Why Study Geysers?

Aside from captivating our senses, geysers have much to tell us about subsurface fluids, climate change effects, and the occurrence and limits of life on Earth and elsewhere in the solar system.

Several scientific experiments have been conducted at Lone Star Geyser in Yellowstone National Park, seen here erupting in October 2014. Credit: Neal Herbert, National Park Service

By Shaul Hurwitz, Michael Manga, Kathleen A. Campbell, Carolina Muñoz-Saez, and Eva P. S. Eibl 9 hours ago

Each year, millions of tourists visit geysers around the world, marveling at the jets of water spouting high into the air from subterranean reservoirs. Fascination with these rare features is nothing new, of course: Written records of their occurrence date back to the 13th century at least, and for more than 2 centuries, scientists have been improving our understanding of Earth's geysers.

The English word *geyser* originates from *geysir*, a name given by Icelanders in the 17th century to intermittently discharging hot springs. The name descends from the verb *gjósa*, which means to gush or erupt. Natural geysers are rare—fewer than a thousand exist today worldwide, and only a handful of fossil examples are known from the geological record. About half of Earth's geysers are located in Yellowstone National Park (https://eos.org/articles/can-carbon-dioxide-trigger-geyser-eruptions) in the United States. Other large geyser fields include the Valley of Geysers in the Kamchatka Peninsula of Russia, El Tatio in Chile, and Geyser Flat at Te Puia, Rotorua, in New Zealand.

In 1846, French mineralogist Alfred Des Cloizeaux and German chemist Robert Wilhelm Bunsen formulated an early model to explain geyser eruptions based on field measurements (https://doi.org/10.1029/EO055i012p01052) of temperature, chemistry, and circulation and eruption patterns at Geysir (https://www.britannica.com/place/Geysir) in Iceland. Since then, scientific knowledge (https://www.usgs.gov/center-news/how-do-geysers-work-knowledge-gained-two-centuries-scientific-research-and-observations) of geysers has advanced significantly [*Hurwitz and Manga* (https://doi.org/10.1146/annurev-earth-063016-015605), 2017], providing valuable insights into volcanic processes, the origin and environmental limits of life on Earth (and potentially elsewhere, including on Mars), and similar geysers on icy outer solar system satellites. Demonstrating these connections, geologist and planetary scientist Susan Kieffer wrote the following in a perspective (https://doi.org/10.1146/annurev-earth-063016-020501) on her research career:

"[M]y initial idea of studying Old Faithful geyser as a volcanic analog [*sic*] led me to work not only on the dynamics of eruption of Mount St. Helens in 1980 but also on geysers erupting on Io (a fiery satellite of Jupiter), Triton (a frigid satellite of Neptune), and Enceladus (an active satellite of Saturn)."

Continuing research into the inner workings of geysers will help us further understand and protect these natural wonders and will reveal additional insights about volcanism on and off Earth.

Like Volcanoes, but More Accessible

Similar to volcanoes, geysers are transient features with periods of activity (https://eos.org/articles/are-geysers-a-signal-of-magma-intrusion-under-yellowstone) and dormancy. Geyser eruption patterns can change following large earthquakes, shifts in climate, and variations in the geometry of their conduits and subsurface reservoirs. Eruption processes of geysers, which can be driven by geothermal heating and the formation of vapor bubbles, are also akin to those operating in volcanoes.

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The model developed by Des Cloizeaux and Bunsen showed that as water rises toward the surface and pressure decreases (https://onlinelibrary.wiley.com/doi/abs/10.1002/anie.202008727), boiling forms bubbles. The liquid water containing the bubbles further lowers the density and pressure of the mixture. Decreasing pressure similarly causes changes in magma that underpin key volcanic processes, such as melt generation in the mantle and the formation of bubbles in magma that drive eruptions.

Because geysers have smaller eruptions and erupt more frequently than volcanoes, they provide useful natural laboratories to study eruption processes and test new monitoring technologies. Volcanic eruptions are sometimes preceded by magma movement that is difficult to monitor (https://doi.org/10.1029/2018JB016974) because of the large spatial scales and long timescales involved. In contrast, measurements of fluid movement, for example, can be made relatively easily through many geyser eruption cycles, providing data that can be used to improve the interpretation of volcanic phenomena. Measurements and video observations can also be collected within the conduits of active geysers (https://www.youtube.com/watch?v=8luNCFUnvBw)—a feat that is impossible at active volcanoes.

