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The Fascinating and Complex Dynamics of Geyser Eruptions

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Abstract

Geysers episodically erupt liquid and vapor. Despite two centuries of scientific study, basic questions persist—why do geysers exist? What determines eruption intervals, durations, and heights? What initiates eruptions? Through monitoring eruption intervals, analyzing geophysical data, taking measurements within geyser conduits, performing numerical simulations, and constructing laboratory models, some of these questions have been addressed. Geysers are uncommon because they require a combination of abundant water recharge, magmatism, and rhyolite flows to supply heat and silica, and large fractures and cavities overlain by low-permeability materials to trap rising multiphase and multicomponent fluids. Eruptions are driven by the conversion of thermal to kinetic energy during decompression. Larger and deeper cavities permit larger eruptions and promote regularity by isolating water from weather variations. The ejection velocity may be limited by the speed of sound of the liquid + vapor mixture.

1. INTRODUCTION

> Geysers are exceedingly complex hot springs, no two of which are alike.
>
> —Donald E. White and George D. Marler (White & Marler 1972, p. 5825)

The English word *geyser* is derived from *Geysir*, a name given by Icelanders in the seventeenth century to an intermittently discharging hot spring in southwest Iceland. The name descends from the verb *gjosa*, which means gush, spout, or erupt.

We adopt the definition of geyser provided by White (1967, p. 642): "a hot spring characterized by intermittent discharge of water ejected turbulently and accompanied by a vapor phase." The term *geyser* is now also used to describe episodic discharge of multiphase fluids in engineering (e.g., Casarosa et al. 1983, Hung & Shyu 1992, Kagami 2010) and geothermal wells that erupt episodically. Geyser-like behavior in natural systems has been observed on the ocean floor (Tryon et al. 1999, Furushima et al. 2009, Sohn et al. 2009) and is inferred to occur on Saturn's moon Enceladus (Porco et al. 2006, Brilliantov et al. 2008) and Neptune's moon Triton (Brown et al. 1990, Soderblom et al. 1990). Here we focus on hot springs that intermittently discharge liquid water, steam, and noncondensable gas at temperatures that are close to the boiling temperature of pure water for their respective elevations (**Figure 1**).

Natural geysers are rare; there are fewer than 1,000 worldwide. About half of Earth's geysers are in Yellowstone National Park, in the United States (Bryan 2008). Other large geyser fields include the Valley of Geysers, in the Kamchatka Peninsula, Russia; El Tatio, in the northern Chilean Andes; Geyser Flat, Whakarewarewa, in the Taupo Volcanic Zone, New Zealand; and the shores of Lake Bogoria, Kenya (**Figure 2**). Most of the geysers in the Taupo Volcanic Zone (Barrick 2007) and at Steamboat (White 1967) and Beowawe (White 1992) in Nevada have vanished in response to geothermal energy production. The rarity of geysers reflects the special conditions needed for their formation: availability of water, a supply of heat, and a subsurface that has the right geometry of fractures and cavities to permit episodic discharge.

Geysers attract researchers from multiple disciplines in part because they provide natural laboratories to study eruption processes and the geophysical signals that can be measured before,

Figure 1

(*a*) Map showing the locations of the major natural thermal geyser fields in the world. (*b*) The boiling temperature of pure water as a function of the elevation of each geyser field.

Figure 2

Examples of geysers from each of the major geyser fields. (*a*) Pohutu geyser, Whakarewarewa, Taupo Volcanic Zone, New Zealand. (*b*) Pervenets geyser, Valley of Geysers, Kamchatka, Russia. (*c*) Lone Star geyser, Yellowstone National Park, United Sates. (*d*) Geyser K30, Lake Bogoria, Kenya. (*e*) Upper Basin, El Tatio, Chile. (*f*) Great Geysir (*left*) and Strokkur (*right*), Iceland. People are shown for scale in panels *b*, *c*, and *f*. Photo in panel *a* reproduced with permission from Brad Scott; photo in panel *b* reproduced with permission from Alexander Belousov; photo in panel *d* reproduced with permission from Robin Renault; and photos in panels *c*, *e*, and *f* from the authors.

during, and after an eruption. Many of the processes associated with geyser eruptions are similar to those operating in volcanoes. However, because geyser eruptions are smaller than volcanic eruptions, and geysers erupt more frequently, there is an opportunity to collect more data and develop approaches for integrating and interpreting geophysical and hydrological measurements. An improved understanding of geyser behavior may yield insight into other multiphase and multicomponent episodic processes and other self-organized, intermittent processes in nature that result from localized input of energy and mass. A better quantitative understanding of the processes that control geyser eruptions is also critical for their preservation.

Written documents describing scientific measurements and models of geyser eruptions date back to the nineteenth century (e.g., Mackenzie 1811, Krug van Nidda 1836, Bunsen 1847, Le Conte 1878, Peale 1884, Jaggar 1898), and there have been several reviews since then (e.g., Weed 1912; Thorkelsson 1928; Allen & Day 1935; Fukutomi 1942a,b; Bloss & Barth 1949; White 1967). In addition, there are many amateur enthusiasts dedicated to the study of geyser eruptions, such as members of the Geyser Observation and Study Association (**http://www.geyserstudy.org/**).

Much of our knowledge about various aspects of geyser activity comes from visual observations made by park rangers and amateurs.

Each year, millions of visitors watch geysers erupt in Yellowstone National Park, and the geysers of El Tatio in Chile and the Valley of Geysers in Kamchatka draw tens of thousands of visitors to some of the most remote places on Earth. Despite public interest and the long history of scientific study, there remain fundamental questions about geysers that continue to guide research efforts:

1. Why do some springs discharge continuously and others (geysers) erupt intermittently? Why are geysers rare?
2. How old are geysers? How long does it take their mounds and cones to grow? What causes them to change eruption patterns and vanish?
3. Why do some geysers erupt periodically and others at irregular intervals?
4. Why do only a few geysers erupt to heights of tens of meters?
5. How is heat transformed to mechanical energy to drive the multiphase and multicomponent eruptions?
6. What processes, both internal and external to the geyser, influence duration and volume of an eruption and the interval between eruptions?

Here we summarize progress in addressing these fundamental questions.

