completely burying the top of peaks as high as Mt. Washburn (elevation 10,243 feet). Each time the Earth warmed up, remaining ice dammed the Yellowstone River in the Canyon area. Layers of sediment were deposited in glacial lakes that formed behind the ice dams. Lake sediments can be seen today on top of the Canyon lava flows - on the South Rim Trail between the Upper and Lower Falls; just east of Chittenden Bridge on the road to Artist Point; and on the north face at Red Rock Point.

Carving the Canyon

Did ice or water carve the Grand Canyon of the Yellowstone? When glacial ice carves a valley, it makes a characteristic "U-shape," like many of the broad valleys of Grand Teton, Glacier, and North Cascades national parks. But water carves a "V-shaped" valley, with sides sloping at the same angle from top to bottom. The "V-shape" of the Canyon thus shows that the Yellowstone River was the primary carving agent. However, ice did contribute in an indirect way. At times, ice damming the Canyon broke suddenly, releasing huge torrents of water that scoured the walls.

Yellowstone

Yellowstone National Park
P.O. Box 168
Yellowstone, WY 82190

Mammoth Hot Springs—
Are They Drying Up?

Visitors who have seen Mammoth Hot Springs more than once often ask "Are the Mammoth Hot Springs drying up?" They have asked this question since the late 1890s, when visitors began making their second and third trips to Yellowstone. Today, returning visitors often ask the same question. They remember the active, colorful springs shown in their photos and postcards. They usually don't remember the expanses of bare sinter, which are as common here as in the geyser basins. So they often conclude that the springs are drying up—and they want to know why.

The simple answer is *No, they are not drying up.* These terraces change constantly—sometimes overnight—but the overall activity of the entire area and the volume of water discharge remain relatively constant.

The explanation is in terraces

The terraces are formed from the interaction of hot water, limestone (calcium carbonate), and heat. In the surrounding mountains, rain and snow percolate down through the ground. The water is heated by volcanic heat sources below the surface. As the hot water rises, it dissolves limestone rock beneath the Mammoth area. The limestone was deposited under a sea approximately 500–300 million years ago, during the Paleozoic Era.

When the mineral-rich water reaches the surface, it cools and its pressure decreases, gases are released, and the calcium carbonate is deposited as travertine. Travertine builds up rapidly here at Mammoth and causes the features to change quickly and constantly. Some vents will clog completely, new vents may form, and old vents may reopen. Sometimes the water is concentrated in a few springs while at other times it may spread across many outlets.

In every case, water follows the path of least resistance, which could be above ground or underground. Scientists estimate that, at any given time, about 10 percent of the water in the Mammoth Hot Springs system is on the surface; the other 90 percent is underground.

Life in the Water

Thermophiles (heat-loving microorganisms) thrive in the hydrothermal features here, as they do throughout the park. *Archaea* live in the hottest waters (above 165°F/74°C). Sulfur-oxidizing filamentous bacteria live in slightly cooler water. Below 131°F/55°C, cyanobacteria form dense mats containing millions of organisms. These living mats may change color according to changes in the water temperature, flow, and the amount of sunlight available both seasonally and daily. Scientists are studying Mammoth's thermophiles to find out if they affect the travertine deposition rate or the hot springs' activity.

Expect Change

The changes at Mammoth Hot Springs cannot be predicted, but you can be certain that change will occur between now and the next time you visit. If one of your favorite features at Mammoth is dormant today, look for a new feature or more rapid growth of an established one. Check your favorite spring on your next visit. It may very well be back!

At Mammoth Hot Springs, geology is happening before your eyes.

For More Information

www.nps.gov/yell
"Mammoth Area Trail Guide," updated annually, available at Mammoth area trailheads and visitor centers
Yellowstone Resources & Issues, revised annually
Life at High Temperatures, 1994 Thomas D. Brock
Yellowstone: Official National Park Handbook, 2001 David Rains Wallace

Yell 243 revised 12/03

YELL 250
6/00

OBSIDIAN CLIFF

Obsidian Cliff, 11 miles south of Mammoth Hot Springs, is at the northern end of Beaver Lake in Yellowstone National Park. The cliff forms the eastern wall of a narrow cut in plateau country. At an elevation of nearly 7,400 feet above sea level, the cliff extends for a half mile, rising from 150 to 200 feet above Obsidian Creek and falling gradually away to the north. The upper half is a vertical face of rock; the lower half is composed of loose and broken rocks forming a talus slope. The cliff is the remainder of a flow of lava that erupted onto the earth's surface and then poured down the plateau.

