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1 About Geysers

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What Is a Geyser?

The standard definition of *geyser* in general worldwide use reads like this:

> *A geyser is a hot spring characterized by intermittent discharge of water ejected turbulently and accomplished by a vapor phase.*

It sounds simple enough, but it really is not. The definition includes several "gray areas" that can be interpreted in different ways—how hot is hot; how high must the turbulence be; are there limits as to how long or short the intermittency needs to be? Such questions will probably never be answered to everyone's satisfaction, but there are two similar varieties of hot springs that definitely do not qualify as geyser. *Intermittent springs* undergo periodic overflows but never actually erupt; and *perpetual spouters* (called *pulsating springs* in some parts of the world) may erupt, but their action never stops. In all three of these cases, however, the cause of the *eruption* is the same—namely, the formation of pressured steam (a "vapor phase") at some depth below the ground.

What Makes a Geyser Work?

Three things are necessary for a geyser to exist: an abundant supply of water, a potent heat source, and a special underground *plumbing system*.

The water and heat factors are fairly common. Hot springs are found in virtually all of the world's volcanic regions. The plumbing system is the critical aspect. Its shape determines whether a spring will be quiet or will erupt. It must be constructed of minerals strong enough to withstand tremendous pressure, and it must include a permeable volume so as to hold the huge amounts of water ejected during an eruption.

Nobody really knows what a plumbing system looks like—it is, after all, belowground and filled with hot water and steam. Considerable research drilling has been done in some of the world's geyser areas, and apparently no drill hole has encountered any large, open water storage cavern. This led to the conclusion that much of a geyser's water reservoir is nothing more than a complex network of small spaces, cracks, and channels in the porous rocks that surround the plumbing system. However, as shown below, recent research has shown that cavernous reservoirs might exist after all.

In 1992 and 1993, an experimental probe equipped with pressure and temperature sensors plus a miniature video camera was lowered into Old Faithful Geyser's *vent* shortly after an eruption had ended. At a depth of only 22 feet, there was a narrow slot barely 4 inches wide. Just below that was a wider area that had a waterfall of relatively cool, 176°F (80°C), water pouring into it. Then, at about 35 feet, the probe entered a chamber "the size of a large automobile" that extended to some depth greater than 46 feet, the greatest depth reached by the probe. As Old Faithful refilled, the temperature of the rising water was 244°F (117°C), fully 45°F (25°C) hotter than the normal surface boiling point at that altitude. The researchers reported that the action resembled a seething "liquid tornado" of unbelievable violence. This was enough to support the long-held conclusion that geyser plumbing systems, at least near the surface, consist largely of simple tube-like conduits with occasional wide spaces but without large reservoirs.

However, also in 1992, a separate study used 96 sensors to record the vibrations of tiny seismic tremors caused by the bubbling and boiling of water within Old Faithful Geyser's plumbing system. There was so much "noise" in the data that a concentration of activity a short distance southwest of Old Faithful was overlooked. In 2013, a new study reanalyzed the 1992 data. It indicated that a rather large chamber does, in fact, exist at the southwest side of Old Faithful Geyser's main conduit. This was followed by a project in 2015 that used ground-penetrating radar to examine that area. It revealed a chamber at least 30 feet across and of unknown depth. A second report from the same study claimed the chamber to be 60 feet wide. The

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top of this chamber is about 50 below the ground surface, and it connects to Old Faithful at a depth of about 65 feet. The result is shown in figure 1.1 (left). There is also a connection between the reservoir and nearby Split Cone Geyser. Old Faithful still erupts out of a relatively straight and narrow conduit, but it is additionally served by this side chamber. Note that another analysis of this seismic data suggested that this could be a zone of exceptionally porous, water-saturated rock rather than a truly open chamber. Even if that is the case, as one researcher said, the result is that "Old Faithful's plumbing is more like a bagpipe than a flute."