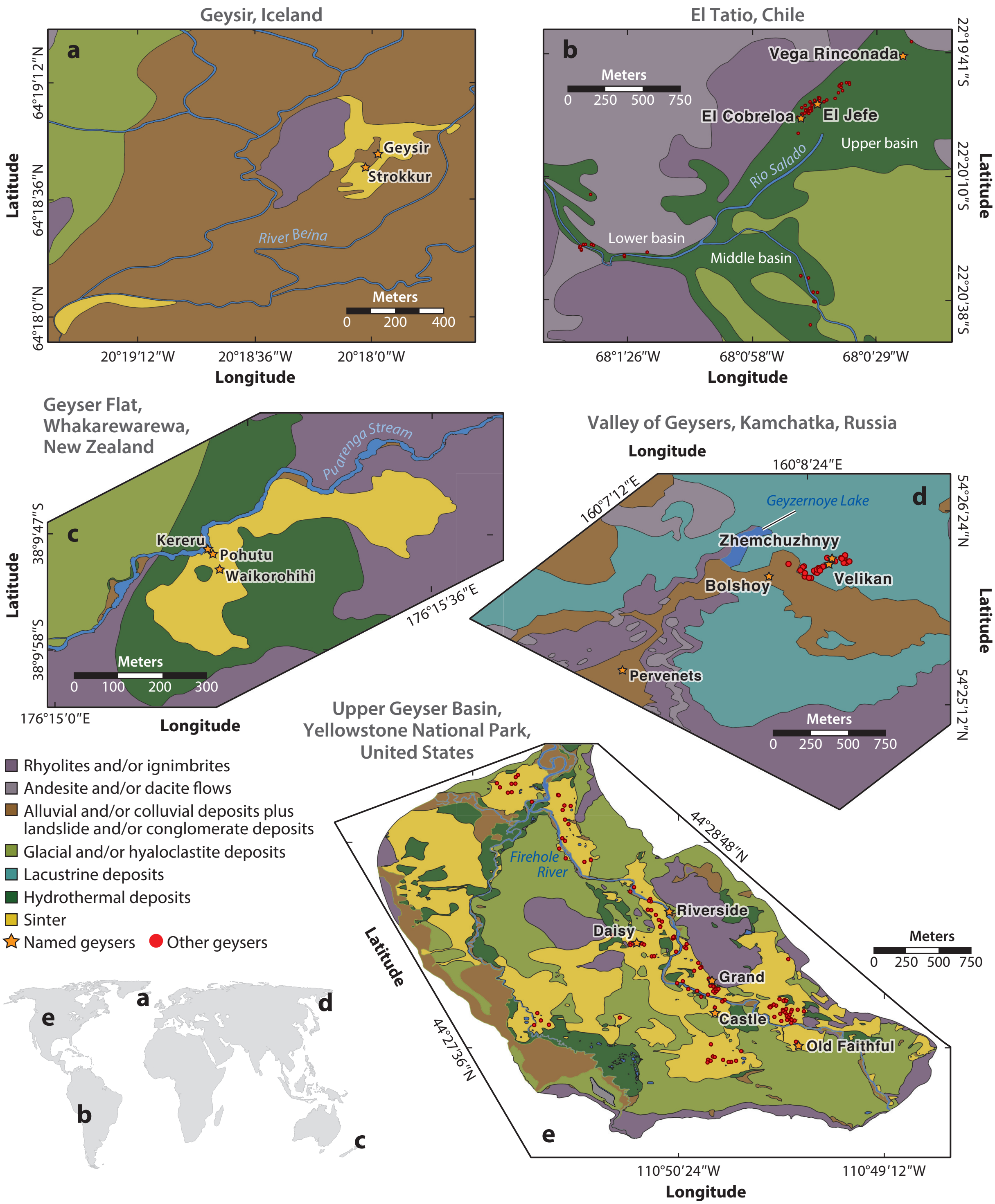
2. GEOGRAPHY AND GEOLOGY OF GEYSERS

The geological settings of most of the major geyser fields in the world (**Figure 3**) have common features. The fields occur in areas of recent or active magmatism where the supply of heat is abundant, mostly at high latitudes where precipitation rates are high, and where glacial deposits overly SiO_2-rich rhyolite flows or ignimbrites. Most formed following the last glaciation, as inferred by stratigraphy and the few radiometric dates of sinter deposits (Foley 2006, Jones et al. 2007, Lynne et al. 2008, Howald et al. 2014, Lowenstern et al. 2016). Some exceptions to this generalization include geysers along the East African rift system, mainly along the shores of Lake Bogoria in Kenya (Renaut & Owen 2005, McCall 2010), where geyser activity is not linked to rhyolitic volcanism. Rather, the Lake Bogoria geyser sites are underlain predominantly by ~150-m-thick and finely crystalline trachyphonolite and trachyte lavas (60% to 65% silica content, which is less than in rhyolite) (Renaut & Owen 2005). Geysers are transient features with periods of activity and dormancy that are affected by earthquakes, changes in water recharge rates, erosion of their cones and/or mounds, and slow silica deposition in flow channels and reservoirs.

There are several observations that imply that the volumes of geyser reservoirs and fracture complexes are significantly larger than the volumes of water discharged during a single eruption. Some of the relevant observations include the following: (*a*) Fluorescein dye experiments in 1951 and 1959 at Geyser Flat, Whakarewarewa, in New Zealand (Lloyd 1975) imply a very direct and

Figure 3

Simplified geological maps for the major geyser fields. (*a*) The map for Geysir, in Iceland, was digitized from Torfason (1985), with geyser locations from Google Earth. (*b*) The map for El Tatio, in Chile, is based on Marinovic & Lahsen (1984), with geyser locations from Glennon & Pfaff (2004) and names from Munoz-Saez et al. (2015b). (*c*) The map for Geyser Flat, Whakarewarewa, in New Zealand, is based on Lloyd (1975), with active geysers in 1990 from Cody & Lumb (1992). (*d*) The map for the Valley of Geysers, in Kamchatka, Russia, was digitized from Kiryukhin et al. (2012), based on Leonov (2009)—hydrothermal deposits refer to cemented glacial, alluvial, or hyaloclastite deposits. (*e*) Data sets and units for Upper Geyser Basin, in Yellowstone National Park, United States, are from Abedini et al. (2015), based on Muffler et al. (1982). The original maps for the Valley of Geysers and El Tatio do not show sinter deposits despite their widespread occurrence. The map for the Valley of Geysers was made prior to the large landslide in 2007, which resulted in drastic changes (Kiryukhin et al. 2012). Maps redrafted and simplified by Behnaz Hosseini.



Geysir, Iceland
a
Geysir
Strokkur
River Beina
Meters
0
200
400
Latitude
64°19′12″N
64°18′36″N
64°18′0″N
20°19′12″W
20°18′36″W
20°18′0″W
Longitude
El Tatio, Chile
b
Meters
0 250 500 750
Vega Rinconada
El Cobreloa
El Jefe
Upper basin
Rio Salado
Lower basin
Middle basin
22°19′41″S
22°20′10″S
22°20′38″S
Latitude
68°1′26″W
68°0′58″W
68°0′29″W
Longitude
Geyser Flat,
Whakarewarewa,
New Zealand
c
Puarenga Stream
Kereru
Pohutu
Waikorohihi
Meters
0 100 200 300
Latitude
38°9′47″S
38°9′58″S
176°15′0″E
176°15′36″E
Longitude
Valley of Geysers, Kamchatka, Russia
Longitude
160°8′24″E
160°7′12″E
d
Geyzernoye Lake
Zhemchuzhnyy
Velikan
Bolshoy
Pervenets
Meters
0 250 500 750
54°26′24″N
54°25′12″N
Latitude
Upper Geyser Basin,
Yellowstone National Park,
United States
Rhyolites and/or ignimbrites
Andesite and/or dacite flows
Alluvial and/or colluvial deposits plus
landslide and/or conglomerate deposits
Glacial and/or hyaloclastite deposits
Lacustrine deposits
Hydrothermal deposits
Sinter
Named geysers
Other geysers
a
d
e
b
c
44°28′48″N
Firehole
River
Riverside
Daisy
Grand
Castle
Old Faithful
Meters
0 250 500 750
Latitude
44°27′36″N
e
110°50′24″W
110°49′12″W
Longitude

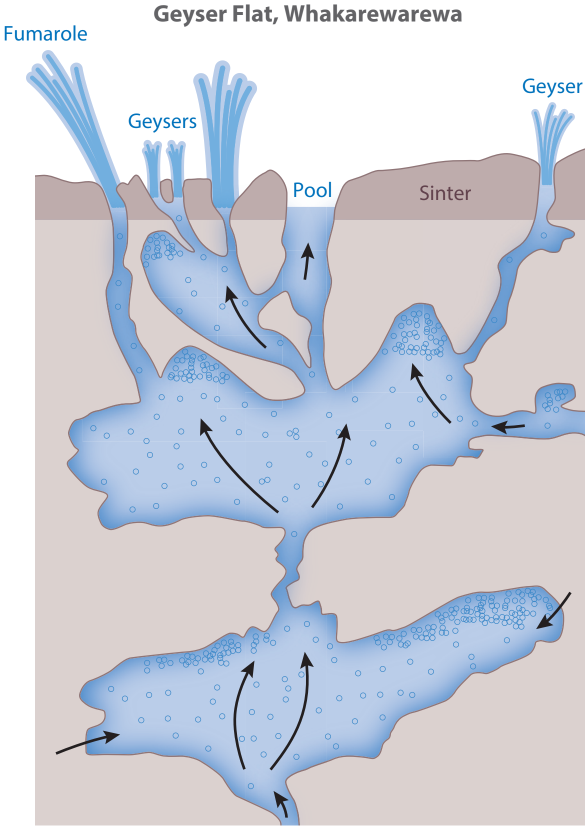


Figure 4

Schematic illustration showing the inferred subsurface structure of Geyser Flat, Whakarewarewa, in the Taupo Volcanic Zone, New Zealand. Drafted by Carolina Munoz-Saez based on a figure from Lloyd (1975), modified with permission.

shallow connection between the major geysers (**Figure 4**). (*b*) In a tracer experiment in Old Faithful geyser in Yellowstone, carried out in 1963, more than 24 consecutive eruptions were required to clear the erupted water of the introduced rhodamine B (Fournier 1969). (*c*) The eruption of many geysers in Yellowstone's Upper Geyser Basin and in El Tatio, Chile, are influenced by adjacent geysers, suggesting a subsurface hydraulic connection (Marler 1951, Rojstaczer et al. 2003, Munoz-Saez et al. 2015b). (*d*) The volumes of shallow (<10 m) exposed geyser cavities at Whakarewarewa range from ~20 to ~100 m^3 (Weir et al. 1992), significantly larger than erupted volumes. (*e*) At El Jefe geyser in El Tatio, eruption intervals are insensitive to changes in ambient temperature despite the large amount of cooled water that flows back into the conduit following the eruption (Munoz-Saez et al. 2015a). (*f*) Major eruptions of Steamboat geyser in Yellowstone's Norris Geyser Basin, which with measured eruption jets ~115 m high is considered the largest geyser in the world, are followed by the gradual drainage of Cistern Spring (~90 m away) by as much as 4 m (Bryan 2008)—this volume alone is ~500 m^3.