Obsidian forms when lava cools so quickly that crystals do not have time to form and grow. Because obsidian is usually found as small globes in other rocks, a massive outcrop the size of Obsidian Cliff is quite rare. Obsidian Cliff possibly formed when molten rock (magma) erupted onto the earth's surface and came into contact with the ice of a glacier. This quick cooling of large amounts of magma prevented the growth of crystals. Also, chemical analyses of the obsidian show that there was very little water in the lava. Without water, crystals could not form, thereby resulting in glassy rock. On close observation, one can see the swirling flow in the rock that shows the last movement of the liquid magma before it cooled and hardened.

Found on the southern face of the cliff are a series of columns which commonly occur in rocks of volcanic origin. Columnar jointing, as this formation is called, is another result of the rapid cooling of magma. The liquid rock shrinks inward, cracks, and contracts as it cools to form these four-to-six sided columns.

For centuries, Native Americans made their arrowheads and spear points from obsidian. The rock itself is dark and glassy in appearance (black in this case), and, when broken, fractures into rounded pieces with sharp edges. Arrowheads from as far away as the Midwest have had their origin traced back to Obsidian Cliff in Yellowstone. This indicates that the quality of obsidian found here was great enough for it to spread long distances in its use among various Indian tribes.

Up the Temperature Gradient

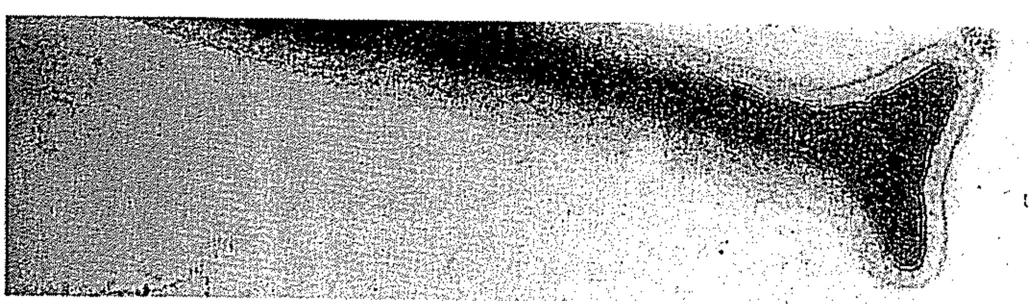
Temperature is one of the most important environmental factors and organisms differ strikingly in their ability to adapt to high temperatures. Biologists recognize three major categories of living organisms, called Eucarya, Archaea, and Bacteria. Higher organisms (plants and animals) are all Eucarya, so called because their cells have true nuclei and undergo cell division by mitosis. We call these organisms with true nuclei **eucaryotic**. Archaea and Bacteria are both much simpler organisms, seldom occurring as multicellular forms, and lacking true nuclei and mitosis. They are called **procaryotic**.

The table on the next page shows the upper temperature limits for growth of various types of living organisms. Note that the eucaryotes are unable to adapt to high temperatures, their upper limit being about 60–62°C (140–144°F). The upper temperature limit for plants and animals is even lower, less than 50°C (122°F). It is important to note that only a very few eucaryotes are able to adapt to these upper limits, the majority being restricted to much lower temperatures.

At temperatures above 60–62°C (140–144°F) the only organisms present are procaryotes. The photosynthetic bacteria have upper temperature limits lower than those of nonphotosynthetic bacteria. The upper limit of photosynthetic bacteria, defined by the "V" shown in the photo on page 8, is about 70–73°C (158–163°F). At higher temperatures, only nonphotosynthetic bacteria are able to grow. At the highest temperatures, over 100° C (212°F), the only bacteria found are a few unusually heat-adapted Archaea called *hyperthermophiles*.