This is quite unlike the standard model of a plumbing system, which has the water rather quietly flowing upward into a single main tube. It is now believed that this revised model probably applies to all geysers—similar, although much smaller, chambers have also been found in some of the geysers on Russia's Kamchatka Peninsula. It makes the water supply network more complex but changes nothing about how geysers actually operate. The character and eruptive performance of every geyser are determined by the geyser's plumbing system and, as in all of nature, no two are alike.

When all available data are combined, enough information is available for us to construct a schematic plumbing system of a geyser. An example is shown in figure 1.2 (right). It consists mainly of tubes extending into the ground, containing many sharp bends and constrictions along their lengths. Connected to the tubes are occasional open chambers and, especially, layers of water-storing sand and gravel of high porosity. Most of this plumbing is fairly close to the surface, and even the largest geysers extend to a depth of only a few hundred feet. Finally, much of the upper part of the plumbing system is coated with a lining of *siliceous sinter*, or *geyserite*, which, combined with an inward force exerted by cold, dense water outside the plumbing, makes the system pressure-tight. Siliceous sinter is also deposited outside the geyser, and in and about the quiet hot springs. Of course, the geyserite is not magically deposited by the water. Its source is quartz (or silica) in the volcanic rocks underlying the *geyser basin*.

The water that erupts from a geyser arrives there only after a long, arduous journey. Water first falls in Yellowstone as rain and snow, then percolates through the ground to as much as 8,000 feet below the surface and back again. The round-trip takes at least several hundred years. This is something that can be determined with reasonable accuracy by studying the tritium (sometimes called "heavy-heavy hydrogen") content of the geyser water. Tritium is radioactively unstable and decays with age. Young

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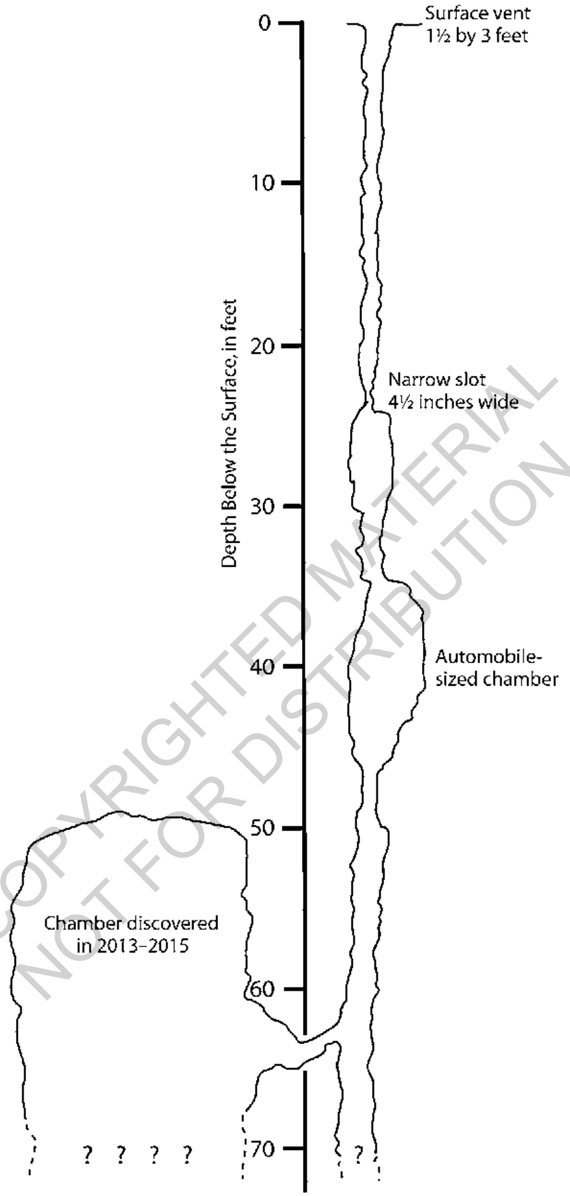