An array of instruments (foreground) measures seismic tremor around geysers at El Tatio in Chile. Credit: Shaul Hurwitz, U.S. Geological Survey

Signals such as seismic tremor (https://seismo.berkeley.edu/blog/2013/11/18/seismic-tremor-rumbles-without-the-jolts.html)—sustained ground vibrations that are common prior to and during volcanic and geyser eruptions—can be very informative (https://link.springer.com/chapter/10.1007/978-3-642-80087-0_2) for monitoring subsurface processes at active volcanoes and geysers. Tremor in volcanoes can last for days, weeks, or even longer leading up to volcanic eruptions (https://eos.org/articles/fingerprinting-volcanic-tremors-may-help-forecast-eruptions) [*Chouet and Matoza* (https://doi.org/10.1016/j.jvolgeores.2012.11.013), 2013]. Tremor may be caused by degassing of magma (https://doi.org/10.3389/feart.2018.00157) and by the movement of fluids within a volcanic edifice. However, identifying fluid types (gas, liquid water, magma) and the processes responsible for episodes of tremor is challenging because of the geometric complexities and sizes of volcanic systems.

Seismometers deployed around the iconic Old Faithful (https://www.usgs.gov/center-news/a-new-view-old-faithfuls-underground-plumbing-system) and Lone Star (https://doi.org/10.1029/2020JB019711) geysers in Yellowstone have detected tremor caused by continuous bursts of rising steam bubbles (https://doi.org/10.1029/98JB01824), analogous to bubbles forming and bursting in a teakettle (https://blogs.nasa.gov/ISS_Science_Blog/2011/04/15/post_1301433765536/). Thus, by analogy, such measurements of tremor in geyser systems can help elucidate processes that generate volcanic tremor.

Tracking tremor signals in time and space using dense arrays of seismometers also has illuminated the subsurface structure of volcanoes and geysers [*Eibl et al.* (https://doi.org/10.1029/2020JB020769), 2021; *Wu et al.* (https://doi.org/10.1029/2018GL081771), 2019]. The locations of tremor sources around Strokkur (https://blogs.egu.eu/divisions/sm/2020/11/24/field-work-in-winter-in-iceland-the-beautiful-nature-of-strokkur-geyser/) Geyser in Iceland, and Old Faithful (https://blogs.agu.org/geospace/2017/10/06/old-faithfuls-geological-heart-revealed/), Lone Star, and Steamboat (https://eos.org/articles/are-geysers-a-signal-of-magma-intrusion-under-yellowstone) in Yellowstone, for example, indicate that these geysers' reservoirs are not located directly beneath their vents. Tilting of the ground surface around Lone Star Geyser (https://doi.org/10.1002/2014JB011526) and a geyser at El Tatio (https://www.scientificamerican.com/article/instant-egghead-how-do-geysers-erupt-over-and-over/), as well as video observations (https://doi.org/10.1130/G33366.1) in the conduits of geysers in Kamchatka, also indicate reservoirs that are not aligned below the geysers' vents. This type of reservoir, in which liquid and steam bubbles accumulate and pressure builds prior to an eruption, is called a bubble trap and might be a common feature of many geysers [*Eibl et al.* (https://doi.org/10.1029/2020JB020769), 2021].

Carolina Muñoz-Saez inserts pressure and temperature sensors into a geyser conduit at El Tatio in northern Chile. Seismometers that measured seismic tremor throughout many eruption cycles are visible in the background. These experiments were conducted in coordination with the communities of Caspana and Toconce. Credit: Max Rudolph, University of California, Davis

Laboratory experiments of geysers have shown how heat and mass transfer between laterally offset reservoirs and conduits control eruption patterns [*Rudolph et al.* (https://doi.org/10.1016/j.jvolgeores.2018.11.003), 2018]. Geophysical imaging has similarly revealed that although most volcanic vents are located directly above their magma reservoirs, many reservoirs are laterally offset (https://www.scientificamerican.com/article/faraway-magma-reservoirs-complicate-volcano-monitoring/) from their associated volcanic edifices [*Lerner et al.* (https://doi.org/10.1029/2020GL087856), 2020].

