Letting Off Steam

By Carolyn Ruth

Hundreds of visitors sit on benches or gather around the grassless, barren-looking geyser site. Some check their watches. Others get their cameras ready. One of nature's most spectacular events, the eruption of Old Faithful in Yellowstone National Park, is about to occur.

Soon, hot water bubbles upward and then something gives. Steam well over 100 °C shoots up through a single nozzle-like vent. Each cone-shaped eruption of Old Faithful

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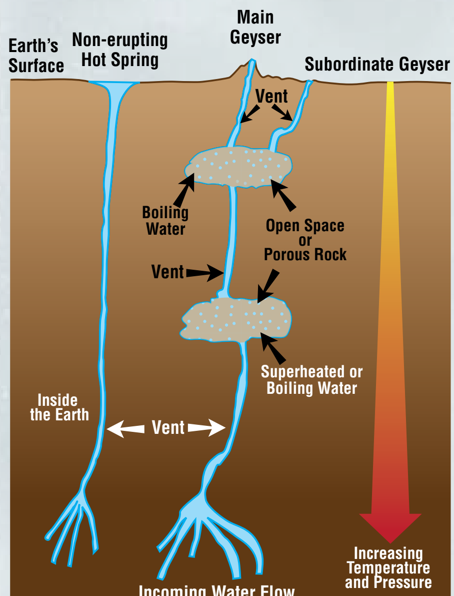
Cone-shaped eruption of Old Faithful at Yellowstone National Park.

lasts between 90 seconds and 5 minutes, with jets shooting as high as 30 to 55 meters in the air, expelling between 13,000 to 30,000 liters of water.

Yellowstone contains more than 10,000 geysers, hot springs, and steaming volcanic vents that can erupt at any moment in various locations. Because these eruptions are not as big as volcanoes, they can be seen from a short distance, offering a unique experience. Imagine staring at Old Faithful when, suddenly, you hear the hissing sound of another geyser erupting a few hundred yards away to your right, followed by mud bubbling out not far away. Then, you turn around, realizing the presence, to your left, of hot, bubbling water flowing out of the ground continuously.

BACKGROUND PHOTO: JUPITERIMAGES

Many scientists are as fascinated by this spectacle as the 2 million tourists visiting the park each year. Those scientists also seek to understand how these geysers and hot springs come to life and the chemical composition of the water they generate. It turns out that the water contains chemicals unique to that area as well as bacteria that thrive at very high temperatures. Also, scientists have discovered that the geysers and hot springs are caused by the upward movement of molten rock and hot water through an elaborate network of vents and caves, although the details of how this happens are still being fleshed out.



TONY FERNANDEZ, BASED ON A DRAWING BY CAROLYN RUTH

Figure 1. Schematic representation of the underground plumbing system for geysers and hot springs.

Plumbing system underground

On the basis of data gathered so far, scientists suggest that the network of vents and caves under Yellowstone National Park looks like the one represented in Fig. 1.

Most of the water ejected by Yellowstone's hot springs and geysers—250 million liters per day!—started out as rain or snow that trickled through small cracks and around mineral grains in the rocks and went down thousands of meters below the surface. There, the water sits in underground caves called chambers.

West Thumb Geyser Basin blue hot spring.

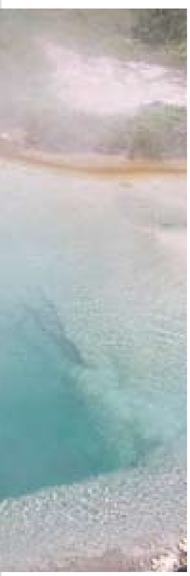
Although temperatures in these chambers reach 300 °C or more, the water does not vaporize but remains liquid because it is under great pressure from the rocks and water lying above. (Note that under high pressures, the boiling temperature of water changes. For example, water at twice the atmospheric pressure boils at 121 °C—instead of 100 °C—and water at 10 times the atmospheric pressure boils at 180 °C!) The superheated water pushes its way up through openings, and, as the water rises, the pressure is reduced and the water begins to boil.