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FIGURE 1.1. *The use of a video probe lowered 46 feet into Old Faithful Geyser combined with seismic and ground-penetrating radar studies show the plumbing to be an irregular tube connected to a large chamber filled with violently boiling water. All geysers probably have similar plumbing systems.*

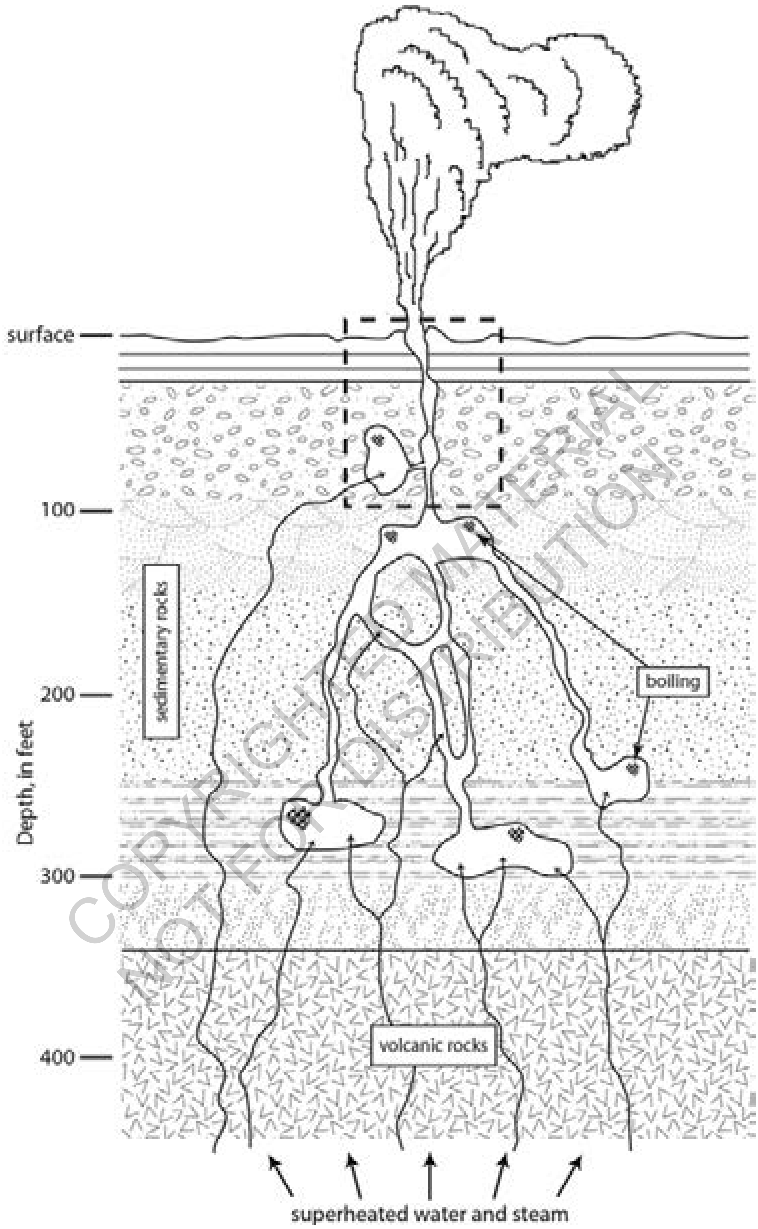

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FIGURE 1.2. *Although nobody really knows what a geyser's deeper plumbing system looks like, research indicates that it probably is similar to this illustration. The dashed box (top-center) might represent Old Faithful Geyser.*

water contains considerable amounts of tritium, while old water contains little or none. It is nearly absent in most Yellowstone waters; in fact, it is believed that the water erupting from Old Faithful today fell as precipitation at least 500 years ago—around the time that Columbus was exploring the West Indies—and other geochemical evidence indicates that 1,100 years is more likely.