Video observations made in the conduit of Old Faithful geyser in the summer of 1992 (**https://www.youtube.com/watch?v=8luNCFUnvBw**) to a depth of nearly 13 m (Hutchinson

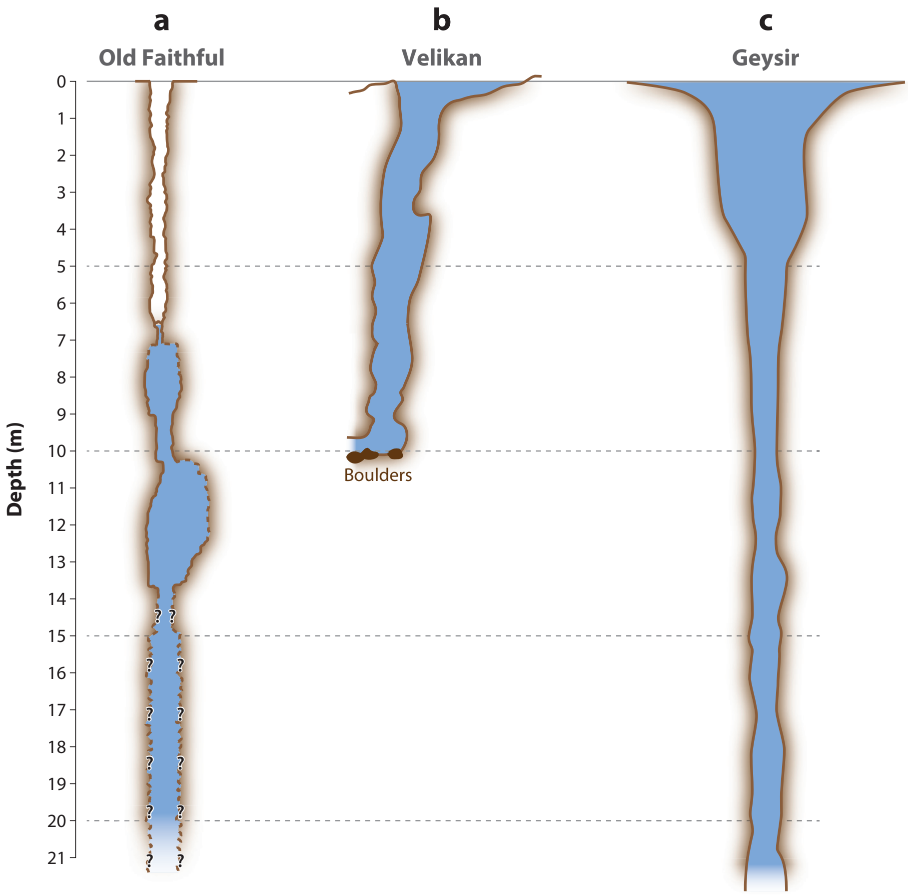


Figure 5

Schematic illustration showing the inferred irregular conduit geometries of (*a*) Old Faithful geyser, in Yellowstone National Park, United States (after Hutchinson et al. 1997); (*b*) Velikan geyser, in Kamchatka, Russia (after Belousov et al. 2013), with boulders at the bottom depicted in brown; and (*c*) Geysir, in Iceland (after Torfason 1985). The walls of the conduits are lined with white silica sinter similar to that exposed on the surface.

et al. 1997) reveal an irregular, elongated fissure-like channel with fractured walls lined with white silica sinter (**Figure 5*a***). The conduit is a narrow slot at the surface that changes shape significantly with depth. At a depth of ∼7 m below the surface, the slot narrows to ∼11 cm, forming a constriction. Shallower video observations made in the geysers of Kamchatka (<5 m, except for Velikan geyser, shown in **Figure 5*b***; Belousov et al. 2013) and El Tatio (∼1 m; Munuz-Saez et al. 2015a) also show irregular and highly contorted conduits with narrow constrictions. The conduit of Geysir, in Iceland (**Figure 5*c***), is also described as irregular, with a diameter varying between 0.4 and 1.0 m between the ground surface and a depth of ∼23 m, where a narrow constriction prevents further measurements (Torfason 1985).

White (1967) proposed that geyser reservoirs form by physical ejection of rock fragments as a new geyser develops from a facture or some other interconnected channels. The glacial deposits

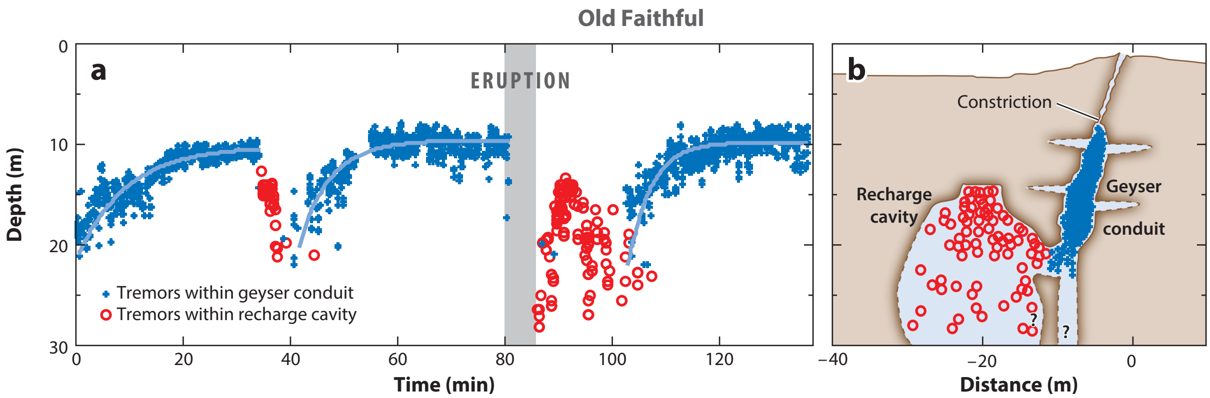


Figure 6

Time-depth variation of seismic tremor sources at Old Faithful geyser in Yellowstone National Park, United States. (*a*) Time variation of tremor sources over three successive geyser cycles. The blue crosses correspond to tremor sources located in the geyser conduit and the red circles to tremor sources in the recharge cavity. (*b*) Projection of the tremor sources along the inferred subsurface structure of the geyser, showing a subvertical conduit connected to a lateral cavity (termed a bubble trap). The top of the cavity is highlighted by the high density of red circles. Modified with permission from Vandemeulebrouck et al. (2013).

or landslide deposits [as in the Valley of Geysers, in Kamchatka (**Figure 3**)], or the hyaloclastites [hydrated tuff-like breccia consisting of glassy clasts formed during volcanic eruptions under water or ice, as in Geysir, in Iceland (**Figure 3**)], may provide the optimal fracture network required for the occurrence of natural geysers (White 1967, Belousov et al. 2013). Seismic imaging around Old Faithful geyser, in Yellowstone (**Figure 6**) (Vandemeulebrouck et al. 2013); tilt measurements around Lone Star geyser, also in Yellowstone (**Figure 7**) (Vandemeulebrouck et al. 2014); and video observations in the conduits of Kamchatka geysers suggest that a lateral reservoir where multiphase fluid accumulates and pressure builds prior to an eruption might be a common feature. This reservoir was termed a bubble trap (Belousov et al. 2013), because steam bubbles within the ascending fluid cannot escape (**Figure 6*b***). However, considering the large volumes of subsurface fracture and reservoir complexes, these bubble traps are likely only a small part of a much larger system, as depicted schematically in **Figure 4**. Future high-resolution imaging of the subsurface using a variety of geophysical methods will likely provide more detailed information about these structures and their role in eruptions.

There are many episodically discharging wells around the world that were drilled for geothermal energy extraction and are often referred to as geysers. The Geyser Well in Steamboat Springs, Nevada, was very active during 1945 and early in 1946, with major eruptions generally occurring at intervals of 5 to 7 days. The bottom of the casing is in a formation that has sand and gravel cemented by silica, and the bottom of the hole is packed with boulders and sand (White 1967). The Old Faithful geyser in Calistoga, Napa Valley, California (Rudolph et al. 2012), is a well that was drilled in the late 1800s to an unknown depth and into an unknown lithological unit. However, lithological logs from the many geothermal wells in Calistoga indicate that, similar to active geyser fields, the uppermost 40–60 m consists of silica-cemented tuffaceous material and breccia overlying upper Pliocene volcanic rocks (Murray 1996).