If the pressure decreases rapidly, the boiling water is released as steam, triggering a geyser eruption. But if the pressure is released more slowly or the opening on the surface is wide, the water bubbles to the surface into a pool of hot water, creating a hot spring (Fig. 1).

The underground plumbing system for geysers is different from that of hot springs. In the case of a hot spring, the plumbing system is usually open enough to allow water to flow freely to the top (Fig. 1).

In a geyser, the plumbing system contains at least one narrowing, usually close to the surface. Water above the narrowing acts like a lid, helping to maintain the pressure on the boiling water below. So, when the geyser erupts, it blows off this lid and shoots upward, its size being determined by the width of the narrowing. The narrower the constriction, the higher the plume of steam.

After a geyser erupts, the underground chamber is emptied, so surrounding cooler water starts moving downward to replace the erupted water, and the cycle of water accumulating underground and erupting begins again. The entire trip from the surface and back probably takes at least 500 years. The water erupting today fell as rain or snow about the time that Christopher Columbus was exploring the New World!



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Occasionally, the vents become clogged and the water moving upward is stopped. The clogs are usually cleared by earthquakes, which occur frequently in the Yellowstone area. About 2,000 earthquakes shake the Park each year, which corresponds to an average of more than five earthquakes per day. Most are too small to feel, but some are significant.

Heat, earthquakes, and carbon dioxide

The heat source for Yellowstone's geysers and hot springs is about six kilometers below the surface in the form of partly molten rock called magma. The magma is located in a reservoir that extends from 8 to 16 kilometers underground and that was discovered by seismologists at the University of Utah, Salt Lake City. Before reaching this reservoir, the magma originates in a mantle plume that is 80 to 650 kilometers deep underground. This magma likely rises through fractures from the plume to the reservoir.

Robert Smith, professor of geophysics at the University of Utah and colleagues have recently determined the size of the upper magma reservoir horizontally and vertically. While studying how earthquakes occur around Yellowstone, the scientists noticed that underground waves caused by these earthquakes moved slower than usual in a particular area. This is because sound is delayed in melted rock compared to surrounding, cooler rocks.

Smith and his team suggest that this area, located more than 6 kilometers underground, consists of a large quantity of partly molten magma. As a result, rocks in that area are melted, which explains why earthquake waves move slower there than in surrounding rocks.

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Minerva terrace at the top of Mammoth Hot Springs, showing deposits of white calcium carbonate.

The scientists also measured unusual speeds for earthquake waves in a nearby area, located 2 kilometers underground. This time, the scientists suspect that fractures in the Earth may contain gases such as carbon dioxide, which would come from the partly molten rock area when some of the rocks crystallize.

"When an earthquake happens in that area, this carbon dioxide could migrate to the surface and cause significant damage," Smith says. "For example, an earthquake in California in 1989 caused a massive killing of trees, which could be due to release of carbon dioxide located underground, as seems to be the case in Yellowstone."

These results suggest that Yellowstone staff should not only monitor geysers and hot springs, but the possible emission of carbon dioxide as well, since it may pose a risk to human safety.

Water full of unique chemicals

What bubbles or erupts from geysers and hot springs is not pure water. As water goes downward through the ground and becomes hotter, it dissolves some of the minerals from the rocks. The rock underneath Old Faithful is primarily made of a type of highly viscous magma called rhyolite, which contains at least 70% of silicon dioxide (SiO_2).

As long as the water stays at high temperatures and pressures, the dissolved silicon dioxide stays in solution. But as the hot water rises up in a vent, it cools, the silicon dioxide becomes less soluble, and it deposits on the sides of the vent. The pathway in the vent narrows.

Water that erupts from Old Faithful cools on the surface, and an increasing amount of silicon dioxide settles around the vent in the form of a cone.

At Mammoth Hot Springs, the emerging water contains calcium carbonate ($CaCO_3$). As water erupts, white terraces of porous calcium carbonate called travertines form around the hot springs as the calcium carbonate settles out of the cooling water.

Silicon dioxide and calcium carbonate are not the only chemicals that are found in geyser and hot spring waters. Scientists have also found arsenic.