At depth, the percolating surface water is heated where it contacts a high-temperature brine, which in turn circulates as deep as 15,000 feet where it is heated by the enclosing volcanic rocks. Once heated, it dissolves some of the silica from the rocks. All this takes place at very high temperatures—over 500°F (200°C) in many cases, and 459°F (237°C) was reached in a research drill hole only 1,087 feet deep. This silica will not be deposited by the water until it has approached the surface and cooled to a considerable extent.

Now an interesting and important phenomenon occurs. Although it was the mineral quartz that was dissolved out of the rocks, the deposit of geyserite is a form of opal (never of gem quality). The mechanisms involved in this process are complex, involving temperature, pressure, acidity or alkalinity of the water, and time.

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How a Geyser Erupts

The hot water, circulating up from great depth, flows into the geyser's plumbing system. Because this water is many degrees above the boiling point, some of it turns to steam instead of forming liquid *pools*. Meanwhile, additional cooler water is flowing into the geyser from the porous rocks nearer the surface. The two waters mix as the plumbing system fills.

The steam bubbles formed at depth rise and meet the cooler water. At first, they condense there, but as they do they gradually heat the water. Eventually, these steam bubbles rising from deep within the plumbing system manage to heat the surface water until it also reaches the boiling point. Now the geyser begins to work like a pressure cooker. The water within the plumbing system is hotter than boiling but is "stable" because of the pressure exerted by the water lying above it. (Remember that the boiling point of a liquid is dependent on the pressure. The boiling point of pure water is 212°F [100°C] at sea level. In Yellowstone, the elevation is about 7,500 feet [2,250 meters], the pressure is lower, and the boiling point of water at the surface is only around 198°F [93°C].)

The filling and heating process continues until the geyser is full or nearly full of water. A very small geyser may take but a few seconds to fill, whereas some larger geysers take several days. Once the plumbing system is full, the geyser is about ready for an eruption. Often forgotten but of extreme importance is the heating that must occur along with the filling. Only if an adequate store of heat exists within the rocks lining the plumbing system can an eruption last more than a few seconds. (If you want to keep a pot of water boiling on the stove, you have to keep the fire turned on. The hot rocks of the plumbing system serve the same purpose.) Again, each geyser is different from every other. Some get hot enough to erupt before they are full and start to *play* without any preliminary indications of an eruption. Others may be completely full long before they are hot enough, and may overflow quietly for hours or even days before an eruption finally occurs. But eventually, an eruption will take place.

Because the water of the entire plumbing system has been heated to boiling, the rising steam bubbles no longer collapse near the surface. (Recent research, only published in 2016, indicates that the formation of carbon dioxide bubbles is also an important part of the process—indeed, there is an implication that eruptions might not happen at all if carbon dioxide was not present.) As more very hot water enters the geyser at depth, even more and larger bubbles form and rise toward the surface. At first, they are able to make it all the way to the top of the plumbing with no problem. But a time will come when there are so many bubbles that they can no longer freely float upward. This pressure forces overlying water ahead of them, and up and out of the geyser. This initial loss of water reduces the pressure at depth, lowering the boiling temperature of water already hot enough to boil. More water boils, forming more steam. Soon there is a virtual explosion as the steam expands to over 1,500 times its original, liquid volume. The boiling becomes violent, and water is ejected so rapidly that it is thrown into the air. In fact, people standing near very large geysers sometimes hear and feel a thudding, popping sound. Research indicates that this happens because the *superheated* water is ejected so quickly and then explodes into steam so violently within the water column that the total speed exceeds the sound barrier—the thuds are actually small sonic booms within the expanding column of steam and water!

The eruption will continue until either the water is used up or the temperature drops below boiling. Once an eruption has ended, the entire pro-

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cess of filling, heating, and boiling will be repeated, leading to another eruption.

The Different Kinds of Geysers

All geysers operate in the same fashion, but they come in three varieties. The differences depend on the size and shape of the plumbing system and its constriction, the depth of a pool, the volume of available water, and so on.