Water boils in Yellowstone at about 92°C (198° F). These bacteria are thriving in boiling water!

Group	Upper temperature limits (°C)	Upper temperature limits (°F)
Animals		
Fish	38	100
Insects	45-50	113–122
Ostracods (crustaceans)	49-50	120–122
Plants		
Vascular plants	45	113
Mosses	50	122
Eucaryotic microorganisms		
Protozoa	56	133
Algae	55-60	131–140
Fungi	60-62	140–144
Procaryotes		
Bacteria		
Cyanobacteria (oxygen-producing photosynthetic bacteria)	70-73	158–163
Other photosynthetic bacteria (do not produce oxygen)	70-73	158–163
Heterotrophic bacteria (use organic nutrients)	90	194
Archaea		
Methane-producing bacteria	110	230
Sulfur-dependent bacteria	115	239



This bacterium, shown under the electron microscope, lives well in boiling water.

The Upper Temperature for Life

When microbiological researchers first began to study the Yellowstone hot springs in the 1960s, one of the biggest surprises was the discovery that procaryotes were thriving even in boiling water. These procaryotes were not obvious, such as those of the microbial mats, but rather lived attached to the rock-like walls of the springs or to pebbles, and sometimes their long intertwined filaments accumulated on the bottom of the channels (photo bottom of next page). Even if the source pool looks white and sterile, microscopic study usually reveals large numbers of procaryotes. Such procaryotes are found not only in Yellowstone, but in hot springs all over the world, even where springs are at lower altitudes and water therefore boils at higher temperatures. It is amazing that in addition to living in boiling water, these procaryotes are growing surprisingly rapidly; a population can double in as few as two hours.

The presence of procaryotes in boiling water (100°C) (212°F) makes us wonder if there is an upper temperature for life. Temperatures even hotter than 100°C occur in the thermal vents found at the bottoms of the oceans. Because of the high pressure in the ocean depths, temperatures of over 300°C (572°F) are found. Careful study has shown that at such high temperatures, no living organisms are present, but evidence exists of procaryotes living at temperatures as high as 115°C (239°F). In fact, cultures have been obtained that can be easily grown at this temperature in the laboratory.

It is an interesting fact that 115°C (239°F) is near the temperature at which hospital sterilizers are operated, yet here are procaryotes that actually *prefer* such temperatures!

Procaryotes can grow over the complete range of temperatures in which life is possible, but no one organism

can grow over this whole range. The bacteria that cause disease, for which the hospital sterilizer is intended, are completely unable to grow at the high temperatures of hot springs. Likewise, the bacteria living in hot springs are unable to grow at the temperature of the human body.

Thermophiles and Evolution

How is it possible for living organisms to survive at such extremes of temperature? Actually, we are only surprised that life thrives in boiling water because of our anthropocentric orientation. It is true that humans and other animals are very heat-sensitive, but the biological world is much more diverse than we realize from our experience. Life, and especially procaryotic life, is able to adapt to environmental conditions that are deadly to humans.