A striking example of an offset magma reservoir was highlighted in a 1968 study of the Great Eruption of 1912 (https://www.nps.gov/articles/aps-v11-i1-c2.htm) in Alaska [*Curtis* (https://doi.org/10.1130/MEM116-p153), 1968], in which magma erupted from Novarupta volcano, but collapse occurred some 10 kilometers away at Mount Katmai, where most of the magma that erupted at Novarupta had been stored. Mapping of such laterally offset magma storage systems, as well as detailed physical knowledge of how they work as gleaned from studies of and experiments with geysers, may help scientists design better volcano monitoring networks.

Earth Tides, Earthquakes, and Climate Change

Eruptions at geysers and volcanoes are controlled by delicate balances in heat supply and gas and fluid flows within their systems, and by the tortuous pathways that liquid water, steam, and magma take to the surface—balances that can be affected by external forces. Documenting whether geysers and volcanoes respond to tides and earthquakes provides opportunities to quantify their sensitivity to changes in physical stress in the subsurface and to help evaluate whether they are poised to erupt [*Seropian et al.* (https://doi.org/10.1038/s41467-021-21166-8), 2021].

Past studies have suggested, on the basis of statistical correlations, that small forces exerted by Earth tides can trigger volcanic eruptions (https://doi.org/10.1029/JB078i017p03363). However, statistical tests of tidal influence on volcanic eruptions are limited because of the rarity of eruptions from a single volcano. In contrast, the thousands of geyser eruptions that occur annually form a much broader sample pool on which to base statistical tests. One such evaluation uncovered a lack of correlation (https://doi.org/10.1002/2014EO210008) between Earth tides and the intervals between geyser eruptions, a finding that suggests that a correlation between Earth tides and volcanic eruptions is also unlikely.

In Yellowstone, some geysers stopped erupting whereas others started erupting, after the magnitude 7.3 Hebgen Lake earthquake in Montana in 1959.

Although tides might not affect geyser eruptions, regional and even very distant large earthquakes can. Written accounts document renewed activity of Geysir (https://doi.org/10.1007/978-3-319-55152-4_7) following large earthquakes in southern Iceland in 1294. In Yellowstone, some geysers stopped erupting whereas others started erupting (https://doi.org/10.1130/0016-7606(1975)86%3C749:SGAIBO%3E2.0.CO;2), after the magnitude 7.3 Hebgen Lake earthquake in Montana in 1959. The magnitude 7.9 Denali earthquake in Alaska in 2002 affected eruptions of some Yellowstone geysers (https://doi.org/10.1130/G20381.1) 3,000 kilometers away.

Earthquakes can also promote volcanic unrest and eruptions. Establishing causal relations (https://doi.org/10.1007/s00445-018-1232-2) between earthquakes and eruptions is challenging because few active volcanoes occur in any given area, and changes in the subsurface can take longer to manifest as an eruption. However, geysers erupt more frequently than volcanoes, which again points to the utility of studying geysers as volcanic analogues.

Precipitation trends and climate changes can affect geysers as well. Eruption intervals at Old Faithful Geyser have changed in the past, and it even ceased erupting in the 13th and 14th centuries (https://eos.org/research-spotlights/megadrought-caused-yellowstones-old-faithful-to-run-dry) because of a severe drought. How often geysers erupt may also change in response to seasonal and decadal changes (https://doi.org/10.1038/4531146f) in precipitation, which affect the supply of groundwater that feeds the eruptions.

Volcanoes also display slight seasonal patterns (https://doi.org/10.1029/2002JB002293) in their eruptions, and they respond to changing climate (https://www.scientificamerican.com/article/get-ready-for-more-volcanic-eruptions-as-the-planetwarms/). As air temperatures warm, for example, glaciers covering volcanoes melt (https://doi.org/10.1016/j.earscirev.2017.11.009), which in turn reduces pressure (https://www.sciencedirect.com/science/article/abs/pii/S0012825213000664?via%3Dihub) on underlying magma. Pressure reduction causes gas bubbles to form, and the buoyant mixture of magma and bubbles is then more primed for eruption (https://eos.org/science-updates/messages-in-the-bubbles).