Kirk Nordstrom, a geochemist at the U.S. Geological Survey in Boulder, Colo., and colleagues have studied the arsenic concentrations in Yellowstone hot springs for many years. The testing conditions are hazardous. Protective measures, such as wearing rubber gloves and using clean collection procedures, are necessary.

"Any equipment that gets hot spring water on it is washed with distilled water in the field before packing up," Nordstrom says. "We also try to avoid being downwind of hot spring vapors. We sample upwind and don't sit or kneel near hot, vaporous areas more than necessary. The vapors from hot springs may contain toxic levels of mercury (Hg), carbon dioxide, (CO_2), and hydrogen sulfide (H_2S)."

Norris Geyser Basin in Yellowstone National Park has the highest arsenic concentrations. Arsenic tends to associate with gases such as hydrogen sulfide. Also, the water is multicolored, thanks to minerals such as porous silicon dioxide; yellow sulfur; red, yellow, and orange arsenic compounds; and gray and black iron sulfides.

New types of bacteria

Yellowstone's hot springs also contain bacteria that flourish near boiling temperatures and add bright green, yellow and orange colors to the water. There are so many bacteria that they form mats consisting of series of bacteria next to each other. Not only that, but many bacterial mats are formed, sitting on top of each other.

DAVID WARD, MONTANA STATE UNIVERSITY

Mushroom Spring in Yellowstone National Park, with an enlarged inset showing a cross section of a microbial mat.

"These bacterial mats look like a piece of spinach lasagna," says Don Bryant, professor of biotechnology at The Pennsylvania State University, State College. "You can find different species of bacteria in the different layers, yet all these bacteria live together and cooperate to help one another."

Recently, Bryant and David Ward, a microbial ecologist at Montana State University, Bozeman, made an unexpected discovery. While studying the photosynthetic bacteria on the upper surface of a hot spring called Octopus Spring, they found a totally new bacterium. By looking at its DNA, they found that not only was it using light as energy for growth—a process called photosynthesis—but that it was a new species of bacteria.

Like other photosynthetic bacteria, plants, and algae, this new type of bacterium, called *Candidatus* Chloracidobacterium thermophilum, uses chlorophyll molecules to capture sunlight, but in a way different than other bacteria.

In some chlorophyll-containing bacteria and all plants, light absorbed by the chlorophyll molecules is used inside cells to produce the energy necessary to transform carbon dioxide and water into carbohydrates and oxygen, a process called photosynthesis:

$$CO_2 + H_2O \xrightarrow{\text{light}} \text{carbohydrates} + O_2$$

The new bacterium has specialized antenna-like structures called chlorosomes, each of which contains about 250,000 bacteriochlorophyll molecules—a special type of chlorophyll molecules found in bacteria. This way, this bacterium can collect light more efficiently than other bacteria—meaning that it can perform photosynthesis with much less light than its neighbors.

"We estimate that this bacterium can efficiently grow at light intensities that are 1000 times lower than that required by a blade of grass," Bryant says. "Based on further studies in my lab, we are starting to understand how this is accomplished and how it differs from the photosynthesis that occurs in other bacteria."

"The discovery of this new bacterium may provide new insights into how life can thrive without too much light," Ward says. "It may tell us how photosynthesis started on Earth—at a time when there was little or no oxygen—and whether life can exist in extreme environments with very high temperatures and low light intensity, as on some other planets."

A constantly changing landscape

Even though scientists have a better understanding of Yellowstone National Park's underground structure and the chemistry and life on its surface, this is not the end of the story. The park is constantly changing, making it hard to know what will happen in the future.

"Our understanding of what happens in the deep Earth is limited by our inability to get down there for a direct look," says Hank Heasler, a geologist at Yellowstone National Park. "Current techniques—such as radar interferometry and Global Positioning System—can tell us fairly accurately what is happening on the surface but not what goes on underground."

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Calcium carbonate formations at Mammoth Hot Springs in Yellowstone National Park.

Scientists suggest that the upward and downward movements result from the nearly continuous movement of hot water and molten volcanic rocks called basalt and granite that are coming from the magma chamber discovered by the University of Utah scientists. In some areas, the magma and hot water flow faster, resulting in an uplift of the soil surface, and in other areas, the circulation of magma and hot water is slower, leading to downward movements. But what causes theses changes in magma and hot water circulation is still a mystery.