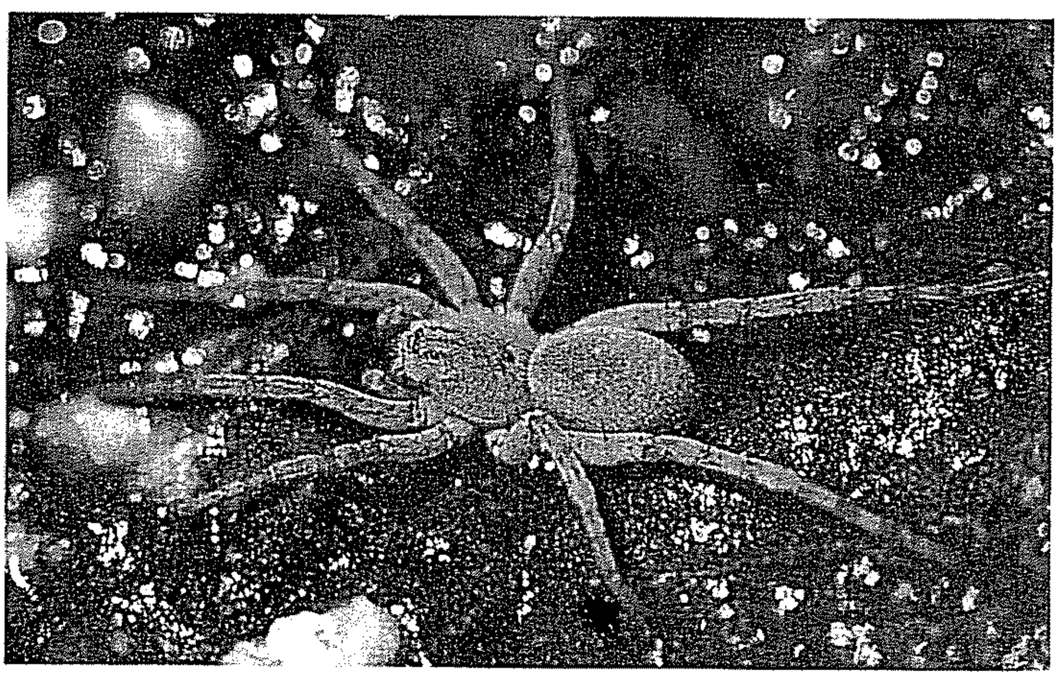
In fact, many scientists believe that life as we know it might first have arisen three billion or so years ago in high-temperature environments, and that the first organisms on earth might therefore have been thermophiles. Such thermophiles would then have continued to exist on earth in the intervening period, finding refuges in the hot springs that continue to dot the earth. In addition, these thermophiles would have been the forerunners of all other life forms, including, eventually, humans.

The Life Cycle of the Ephydrid Fly

The eggs usually hatch within a day and the larvae creep onto the surface of the microbial mat or burrow into it, devouring large amounts of the microbial cells. Within a week the larva is fully grown and it transforms into a pupa. Metamorphosis occurs and in a matter of days the adult fly emerges. The life cycle from adult to adult takes about two weeks. As many as 500 adult flies have been counted in an area of a square yard, and one spring had over 100,000 larvae per square yard!

The maximum temperature at which the adult flies can live is about 43°C (109°F). However, the adults can go partway underwater surrounded by a bubble of air which acts as insulation, so that they can feed in hotter water.

The ephydrid flies are strict vegetarians, but other animals associated with hot springs are carnivores and eat the ephydrids. One common carnivore is the spider. These animals live at the edges of springs, making mad dashes out onto the mat to catch adult ephydrids. As long as the spider keeps moving, it can traverse hotter water than it can otherwise stand.



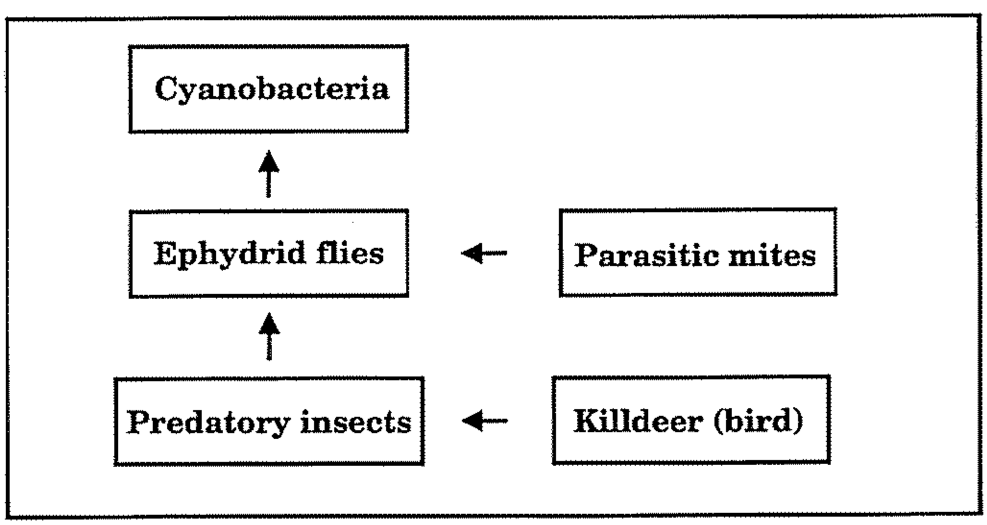
The Hot Spring Food Chain

We have seen that hot springs support a diversity of life, and at the lower temperatures in the run-off channels rather complex feeding relationships have developed. Photosynthetic bacteria, primarily cyanobacteria, are at the beginning of the food chain, capturing light energy and converting it into organic matter.