On longer timescales, rates of volcanism vary over glacial cycles, with more eruptions and larger volumes of magma erupted as glaciers retreat. In line with this observation, we know from dating sinter deposits (https://www.usgs.gov/center-news/geysers-what-exactly-are-they-made) and from geologic mapping that most geyser fields were inactive during Earth's last glacial period (which ended between ~20,000 and 12,000 years ago) when they were covered by ice [*Hurwitz and Manga* (https://doi.org/10.1146/annurev-earth-063016-015605), 2017].

Origins and Limits of Life on Earth and Mars

A recent geyserite deposit from northern Waiotapu, in New Zealand's Taupo Volcanic Zone, shows fingerlike formations. Similar formations have been found in silica-rich deposits on Mars. Credit: Kathleen A. Campbell, University of Auckland

Sinter deposits form when hot water erupting from geysers cools and evaporates rapidly at the surface, causing dissolved silica to precipitate as opaline or amorphous (noncrystalline) solids. High-temperature, vent-related sinter that forms in surge and splash zones around or near erupting geysers is termed geyserite. Around geysers and in downslope pools and discharge channels, the complex sedimentary structures preserved in sinter reflect physical, chemical, and biological processes occurring in hot spring subenvironments. For example, sinter textures produced in hot spring fluid outflows record temperature and pH gradients across a given geothermal field, from vents to discharge channels to pools, and from terraces to marsh settings.

Sinter typically entombs both biotic (e.g., microbes, plants, animals) and abiotic (e.g., weathered sinter fragments, volcanic ash, detritus) materials. Geyserite, in particular, serves as an archive of conditions in Earth's hottest environment on land (up to about 100°C) and of extreme thermophilic (https://www.sciencedirect.com/topics/biochemistry-genetics-and-molecular-biology/thermophile) (high temperature–adapted) life therein [*Campbell et al.* (https://doi.org/10.1016/j.earscirev.2015.05.009), 2015].

Research on modern hot springs suggests that extended hydration and dehydration cycles in geyser outflow channels can give rise to prebiotic molecular systems, which hints at a possible role for geysers in the origin of life on Earth.
Research on modern hot springs suggests not only that they can host extant life, but also that extended hydration and dehydration cycles in geyser outflow channels can give rise to prebiotic molecular systems that display fundamental properties of biology, such as enclosed, cell-like structures composed of lipids and polymers [*Damer and Deamer* (https://doi.org/10.1089/ast.2019.2045), 2020]. This observation hints at a possible role for geysers in the origin of life on Earth billions of years ago. Indeed, inferred geyserite deposits associated with rocks containing microbial biosignatures have recently been reported in approximately 3.5-billion-year-old hydrothermal sedimentary deposits in Western Australia [*Djokic et al.* (https://doi.org/10.1038/ncomms15263), 2017].

On Mars, silica-rich deposits detected by the Spirit rover (https://doi.org/10.1126/science.1155429) amid Columbia Hills in Gusev Crater closely resemble fingerlike sinter textures (https://doi.org/10.1038/ncomms13554) on Earth. This site was proposed as a landing site for the NASA Mars 2020 mission, which will cache samples for eventual return to Earth. Although the Perseverance rover was instead sent to explore deltaic deposits in Jezero Crater, the digitate silica structures at Columbia Hills remain as biosignature candidates that may one day be collected and brought to Earth for in-depth verification of their origin. Therefore, sinters remain a key target in the search for ancient life on Mars (https://doi.org/10.1089/ast.2019.2044), particularly from the time in its history when volcanoes and liquid water were active at the surface—about the same time that life was taking hold in hot water here on Earth.