3. CHEMISTRY OF GEYSERS

Stable isotopes of oxygen and hydrogen indicate that geysers are recharged by meteoric water (Cortecci et al. 2005, Hurwitz et al. 2012, Kiryukhin et al. 2012). However, geyser waters are

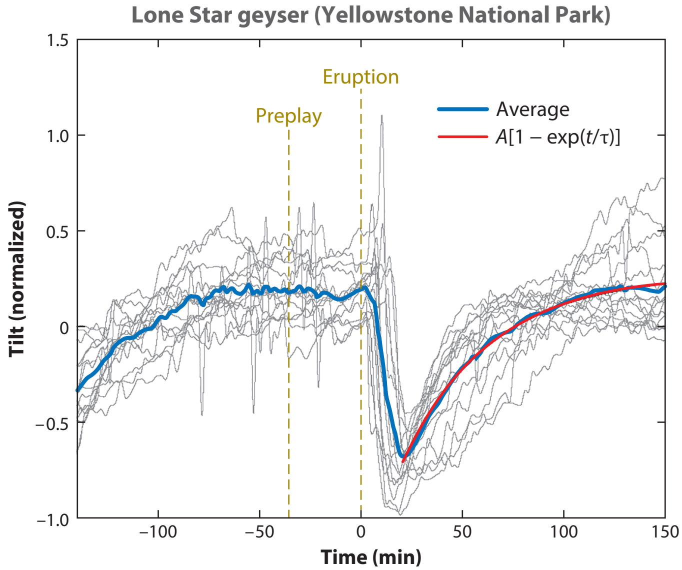


Figure 7

Normalized tilt versus time recorded on a broadband seismometer during 14 eruptive cycles (*gray*) of Lone Star geyser in Yellowstone National Park, United States. Time 0 marks the start of the eruption. The average tilt is shown as a blue curve; the red curve has the form $A[1 - \exp(t/\tau)]$, where A is the tilt amplitude, t is time, and τ is a time constant (after Vandemeulebrouck et al. 2014). A similar pattern was also observed in conduit pressure records, seismicity rate, and hypocentral depth at Old Faithful geyser in Yellowstone (Kedar et al. 1998, Vandemeulebrouck et al. 2013). This pattern is thought to reflect gradual filling of the geysers' shallow reservoir and conduit during the eruption cycle (Kedar et al. 1998; Vandemeulebrouck et al. 2013, 2014). The time constant of the average Lone Star geyser tilt transient is 45 min, compared with a 34-min pressure transient in the conduit of Old Faithful geyser (Kedar et al. 1998).

often enriched (i.e., have more positive isotopic values) compared with the local meteoric water, probably resulting from boiling and steam separation in the shallow subsurface and during eruption as well as from recycling of this erupted water. The concentrations of tritium (^3H), which has a half-life of 12.32 ± 0.02 years, are mostly below the analytical detection limit in geyser waters from Yellowstone (Hurwitz et al. 2012) and El Tatio (Cortecci et al. 2005). Mass balance at these geysers thus implies that the fraction of recent meteoric water is less than 1 wt%.

The major anion in most geyser waters is chloride, and the major cation is sodium (**Table 1**). The major anion in Lake Bogoria geysers is bicarbonate (HCO_3^-) (Renaut et al. 2008). Whereas chloride and sulfate concentrations vary by more than an order of magnitude between geyser fields, the range of silica (SiO_2) concentrations and the sodium-to-potassium ratio (Na/K) vary by less than a factor of three, and by less than a factor of two when excluding thermal waters from El Tatio with a much lower boiling temperature (~86°C) (**Figure 1*b***; **Table 1**). The concentration of silica, which is controlled by temperature-dependent solubility (**Figure 8**) (Fournier 1985), and Na/K, which is controlled by the temperature-dependent equilibrium between thermal water, albite, and K-feldspar, provide a basis for calculating the temperatures at which the thermal waters equilibrated with host rocks (i.e., geothermometry) before erupting (Fournier 1981, Giggenbach 1988).

With cooling, steam separation, and evaporation, thermal waters become supersaturated with respect to amorphous silica (Fournier 1985), and noncrystalline opal-A (a hydrated amorphous form of silica) precipitates to form sinter deposits called geyserite. Repeated wetting and

Table 1 Major element chemistry of representative geyser waters from the major geyser fields in the world (concentration units are in mg/L)

Geyser	Sample	Date	HCO_3	F	Cl	SO_4	Na	K	Mg	Ca	Li	SiO_2	B	$T_{SiO2(adi)}$[a]	$T_{SiO2(con)}$[b]	$T_{Na/K(F)}$[c]
Upper Geyser Basin, Yellowstone National Park, United States (Hurwitz et al. 2012)																
Old Faithful	UGB090707-OFG	Sept. 2007	199	31	487	18	385	24	<0.01	1.0	6.5	374	5.4	206	227	189
Daisy	UGB090707-DZY	Sept. 2007	719	35	357	19	541	23	<0.01	0.3	5.4	314	3.7	195	213	161
Grand	UGB090707-GRN	Sept. 2007	372	31	388	18	423	19	<0.01	0.5	5.5	322	4.0	196	215	165
Valley of Geysers, Kamchatka, Russia (Kiryukhin et al. 2012)																
Velikan	23	After June 2007	46	1	794	171	554	50	6.80	18	–	303	–	193	210	217
Chloridny	54	After June 2007	27	<1	643	103	441	37	0.70	22	–	322	–	196	215	210
Truby	45	After June 2007	155	1	158	146	218	10	2.90	3	–	247	–	180	195	163
Bolshoy	28	After June 2007	59	–	794	163	555	37	–	23	–	231	22	176	190	192
El Tatio, Chile (Tassi et al. 2010; C. Munoz-Saez, unpublished data)																
NS	ET03	NS	32	2	6,500	61	3,390	182	2.10	267	36	188	139	165	176	176
NS	ET06	NS	64	7	5,750	42	3,230	336	0.70	215	39	192	134	166	177	230
Vega Rinconada	225	Oct. 2012	49	4	8,000	42	4,604	598	0.6	290	43	319	207	196	214	250
Great Geysir, Iceland (Pasvanoglu 1998)																
Geysir	980423	Aug. 1998	144	8	125	105	228	24	0.01	0.8	–	501	0.9	226	253	229
Strokkur	920311	Nov. 1992	166	12	121	100	238	14	0.01	0.8	–	437	–	216	240	180

(Continued)

Table 1 ***(Continued)***

Geyser	Sample	Date	HCO_3	F	Cl	SO_4	Na	K	Mg	Ca	Li	SiO_2	B	$T_{SiO2(adi)}$[a]	$T_{SiO2(con)}$[b]	$T_{Na/K(F)}$[c]
Geyser Flat, Whakarewarewa, New Zealand (Giggenbach & Glover 1992)																
NS	S 351	Sept. 1990	179	–	820	69	630	76	0.01	1.8	3.0	402	6.4	211	233	243
NS	S 284	Sept. 1990	118	–	573	76	463	45	0.01	1.2	4.0	399	5.7	210	232	224
NS	S 529	Sept. 1990	148	–	512	71	408	50	<0.01	1.8	2.4	366	5.5	204	225	245
Lake Bogoria, Kenya (Renaut et al. 2008)																
K30		Aug. 2006	2,850	60	306	63	1,440	42	0.34	<0.1	–	115	<0.1	139	145	136
Average[d]														196	214	205
Standard deviation														18	22	32

Geothermometer temperatures are calculated using the equations in table 4.1 from Fournier (1981). Abbreviation: NS, not specified.

[a] $T\,(°C) = 1{,}522/(5.75 - \log[SiO_2]) - 273.15$.

[b] $T\,(°C) = 1{,}309/(5.19 - \log[SiO_2]) - 273.15$.

[c] $T\,(°C) = 1{,}217/(\log[Na]/[K]) + 1.483) - 273.15$.

[d] Averages exclude the sample from Lake Bogoria.

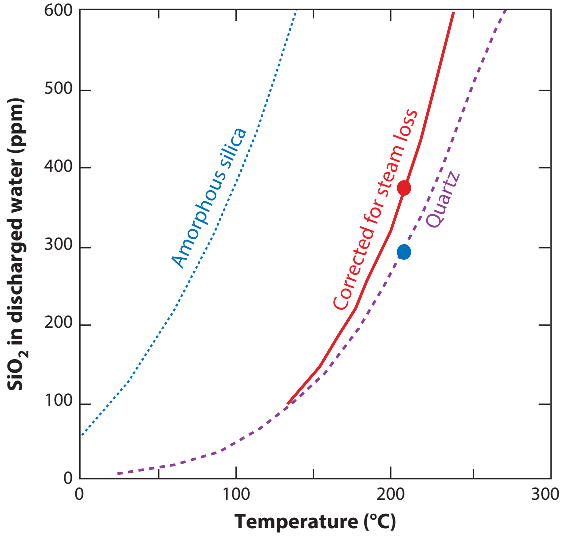


Figure 8

The solubilities of amorphous silica (SiO_2) (*thin dotted blue curve*) and quartz (*thick dashed purple curve*) at the vapor pressures of the solutions. The blue dot shows the concentration of dissolved SiO_2 in equilibrium with quartz at 210°C. The solid red curve shows the concentration of dissolved SiO_2 in solution after adiabatic cooling (boiling) to 100°C; for example, the red dot shows the concentration of dissolved SiO_2 after adiabatic cooling from 210°C to 100°C. Modified from Fournier (1985).

evaporation of surfaces, often to dryness, and capillary effects can control the deposition, morphology, and microstructure of subaerial sinter. The diagenesis, morphology, biota, and chemical composition of sinter deposits from many active thermal fields were summarized by Renaut & Jones (2011) and Campbell et al. (2015). Physical properties of sinter, including porosity, permeability, seismic velocity and electrical conductivity, were reported by Munoz-Saez et al. (2016). Siliceous sinter is absent around the geyser vents along the shores of Lake Bogoria because the discharged waters are undersaturated with respect to amorphous silica (**Table 1**) (Renaut & Owen 2005).