Even Old Faithful is changing. Its eruptions have been occurring further apart in recent years. It could even stop to erupt in the future. Someday, visitors may sit in anticipation at another site in the park as they do in front of Old Faithful now.

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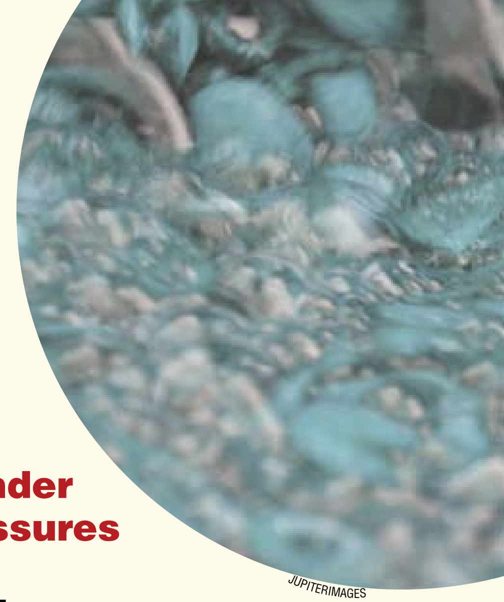
ACTIVITIES



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Activity 1

Make your own volcano

ANNE HELMENSTINE

You will need

Safety goggles
1-liter bottle
6 cups flour
2 cups salt
4 tablespoons cooking oil
2 cups water
Red food coloring
Enough warm water to almost fill the bottle
6 drops of detergent
2 tablesppons baking soda
5%-vinegar solution

What to do

Wear the safety goggles.
Knead the flour, salt, oil, and the 2 cups of water together to make a dough. Stand a bottle in a baking pan and mold the dough around it into a volcano shape. Don't cover the hole or drop dough into the bottle.
Fill the bottle most of the way with warm water and a bit of food color.
Add detergent.
Add baking soda.
Add vinegar slowly until the volcano ceases to produce bubbles.

How it works

The detergent and the baking soda ($NaHCO_3$) dissolve in the warm water. When the vinegar, which contains acetic acid (CH_3COOH) is added, the following chemical reaction occurs:

$$NaHCO_3 + CH_3COOH \rightarrow NaCH_3COO + CO_2 + H_2O,$$

in which $NaCH_3COO$ is sodium acetate, CO_2 is carbon dioxide, and H_2O is water.

Carbon dioxide gets trapped inside the soap bubbles, and the combination of carbon dioxide and soap emerges from the top of the bottle and flows down the sides of the volcano-shaped dough. You are witnessing a volcano explosion!

– Carolyn Ruth

Activity 2

Boil water under different pressures

You will need

Safety goggles
250-mL vacuum filtration flask
Rubber stopper to close off the top of flask
Faucet with suction filtration attachment
Heavy-walled tubing to connect side arm of flask to faucet projection; this tubing should be heavy-walled so that it won't collapse under reduced pressure
50-mL slightly warm water

What to do

Wear the safety goggles
Securely clamp the flask to a heavy stand to prevent it from falling over and breaking; never hold this flask with your hands while doing this activity.
Put the slightly warm water into the flask.
Insert a stopper in the flask.
Attach tubing to the sidearm of the flask and the side of the faucet suction filtration attachment.
Turn on water to highest flow.
At the end of the activity, turn off the water and break the vacuum by gently removing the rubber hose from the side of the faucet suction filtration attachment.

How it works

Boiling is defined as the temperature at which the vapor pressure of water equals the air pressure above the surface of the water. The temperature at which water boils can vary significantly, as revealed by this activity.

Here is what happens: As the tap water flows past the tubing attached to the faucet, air from the tube is drawn into the water that is pouring down the drain. This in turn removes air from the flask. Air from the flask is flowing from the high pressure area inside the flask to the low pressure area in the tubing.

The water in the flask is under atmospheric pressure before the faucet is turned on and does not boil. When the air above the surface of the water in the flask is reduced significantly, the water in the flask is now under very low pressure and boils.

– Carolyn Ruth