Cone-type geysers erupt steady streams of water that jet from small surface openings. The vent is often, but not always, surrounded by a built-up *cone* of geyserite. Cone-type geysers are rather *uncommon*, but because the water is squirted under considerable pressure, they tend to have tall, spectacular eruptions such as those of Old Faithful, Daisy, and Riverside Geysers.

Fountain-type geysers look a lot different from the cone-type, because their eruptions rise out of open pools. Steam bubbles rising and expanding into the pools cause a series of individual *bursts* of water, so the action is more a spraying or splashing than a jetting. The fountain-type makes up the vast majority of the world's geysers. Most are small in size, but there are also large examples such as Grand, Great Fountain, and Echinus Geysers.

Some observers do not accept *bubble-shower springs* as true geysers, but instead list them as a special case of intermittent spring, because no vapor phase can be seen rising from within the spring's plumbing system. The eruption consists entirely of violent boiling near the surface of an open pool. Some bubble-shower springs, such as Crested Pool, have eruptions as high as several feet, but in most cases the boiling turbulence reaches up only a few inches. This book considers bubble-shower springs to be geysers.

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Why Are Some Geysers Regular, Others Irregular?

The inflow of water into a geyser system is constant, so it would seem that the activity of any geyser should show little variation from one eruption to the next. However, only a few are classed as regular geysers. To be regular, a geyser must either be isolated from other springs or connected only with springs whose overall activity is so constant that they do not affect the geyser. Old Faithful is the most famous example of regularity. Its eruptions can be predicted with nearly 90 percent accuracy. Some other geysers are even more regular, occasionally operating with almost stop-watch-like precision.

But most geysers are *irregular*. The time *interval* between successive eruptions is erratic. One time it may be just minutes between the plays, the next several hours. In no way can these geysers be predicted.

The mechanism behind this has been termed *exchange of function*, as first described by G. D. Marler in 1951. What this basically means is that water and energy can be diverted from a geyser to some other hot spring or hot spring group (another geyser is not necessarily involved). This happens because the plumbing systems of most springs and geysers are intertwined with those of others. The activity of any one of those springs must affect all others in the *group*.

Just what makes exchange of function take place is unknown. Something must act as a valve so as to shunt the water and heat from one direction to another, but whether this is a vapor lock as a result of a build-up of steam bubbles, a fluidic switch operation, a Venturi effect, or something entirely different has never been determined. Most exchanges are small scale in both extent and time, and require a knowing eye to detect. Others can be of great significance. Indeed, one group of active springs may suddenly stop functioning altogether while a nearby group of previously insignificant springs becomes animated with an exchange that might last for years. A good example involved Daisy Geyser and nearby Bonita Pool in the Upper Geyser Basin. For years, Daisy was one of the largest and most regular geysers in Yellowstone, while Bonita overflowed only slightly. Suddenly the energy shifted toward Bonita. Daisy was drained of the energy necessary for eruptions as Bonita overflowed heavily and underwent small eruptions. As a result, Daisy erupted just three times in over 13 years. Then the energy flow shifted back toward Daisy. Now it is predictable again while Bonita lies quietly below overflow.

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Why Are Geysers So Rare?

There are few places on earth where the three requirements for the existence of geysers are met. The requisite water supply poses no great problem; in fact, a few geysers are able to exist in desert areas, places normally thought of as dry. But the heat source and plumbing systems are tied to one another and are much more restrictive.

Nature's heat source is volcanic activity. The heat is supplied by large bodies of molten or freshly cooling rock at great depth. Given a proper water supply, hot springs are possible in any area of geologically recent volcanism.

Most hot spring areas do not contain geysers, however, because there is a catch. Not just any volcanism will do. The plumbing systems must be pressure-tight, and that requires silica-rich rocks to provide the source of the geyserite that lines the plumbing systems.