Dissolved gases (mainly CO_2 derived from magma and N_2 derived from air-saturated meteoric water) can modulate the dynamics of geyser eruptions because they move the liquid stability field toward lower temperatures and enhance the explosivity potential with respect to pure water (Lu & Kieffer 2009, Hurwitz et al. 2016, Ladd & Ryan 2016).

4. ERUPTION DYNAMICS

> No geyser looks or acts the same as any other. Each has its own arrangement of reservoirs and tubes, water supply, and heat source. However, by closely observing the activity of individual geysers and groups of them, it is possible to learn much concerning the general nature of operational modes.
>
> —John S. Rinehart (Rinehart 1980, p. 18)

Models of geyser dynamics from the nineteenth century and the first half of the twentieth century were mostly qualitative in the sense that they lacked quantitative fluid-dynamic and thermodynamic interpretations of empirical observations. More recent studies have used geophysical measurements, in situ measurements of pressure and temperature, video recordings, and thermo-mechanical models to quantify various aspects of the geysering process. We first review observational constraints for processes in the reservoirs and conduits that deliver water to the surface, and then we describe the processes that influence the visible surface eruption.

4.1. Subsurface Processes

Inspired mainly by observations made in Geysir ("spout") and to a lesser extent in Strokkur ("churn") in Iceland (**Figure 1**), two early conceptual models sought to explain the main features of geysers. Mackenzie (1811) proposed that eruptions are caused by the increasing pressure exerted by the expansion of steam trapped in a subsurface cavity. Bunsen (1847) suggested that eruptions are caused by ascent-driven decompression boiling in the conduit resulting from overflow. Both conceptual models have some observational support.

As discussed in Section 2, there are a variety of measurements that confirm the existence (**Figure 4**) and importance of subsurface cavities in the eruption process, at least at some geysers. The impulsive pressure signals generated by the nucleation and collapse of vapor bubbles induced by heating and pressure changes (e.g., Rinehart 1965; Kieffer 1984; Kedar et al. 1996, 1998; Cros et al. 2011; Vandemeulebrouck et al. 2013, 2014) allow boiling conditions to be tracked in time and space (**Figure 6**). Seismic energy is generated when the impulsive pressure perturbation in the liquid couples into the elastic matrix surrounding the fluid (Kedar et al. 1998, Thiéry & Mercury 2009), and these impulsive events are superposed to create a tremor-like effect (known as a hydrothermal tremor, further amplified by shallow layers that generate a site effect) when rates are high (e.g., Nicholls & Rinehart 1967; Kieffer 1984; Kedar et al. 1996, 1998; Vandemeulebrouck et al. 2014). Tilt measurements at geysering wells (Nishimura et al. 2006, Rudolph et al. 2012) and Lone Star geyser in Yellowstone (Vandemeulebrouck et al. 2014) also document the gradual recharge of shallow geyser reservoirs and conduits during the eruption cycle and abrupt drainage during eruptions (**Figure 7**).

The Bunsen (1847) model is supported by temperature measurements in the conduits of Old Faithful geyser, in Yellowstone (**Figure 9*a***); Geysir, in Iceland (**Figure 9*b***); Te Horu, in Whakarewarewa, New Zealand; Velikan ("Giant"), in the Valley of Geysers, Kamchatka, Russia; and geysers in El Tatio, Chile (Bunsen 1847; Rinehart 1969; Birch & Kennedy 1972; Noguchi et al. 1983; Hutchinson et al. 1997; Droznin et al. 1999; Munoz-Saez et al. 2015a,b). The temperature-depth profile at Old Faithful geyser shows that at the top of the water column in the conduit, water temperature is at the boiling temperature for pure water, and deeper in the conduit, water is slightly colder than the hydrostatic boiling temperature appropriate to the level of water in the conduit (**Figure 9*a***). The maximum temperature in the conduit of Geysir occurs several meters below the top of the water column (**Figure 9*b***). The differences in the shapes of the curves may reflect differences in the structure of the geysers. Whereas Old Faithful is a cone geyser, so that evaporative heat loss is low (Hurwitz et al. 2014), Geysir is a pool geyser, so that significant amounts of heat are lost to the atmosphere.

Concurrent measurements of pressure and temperature in the conduits of Old Faithful in Yellowstone (Hutchinson et al. 1997) and El Jefe in El Tatio (Munoz-Saez et al. 2015a) showed that, following an eruption, water recharge is gradual and much of the heat is added at later stages (**Figure 10**). Preparation of the geyser for major eruptions is accompanied, in some cases, by minor eruptions, or preplay (see Section 4.2), that may be a manifestation of fluid release from bubble traps and have the thermal consequence of heating water in the conduit. As the eruption progresses, boiling in geyser conduits propagates downward and steam generated at greater depths

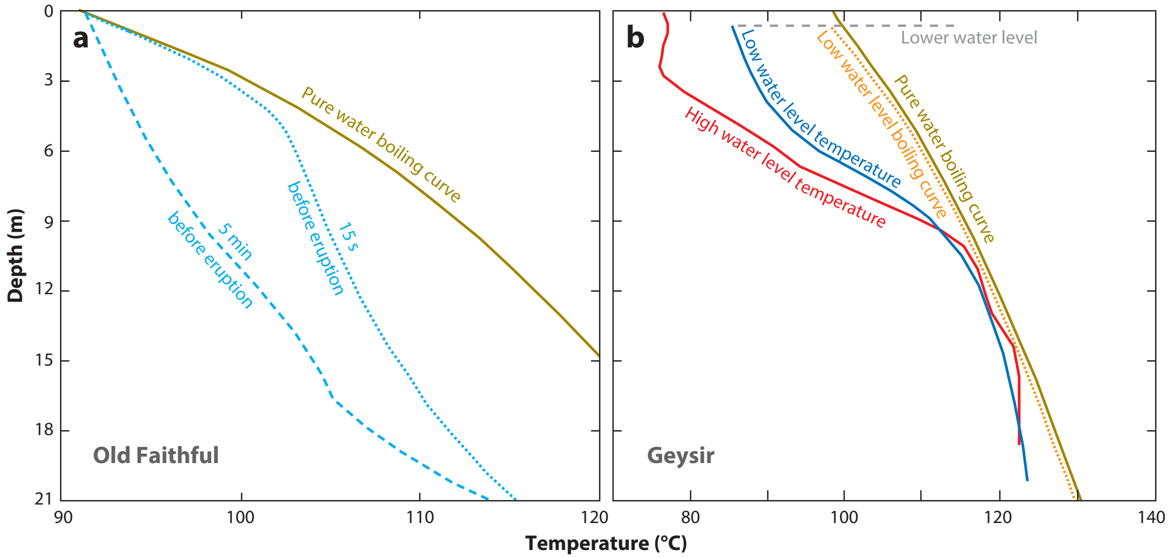


Figure 9

(*a*) Temperature versus depth measurements in the conduit of Old Faithful geyser in Yellowstone National Park, United States. The solid dashed light blue curve shows the temperature-depth profile 5 min before the eruption, and the dotted light blue curve is the temperature-depth profile 15 s before the eruption; the brown solid curve shows the boiling temperature of pure water. In both cases, the temperature at the top of the water column (0 depth in the figure; ∼5.5 m below the top of the cone) coincides with the boiling curve for pure water. Modified from figure 5 in Birch & Kennedy (1972). (*b*) Temperature versus depth measurements in the conduit of Geysir in Iceland. The dark blue curve shows the temperature-depth profile when the water level is low and the red curve when the water level is high. In both cases, the temperature is just below the boiling curve for pure water (*brown solid line*) at a depth of 10–13 m, and the temperature is significantly below boiling temperatures at shallower depths. Modified from figures 1 and 2 in Birch & Kennedy (1972).