In addition to benefiting our understanding of what constitutes life and where it can thrive, advanced biotechnology has also benefited from geyser studies. In 1967, microbiologist Thomas Brock (https://news.wisc.edu/new-book-gives-personal-account-of-pioneering-yellowstone-research/) and his student Hudson Freeze isolated the bacterium (https://science.sciencemag.org/content/158/3804/1012.abstract) *Thermus aquaticus* (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC249935/) from the hot waters of Yellowstone's geyser basins. Later, biochemist Kary Mullis identified an enzyme, named Taq polymerase, in a sample of *T. aquaticus* that was found to replicate strands of DNA in the high temperatures at which most enzymes do not survive. This discovery formed the basis for developing the revolutionary polymerase chain reaction (https://www.genome.gov/about-genomics/fact-sheets/Polymerase-Chain-Reaction-Fact-Sheet) (PCR) technique in the 1980s (for which Mullis shared the 1993 Nobel Prize in Chemistry (https://www.nobelprize.org/prizes/chemistry/1993/summary/)). PCR is now the workhorse method used in biology and medical research to make millions of copies of DNA for various applications, such as genetic and forensic testing. Recently, PCR also became widely used for COVID-19 testing (https://www.usgs.gov/center-news/how-a-thermophilic-bacterium-a-yellowstone-hot-spring-helping-fight-against-covid-19).

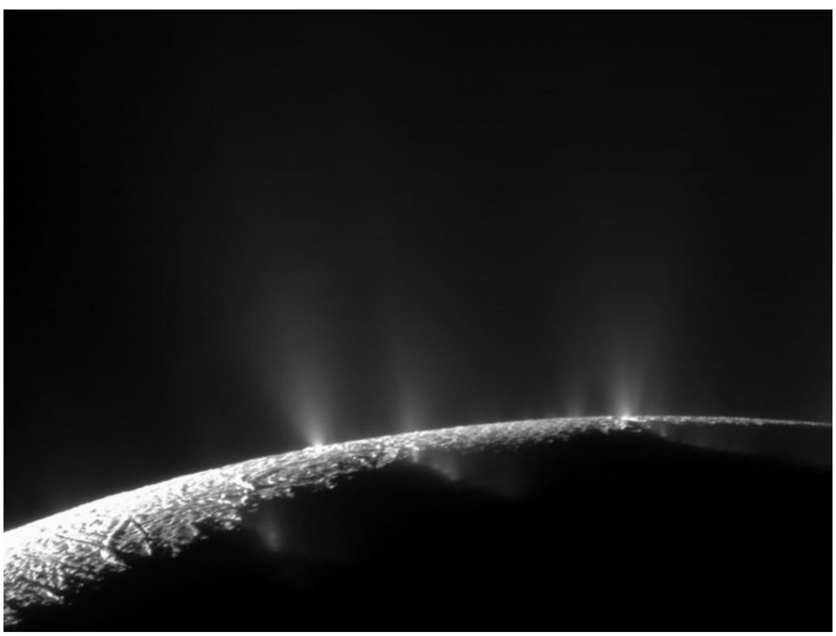
Exploring for Energy and Mineral Deposits

Sinter deposits can also inform exploration for geothermal energy (https://www.usgs.gov/energy-and-minerals/energy-resources-program/science/geothermal?qt-science_center_objects=0#qt-science_center_objects), helping locate resources, as well as for mineral deposits (https://doi.org/10.1007/s00126-016-0658-8). Whereas currently active hydrothermal systems provide energy for electricity generation, industry, and agriculture (https://teara.govt.nz/en/geothermal-energy/page-4), giant fossil hydrothermal systems (https://doi.org/10.1016/j.gsf.2020.04.001) host many of the world's most productive precious metal mining operations [*Garden et al.* (https://doi.org/10.1016/j.jvolgeores.2020.106794), 2020]. Such epithermal ore deposits (https://doi.org/10.3133/sir20105070Q) form in the shallow subsurface beneath geothermal fields as high-temperature fluids—both magmatic and meteoric in origin—gradually deposit valuable metals (https://doi.org/10.2113/econgeo.111.3.589) including gold, silver, copper, and lithium.

Geyserites form at the surface emission points of rising hot fluids tapped from deep reservoirs and can point to completely concealed subsurface ore deposits [*Leary et al.* (https://doi.org/10.2113/econgeo.111.5.1043), 2016], thus informing exploration for mineral resources; they may also contain traces of precious metals themselves.