Ephydrid flies, both larvae and adults, feed on the cyanobacteria. These flies are themselves fed on by other insects, including dolichopodid flies (a vicious predator of the ephydrids), spiders, dragonflies, beetles, and wasps. In addition, the ephydrids are parasitized by red mites, which attach themselves to the bodies of the adult flies, or feed on the pink egg masses. There is also a wasp which parasitizes the pupae of the ephydrids!

These various parasites and predators are themselves fed upon by larger carnivores, of which the most important are killdeers, birds that are often seen stalking their dinners on the geyser basins.

This whole array of organisms constitutes the hot spring food chain, a surprisingly complex, albeit specialized, ecosystem.



Life and Death at Low pH

The numerous acid hot springs of Yellowstone eventually flow into the surrounding rivers and lakes, adding striking amounts of acid to these waters. Even when cool, these acid waters are not felicitous habitats for most plants and animals. Acid rain from burning fossil fuels has caused the acidification of many lakes in the eastern U.S. and acidic lakes and rivers of Yellowstone provide a natural laboratory to study adaptation to acid.

Group	Lower pH limit	Examples
Animals		
Fish	4	Carp
Insects	2	Ephydrid flies
Plants		
Mosses	3	*Sphagnum*
Vascular plants	2.5-3	Heather, Sedges
Eucaryotic microbes		
Algae	1-2	*Euglena mutabilis*
	0	*Cyanidium caldarium*
Fungi	1-2	*Dactylaria gallopava*
Procaryotes	0.8	*Thiobacillus*
		Sulfolobus
Cyanobacteria	4	*Synechococcus*

We can see from the above table that fish do not live in very acid waters; sport fish, such as trout, are even more sensitive to low pH, disappearing when the pH drops below 6. Interestingly, when fish are wiped out by low pH, invertebrate animals often increase greatly in numbers, because they are less sensitive to acidification and no longer have any predators feeding on them.

An alga of acid waters called *Zygogonium* often forms large mats which spread out over the moist acidic basins. This alga provides the base of a food chain in which a few other algae and certain specialized animals thrive. One ephydrid fly, *Ephydra thermophila*, feeds on the acidophilic algae. Interestingly, this fly of very acid environments can also survive on algae from neutral/alkaline springs, but is not found there apparently because it cannot compete with the pink-egg laying *Ephydra bruesi* we discussed earlier. Another smaller ephydrid, *Scatella paludum*, also carries out its life cycle in acid springs. The ephydrid flies of the acid areas are preyed upon by other insects, such as wasps, mites, and tiger beetles. Birds such as killdeer are often seen on the acid alga mats, picking up a dinner of these acidophilic insects. Surprisingly, the birds do not seem to mind the acidic conditions, although they of course can move to less acid waters also. Certain acid lakes in Yellowstone, for instance Nymph Lake, Turbid Lake, and Clear Lake, have quite large populations of Canada geese.

An interesting pair of lakes is North and South Twin Lakes, along the Mammoth/Norris road. North Twin Lake receives most of its water from the very acid run-off from Roaring Mountain, and has a pH of 3.5, whereas South Twin Lake receives its water from nonacid creeks and has a pH of 6. Thus, even though these two lakes are almost touching, they differ strikingly in pH (and also in biological diversity). Obsidian Creek, near Roaring Mountain, also becomes quite acidic during the summer, and this change in pH is reflected in the algae that develop in its waters.

The table also shows that cyanobacteria are rather intolerant of low pH. Thus, although cyanobacteria form the major components of the orange mats we discussed earlier, they are replaced in acid waters by the eucaryotic thermal alga, *Cyanidium caldarium*, which is dark green.