(possibly in cavities or bubble traps) enters the conduit, delivering latent heat to warm water in the conduit.

Convective oscillations driven by temperature inversions during the recharge period also affect accumulation of heat and steam in the conduit (Hales 1937, White 1967, Murty 1979, Kieffer 1984, Dowden et al. 1991, Hutchinson et al. 1997, Alexandrov et al. 2016), and convection may occur during all stages of an eruption cycle (O'Hara & Esawi 2013). However, in contrast to large-diameter wells, geyser conduits are typically narrow and contorted, limiting the development of convection cells and evaporative heat loss. When buoyant superheated water is convected upward, steam bubbles form and expand when the pressure decreases below the saturation pressure of the water. White (1967) suggested that convective downflow occurs generally near the sides of the conduit, but as the number of bubbles in the conduit increases with increasing temperature, the rising column expands until frictional resistance suppresses convective downflow. Enlargement of a geyser conduit (for example, after an earthquake) may result in enhanced convection and heat loss and alter the dynamics of a geyser or even lead to cessation of eruptions.

Other processes might play a role in the subsurface. The large volume change from the conversion of liquid to steam can cause large pressure changes (White 1967). A kinetic barrier to bubble nucleation has also been invoked: Steinberg et al. (1981) proposed that eruptions are driven by the nucleation of steam bubbles in a superheated fluid, and that the interval between eruptions is governed by the time it takes to achieve the required degree of superheating. There is no strong evidence in any of the reliable published data for superheating in natural geysers. However, there

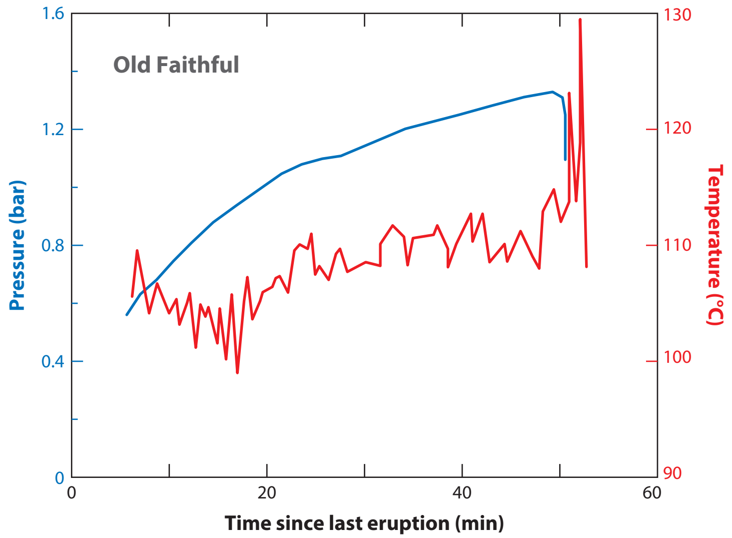


Figure 10

Smoothed temperature (*red curve*) and pressure (*blue curve*) variations with time at a depth between 21 and 22 m following an eruption of Old Faithful geyser in Yellowstone National Park, United States. Data replotted from Hutchinson et al. (1997).

is anecdotal data from the late nineteenth century and early twentieth century, when it was described that dumping soap (which acts as a surfactant) into geysers led to their eruptions (Hague 1889, Torfason 1985), purportedly by removing a kinetic barrier for bubble nucleation from the superheated water. An alternative explanation is that the soap dissolved in the water and lowered the boiling temperature of the solution. Given that temperature variations throughout a geyser cycle can be as modest as a couple of degrees (e.g., Munoz-Saez et al. 2015a), a small change in boiling temperature may be sufficient to initiate eruptions.

Hydrogeological properties also influence the geysering process. Ingebritsen & Rojstaczer (1993, 1996) performed numerical simulations of multiphase fluid flow and heat transport through a porous medium, approximating the geyser system as a permeable conduit of intensely fractured rock surrounded by a less permeable rock matrix. They showed that within a narrow range of parameters that allow geyser-like behavior, eruption frequency and discharge are highly sensitive to the intrinsic permeabilities of the geyser conduit and the surrounding rock matrix, the relative permeability functions assumed for the liquid + steam mixture, and pressure gradients in the matrix. Laboratory experiments have shown that multiphase flow in rough-walled rock fractures is dominated by significant retention of the wetting phase (liquid water) and persistent instabilities, with cyclic pressure and flow rate variations (Persoff & Pruess 1995, Bertels et al. 2001).

To summarize, observations collected over the past two centuries confirm the role of subsurface geometry in accumulating and releasing fluids, highlighted by Mackenzie (1811), and the importance of the pressure dependence of the boiling temperature, highlighted by Bunsen (1847). There are additional observations, however, not explained by these two conceptual models that provide constraints on additional subsurface components of geysers: First, the volumes of the reservoir and fracture complexes from which thermal waters are discharged are significantly larger than the volumes erupted during a single eruption (Section 2). Second, chemical data (**Table 1**) imply that the meteoric waters in these large reservoir-fracture complexes equilibrate thermally (at ~200°C) and chemically at depths of a few hundred meters or more before ascending to the surface where they provide the thermal energy required to drive the eruption. Third, in addition to bubble nucleation and collapse, other types of seismic signals have been recorded. Vandemeulebrouck et al. (2014) identified periodic ~4-min ultra-long-period signals that occur during all stages of the eruption cycle and attributed these signals to ascending gas slugs. Fourth, evaporation and heat loss can have a strong effect on geyser dynamics, especially in pool geysers with a large surface area (Steinberg 1980, Weir et al. 1992, Hurwitz et al. 2014). White (1967) suggested that "the excess heat of many high-temperature systems is lost near the surface by several means, thereby explaining the absence or scarcity of geysers where they might otherwise be abundant" (p. 676), and "the large pools and vents of some geysers may lose so much heat by convection and evaporation that eruption is greatly inhibited" (p. 681). Finally, dissolved gases may influence some eruptions by lowering the boiling temperature of the solution (Hurwitz et al. 2016, Ladd & Ryan 2016).

4.2. Surface Eruption

The visible manifestation of geysering is the surface spout, jet, or plume that ejects a mixture of steam and liquid water. The vigor of eruptions is highly variable between geysers and during a given eruption. Eruptions range from small bubbling fountains, common in large pools, to jets that can reach heights of 115 m at Steamboat geyser in Yellowstone (Bryan 2008) and up to 450 m at Waimangu geyser in the Taupo Volcanic Zone, New Zealand, between 1900 and 1904 (Vandemeulebrouck et al. 2008). However, descriptions of jet heights are mostly anecdotal and not very accurate. Eruptions are also unsteady. Large, long-lived eruptions tend to begin as liquid dominated and evolve to steam dominated.

Many large eruptions are preceded by small preplay events that intermittently eject mostly liquid water, removing mass and pressure from the water column in the conduit. The main eruption often begins with a series of bursts before becoming approximately steady, and then the fountain height typically decreases. Pulsing with periods ranging from seconds (Kieffer 1989) to several tens of seconds (Karlstrom et al. 2013) can occur during all stages, with frequencies that glide during the course of the eruption (Karlstrom et al. 2013).

As water from the reservoir ascends through the conduit and decompresses, some of its thermal energy is converted to kinetic energy. For example, Kieffer (1989) proposed that at Old Faithful, isentropic decompression of water in the conduit initially at 116°C (measured at a depth of 21–22 m) into a 0.8-bar atmosphere loses $\Delta H = 3.9$ kJ/kg (where H is enthalpy), which would lead to eruption velocities $U_0 = \sqrt{2 \cdot \Delta H} = 88$ m/s if all the enthalpy change was converted to kinetic energy. However, if Old Faithful's reservoir temperature of 204 ± 4°C (Hurwitz et al. 2012) were considered as the initial temperature, the amount of converted energy and the jet velocity would be much greater. Measured jet velocities of several large geysers are significantly lower: ~18 m/s in Velikan (Droznin et al. 1999) and 16–28 m/s in Lone Star geyser in Yellowstone (Karlstrom et al. 2013). This discrepancy between ballistic calculations and measured velocities suggests that drag, turbulence, and air entrainment, especially below the vent in the geyser conduit, account for much of the energy balance and significantly reduce the velocity (Karlstrom et al. 2013).