The answer is rhyolite. Rhyolite is a volcanic rock very rich in silica; it is the chemical equivalent of granite. Rhyolite is rather uncommon, though, and large recent fields of it are found in few places. Yet the majority of geysers are found in such areas. Most of the exceptions to this rule are still associated with recent volcanic activity, though their rocks—dacite, andesite, and basalt—are somewhat less rich in silica. And as seems to be usual in science, there are a few anomalous geyser localities, such as Beowawe, Nevada, where the activity is not associated with recent volcanic action but where there is a high geologic heat flow and silica-rich sandstone at depth.

Not only is Yellowstone a major rhyolite field, but it is of recent origin. Although the last major volcanic eruption was 600,000 years ago, minor activity continued as recently as 70,000 years ago. Yellowstone could well be the site of further volcanic eruptions. That is another story entirely, but for now, the park is incomparably the largest *geyser field* in the world.

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How Many Geysers Are There in Yellowstone?

This chapter opens with a basic answer to "What is a geyser?" and notes that there are a number of gray areas and transitional kinds of springs. When such features as bubbling intermittent springs, variable perpetual spouters, and random splashers are eliminated from consideration, the number of geysers actually observed to be active in Yellowstone *in any given year* might exceed 500. Studies by independent researcher Jeffrey Cross, published as part of the 11th Biennial Scientific Conference on the Greater Yellowstone Ecosystem, indicate that a minimum of 1,283 springs have erupted as true geysers since the national park was established in 1872. Note, however, that may of those are very small in size, in remote backcountry locations, and/or of extremely *rare* activity.

Even the count of 500 active geysers is an amazing number. The second largest of the world's geyser fields, Dolina Geizerov on Russia's Kamchatka

Peninsula, used to contain about 200 geysers, but now at best has half that number since it was partly destroyed by landslides in 2007 and 2014. Dagyel Chuja, in Tibet, might also contain 100 geysers, though the count there is controversial. El Tatio, remote in the high Andes Mountains of Chile, has 85 documented geysers. New Zealand's North Island has perhaps 70 geysers, and Iceland hosts around 30. All other areas contain fewer. Taken together, the entire world outside of Yellowstone might total only 500 geysers. (See the appendix for more about the rest of the world's geyser fields.)

Yellowstone, in other words, contains well over half—perhaps even two-thirds—of all the geysers on Earth. The number of geysers is not stable, however. They are very dynamic features, affected by a wide range of physical factors and processes. The slightest change in the geological environment may radically alter, improve, or destroy the geysers.

Recent studies of historical literature have shown that much about Yellowstone had been forgotten. Many springs taken to be "new" geysers in recent years are now known to have been active during the 1800s. Nevertheless, the number of active geysers appears to be increasing year by year. In 1992, a geochemist with the U.S. Geological Survey, who had conducted studies in Yellowstone for more than fifty years, stated that in 1955 one could easily count the number of geysers on Geyser Hill on two hands. This book enumerates 51 individual or clustered geysers on Geyser Hill, and at least 38 of them were active during 2015. Authors E. T. Allen and A. L. Day of the Carnegie Institute of Washington counted 33 geysers at the Norris Geyser Basin in 1926; 83 are enumerated here. Similar situations exist throughout Yellowstone.

All this fits with recent studies that suggest that Yellowstone's geyser basins—all of them and all of the geysers and hot springs within them—operate on what has been termed a "pulse and pause" basis. If this is correct, then decades-long episodes of vigorous geyser activity are separated by long time spans when few or even no eruptions occur. These pauses are long enough to allow the formation of soil and the growth of trees, such as the silicified remains on the cone of Old Faithful Geyser, on the rim of Castle Geyser, and within the formation of Grotto Geyser; even the stand of dead trees on the hill behind Grand Geyser might be evidence of this. The apparent fact is that there really are more active geysers today than perhaps ever before in recorded history. We do not know why this is so, but clearly right now Yellowstone is within a "pulse," and right now is the "good ol' days" of geyser gazing.

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