Geysers in the Solar System

Studies of physical processes in easily observable geysers on Earth can also guide and constrain models proposed to explain eruptions elsewhere in our solar system. The geysers of the icy outer solar system satellites Enceladus (https://solarsystem.nasa.gov/resources/17389/enceladus-cold-geyser-model/) (Saturn), Triton (https://doi.org/10.1126/science.250.4979.410) (Neptune), and Europa (https://earthsky.org/space/europa-water-vapor-geysers-goddard) (Jupiter) are similar to Earth's geysers in that changes of state of materials (e.g., melting and vaporization) drive mixtures of solids and gases to erupt episodically.



NASA's Cassini spacecraft took this image during its survey of the southern hemisphere geysers on Saturn's moon Enceladus. The four fractures from which the geysers erupt, referred to as tiger stripes, are approximately 135 kilometers long and cross Enceladus's south pole. Credit: NASA/JPL/Space Science

Institute (https://solarsystem.nasa.gov/resources/806/bursting-at-the-seams-the-geyser-basin-of-enceladus/)

At the south pole of the ice-covered ocean world Enceladus, some 100 geysers erupt from four prominent fractures (https://eos.org/articles/on-thin-ice-tiger-stripes-on-enceladus), delivering water from a habitable ocean (https://earthsky.org/space/enceladus-ocean-moon-saturn-geochemical-complexity-life) into space and supplying ice particles to Saturn's E ring (https://solarsystem.nasa.gov/news/13021/put-a-ring-on-it/). At Triton, the largest of Neptune's 13 moons, NASA's Voyager 2 spacecraft detected surface temperatures of −235°C and geysers that erupt sublimated nitrogen gas (https://www.newscientist.com/article/mg12817402-500-science-greenhouse-effect-drives-geysers-on-triton/). Whether eruptions currently occur (https://eos.org/articles/geologic-map-of-europa-highlights-targets-for-future-exploration) on Europa remains debated (https://doi.org/10.1029/2020GL091550).

As on Earth, studying physical controls on geyser location, longevity, and eruption intervals on these other worlds can improve our understanding of interactions between their interiors and their surface environments.

Engaging the Public in Research and Conservation

Visitors on a boardwalk watch an eruption of Grand Geyser in the Upper Geyser Basin of Yellowstone National Park in June 2012. Credit: Jim Peaco, National Park Service

New sound and visual approaches developed to convey complex patterns in geyser systems may help identify relationships between volcanic signals that might otherwise be overlooked.

Tourists and amateur enthusiasts (http://www.geyserstudy.org/) are captivated by the views and sounds of geyser eruptions. These spectacular events also provide public showcases (https://knowablemagazine.org/article/physical-world/2018/thar-she-blows-what-why-and-where-geysers) for curiosity-driven scientific research. For example, new sound and visual approaches (https://doi.org/10.1162/comj_a_00551) developed to convey complex patterns in geyser systems could provide valuable educational tools and may also help identify relationships between volcanic signals—such as surface deformation and seismicity indicating preeruptive activity—that might otherwise be overlooked.

Characterizing the sources of thermal water feeding geyser eruptions and mapping the subsurface hydraulic connections between geyser fields and adjacent areas are needed to protect and preserve these natural wonders from human impacts (https://www.nps.gov/yell/learn/upload/YS_17_1_sm.pdf). Geothermal energy production and hydroelectric dam siting have drowned or driven more than 100 geysers to extinction (https://link.springer.com/article/10.1007/s00267-005-0195-1) in New Zealand and in Iceland, for example, and geyser eruptions completely ceased in Steamboat Springs (https://doi.org/10.2475/ajs.265.8.641) and Beowawe (https://doi.org/10.3133/b1998) in Nevada owing to exploitation of geothermal resources. In contrast, some dormant geysers in Rotorua, New Zealand, resumed erupting (https://doi.org/10.3133/b1998) a few decades after geothermal extraction boreholes were shut down.

Geysers are curious and awe-inspiring natural phenomena, and they provide windows into a broad range of science questions. They deserve both our wonder and our protection.

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