A common assumption in models for high-speed eruptions of compressible flows through vents, at both geysers and magmatic volcanoes (Bercovici & Michaut 2010), is that the speed at the vent is choked to the sound speed of the liquid + gas mixture as it passes through a constriction that acts as a nozzle. The sound speed is the velocity at which small perturbations in density or pressure propagate through the fluid (Kieffer 1977). Establishing that flow is indeed choked is a "notoriously difficult problem" (Kieffer 1989, p. 27). Karlstrom et al. (2013) found that U_0 at Lone Star geyser in Yellowstone (16–28 m/s) was close to the sound speed for the estimated steam mass fraction. Munoz-Saez et al. (2015a) inferred that the sound speed inside the conduit of a small

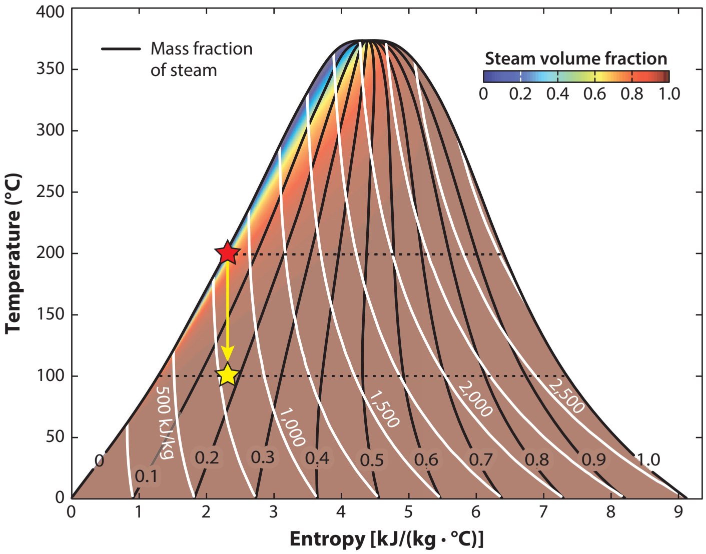


Figure 11

Temperature-entropy phase diagram for pure water. Black curves represent mass fraction of steam, isenthalpic curves (in kJ/kg) are in white, and colors represent the volume fraction of steam. The red star represents liquid water at 200°C, an average reservoir temperature for most geysers based on chemical geothermometry. The vertical yellow arrow ending at the yellow star shows the isentropic decompression to 100°C (boiling temperature of water at sea level), which results in a two-phase mixture with 17 wt% steam. If the 200°C liquids decompress isenthalpically to 100°C, 19 wt% steam will form. Modified from Karlstrom et al. (2013).

geyser at El Tatio, Chile, was similar to U_0 by cross-correlating measured pressure fluctuations in the water column.

The surface manifestation of eruptions varies from bubbling pools to modest fountains to roaring jets. Eruption vigor is presumably controlled by the thermal energy available to drive the eruption, and by the geometry of the conduit through which the fluids erupt, as overpressures in the source are small (Shteinberg et al. 2013). Geysers with deep, large reservoirs lead to large quantities of thermal energy converted to kinetic energy and hence more powerful eruptions. Large water volumes permit longer eruptions. Constrictions in the conduit accelerate fluids (up to the sound speed) so that narrowing conduits favor higher eruption heights.

The heat output from geysers can be calculated from the volume of erupted water assuming isentropic decompression (Kieffer 1989, Mastin 1995, Lu & Kieffer 2009), rather than isenthalpic decompression, from a reservoir where the liquid water was stored prior to the eruption (**Figure 11**). The reservoir temperature can be calculated using chemical geothermometers (Fournier 1981). At Lone Star geyser in Yellowstone, with an erupted volume of 20.8 ± 4.1 m^3, a reservoir temperature of 160–170°C, and eruptions every 3 h, the calculated average heat output is 1.4–1.5 MW (Karlstrom et al. 2013).

4.3. Laboratory Studies

It is not possible to directly image the entire subsurface geysering process in the field, and measurements are limited to discrete locations in a complex, largely unknown plumbing system. Laboratory models thus provide an opportunity to image and measure the geysering process directly and in a controlled manner—parameters can be varied systematically, the plumbing geometry can be simplified, and variables such as pressure and temperature can be measured.

Laboratory studies have been used to show that steady heating and recharge can lead to episodic eruptions (Munby 1902, Forrester & Thune 1942, Steinberg et al. 1982), to show how increasing complexity of plumbing geometries results in greater variation in discharge styles and eruption intervals (Namiki et al. 2016), to understand the effects of geometry on convection and hence temperature in the conduit (Sherzer 1933), to show how increasing reservoir temperature increases the vigor of eruptions (Toramaru & Maeda 2013), to show how the decrease in reservoir pressure over the course of the eruption leads to recharge and the end of eruption (Lasic 2006), to show how bubble formation and collapse generates weak high-frequency tremors (Anderson et al. 1978), and to show how intermittent modulation of the rate of boiling and the closely coupled accelerations and decelerations of the water column generate strong low-frequency tremors (Anderson et al. 1978).

Laboratory studies document how boiling conditions in the reservoir propagate into the conduit as expulsion of water at the surface decompresses the remaining water (Anderson et al. 1978, Lasic 2006). They also provide a tool to understand irregularity in eruptions. For example, Steinberg (1999) showed that the duration of eruption controls the duration of the following quiescent period, and that it is the eruption duration that is stochastic.

Laboratory studies with bubble traps confirm the inferences from natural geysers that vapor can accumulate and then be released episodically, leading to both minor (preplay) and major eruptions (e.g., Davis 2012). Vapor discharged during minor eruptions progressively warms the shallower parts of the geyser, such as the conduit, so that boiling conditions can eventually be reached everywhere in the conduit, leading to larger and more sustained eruptions (Adelstein et al. 2014). This is consistent with the gradual increase in intensity of regularly spaced minor eruptions leading up to the major eruption at some natural geysers (Namiki et al. 2014).

In general, even modest complexity in laboratory models (as in numerical models), such as a single bend in the conduit (Davis 2012, Adelstein et al. 2014) or multiple reservoirs supplying water to the conduit (Anderson et al. 1978, Cross 2010), can lead to irregular eruption intervals. The regularity of many natural geysers is thus all the more remarkable.

5. COLD, CO_2-DRIVEN GEYSERS

The exsolution of dissolved, noncondensable gases from water can serve the same mechanical function as boiling to drive eruptions. If the exsolution and subsequent eruption are episodic, the features are sometimes called cold geysers. There is interest in CO_2-driven geysers because they capture some of the processes that would arise if CO_2 leaked into faults and wellbores during geological carbon sequestration and storage. All of the reported cold geysers are wells that were drilled into carbonate units (e.g., Glennon & Pfaff 2004, Bissig et al. 2006, Watson et al. 2014). For example, the CO_2 discharged from Crystal and Tenmile geysers in the northern Paradox Basin near Green River, Utah, originates from thermal decomposition of marine carbonates (Watson et al. 2014). There are no reports of soda (CO_2-rich) springs with a geysering fountain, possibly implying that deposition of silica-rich sinter (geyserite) is important for most natural geysers. In addition, because the expansion of CO_2 is much smaller than that of steam, ascent of cold CO_2 geysers is only from wells that are much deeper (~800 m in the case of Crystal geyser) than natural geyser reservoirs.

Because the solubility of CO_2 in water increases with increasing pressure, ascent of CO_2-rich water can lead to bubble nucleation. The decreasing density of the water + bubble mixture lowers the pressure deeper in the conduit and promotes further exsolution. The positive feedback then leads to explosive eruptions as rising, expanding, and coalescing bubbles push or drag water toward the surface. Eventually the water in the conduit degasses to the point that the eruption can no longer be sustained by exsolution, and the conduit refills with water that is undersaturated with dissolved gases. The next eruption must wait until leakage of CO_2 into the conduit allows the gas concentration to become high enough to nucleate bubbles. There are thus self-promoting and self-limiting processes that lead to geysering behavior (e.g., Lu et al. 2005, Han et al. 2013, Watson et al. 2014), where the input of CO_2 plays a similar role to the input of heat in normal hydrothermal geysers, and the eruptions are sustained by a positive feedback between pressure decrease and gas-fraction increase. Subsurface geometry may differ, however: Cold geysers probably do not require the separate chamber or bubble trap that appears to be common at hydrothermal geysers. However, there are no images of the subsurface at the bottom of these wells.

6. RESPONSE OF GEYSERS TO EXTERNAL INFLUENCES

The regularity of some geysers is among their most compelling features. This attribute raises the question, What causes variations in the interval between eruptions (IBE)? Because geysers transport fluids and require a narrow range of thermodynamic and hydrogeological conditions to erupt, processes that modify fluid flow, influence recharge, or change temperature could all affect eruptions—geysers may thus be sensitive to crustal deformation and varying weather. Documenting and understanding such sensitivity provides quantitative insight into the processes that deliver multiphase fluids and heat to the surface and lead to eruptions.

Geysers may also serve as a natural laboratory to test hypotheses regarding the triggering of volcanic eruptions, because geysers erupt more frequently than volcanoes do, making statistical analysis more robust. It has been proposed that volcanoes can be triggered by seismic waves (e.g., Linde & Sacks 1998, Manga & Brodsky 2006, Walter & Amelung 2007) and modulated by seasonal climate variations (e.g., Mason et al. 2004), solid Earth tides (e.g., Johnston & Mauk 1972, Mauk & Johnston 1973), precipitation (e.g., Mastin 1994, Matthews et al. 2002), sea-level change (McGuire et al. 1997), and glaciation (e.g., Jellinek et al. 2004, Huybers & Langmuir 2009, Rawson et al. 2016). However, many of these analyses were based on small data sets and/or limited statistical analysis (Emter 1997, Neuberg 2000).

There is a long history of searching for external controls on geysers, and studies often draw contradictory conclusions even for the same geysers. However, the sparsity of continuous and long-term (annual to decadal) instrumental data makes it challenging to identify cause and effect in geyser systems. Uncontroversial is the observation that regional and distant earthquakes can change the IBE (e.g., Marler 1964, Marler & White 1975, Hutchinson 1985, Husen et al. 2004) or initiate a switch from a unimodal to a bimodal IBE (Silver & Valette-Silver 1992). Nearby geysers can also influence each other—through pressure changes in the subsurface (e.g., Ingebritsen & Rojstaczer 1996, Munoz-Saez et al. 2015b). Based on several years of continuous data, it was shown that several of Yellowstone's geysers display seasonal cycles of eruption intervals resulting from variations in the hydrological cycle and/or weather (Marler 1954; Hurwitz et al. 2008, 2012). However, the seasonal cycles of individual geysers were not in phase, suggesting complex responses in the subsurface.

Geysers with records of many thousands to tens of thousands of eruptions provide the best opportunity to understand external influences. Hurwitz et al. (2014) analyzed the eruption records from two geysers at Yellowstone: the pool geyser Daisy (>37,000 eruptions) and the cone geyser Old Faithful (>58,000 eruptions) (both geysers are shown in **Figure 3**). Previous studies drew conflicting conclusions that these geysers are (Rinehart 1972a,b) or are not (White & Marler 1972, Rojstaczer et al. 2003) sensitive to solid Earth tides and variations in barometric pressure. With the larger data set, neither geyser was found to be sensitive to strains from solid Earth tides or barometric pressure variations (**Figure 12**). The cone geyser is not affected by changes in

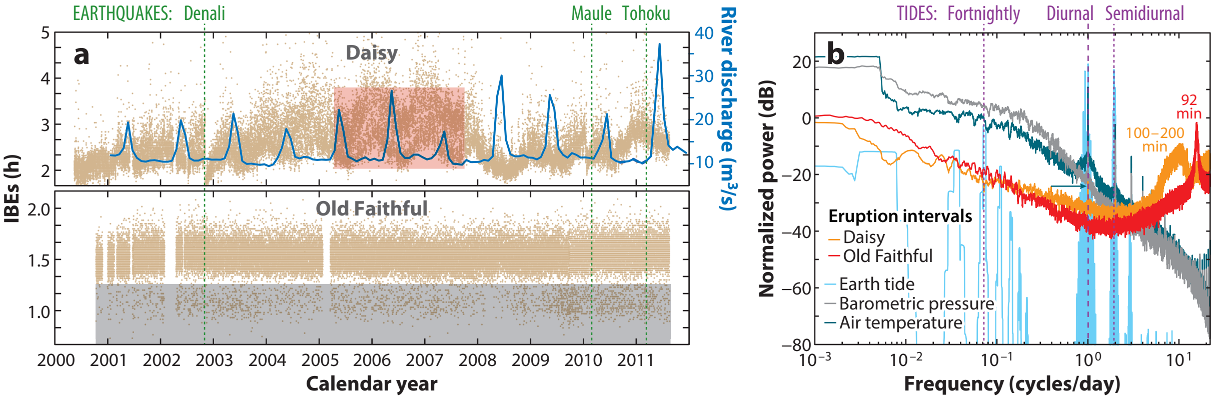


Figure 12

(*a*) Plot showing electronic data of intervals between eruptions (IBEs) for Daisy and Old Faithful geysers in Upper Geyser Basin, Yellowstone National Park, United States, for the period between 2000 and 2011 (*brown dots*). The green vertical dashed lines show the time of the Denali earthquake, which shortened Daisy geyser's IBE, and the Maule, Chile, and Tohoku, Japan, earthquakes, which did not change the IBE. The shaded red rectangle identifies the period when Daisy's IBE had a bimodal distribution, and the gray rectangle identifies Old Faithful geyser's IBEs that are shorter than 75 min. The blue curve is the monthly average discharge of the Madison River, which mimics snow melt and water recharge into the subsurface. (*b*) Power spectra of Old Faithful (*red*) and Daisy (*orange*) IBEs based on the data presented in panel *a*. Also shown are the spectra for solid Earth tides (*light blue*), barometric pressure (*gray*), and air temperature (*aqua*). The purple vertical dashed lines show the frequencies of the three major Earth tides. The plot shows that Daisy geyser's IBE has a diurnal cycle attributed to air temperature changes and evaporation. Both geysers show no statistically resolvable response to solid Earth tides and barometric pressure. Modified from Hurwitz et al. (2014).

air temperature or wind. However, the pool geyser does lengthen eruption intervals in response to strong winds, as also documented by Marler (1951), and to cold air temperatures, presumably because heat loss from the pool leads to longer times for water to reach boiling conditions. Dynamic stresses of >0.5 MPa produced by distant earthquakes can also change eruption intervals.

Continuous data from > 4,000 eruptions over a shorter time interval of ∼1 week from a geyser with a 1–2-min IBE in the El Tatio geyser field in Chile show no sensitivity to air temperature, wind, barometric pressure, or solid Earth tides (Munoz-Saez et al. 2015a). However, there are year-to-year variations (Munoz-Saez et al. 2015b). In fact, drifting of the IBE over annual and decadal timescales is typical of geysers (e.g., Barth 1940). In the same El Tatio geyser field, there is a geyser that had regular eruptions in 2012 (Namiki et al. 2014) but became bimodal in 2014; this same geyser also has regular preplay events, and the interval between preplay events did not change over this time period even though the IBE of main eruption varied (Munoz-Saez et al. 2015b).

The geysers in the Valley of Geysers, Kamchatka, provide another opportunity to study the effect of external influences. Two different landslides dammed the Geysernaya River adjacent to several of the geysers, creating lakes. The resulting changes in recharge and pore pressure led to changes in the IBE or the cessation of geysering; after the dams burst, geysering returned to prelandslide behavior (Kiryukhin et al. 2012, 2015). These observations document a hydrogeological connection between surface water and the geysers, either direct or through pressure changes.

Geyser activity along the shores of Lake Bogoria in Kenya is strongly influenced by climatically controlled lake-level variations of up to several meters over timescales of years to thousands of years. However, the nature of geyser response to lake-level variations is variable, with higher lake level suppressing activity in some geysers but increasing activity in others. Some of the vents are submerged during high lake levels, but activity from the main vents resumes at the same location following lake-level drop (Renaut & Owen 2005, Renaut et al. 2008).

The variable and sometimes contrasting response of geysers to external influences is a reminder that "no two [geysers] are alike" (White & Marler 1972). There are nevertheless some common themes: Pool geysers may be more sensitive to temperature and wind because there is a larger surface area for heat and mass transfer. Solid Earth tides and weather otherwise have no or little influence. Variations over longer time periods may thus be controlled by internal processes such as recharge or evolving permeability. Earthquakes, if the dynamic stresses are large enough, can also influence eruption intervals, perhaps by changing the permeability.

7. GEYSERS BEYOND EARTH

The icy satellites Triton and Enceladus have eruptions that are similar to Earth's geysers in that mixtures of solids and gas erupt episodically, and the eruptions are presumably driven by the volume change caused by phase transitions. The geysers of Triton are driven by solar insolation (Kirk et al. 1990) and are thus fundamentally different from Earth's geysers, which derive their energy from the subsurface.

The geysers of Enceladus erupt from discrete, localized vents along fissures in the South Polar Terrain (Spitale & Porco 2007). Eruptions appear to be modulated by tides, with the timing controlled by viscoelastic tidal response and normal stress across the fissures (Běhounková et al. 2015). Thermal anomalies adjacent to the fissures testify to vertical energy transport by the eruptions (Spencer et al. 2009). The gas is mostly water vapor, with a few percent carbon dioxide (CO_2), methane (CH_4), and ammonia (NH_3) (Hansen et al. 2006); the solid particles are mostly water ice, but may contain $\sim$1% salt (Postberg et al. 2011). About 10% of the particles exceed the escape velocity of Enceladus (Ingersoll & Ewald 2011) and supply particles to Saturn's E ring (Porco et al. 2006), while the rest fall back to the surface.

There remain many mysteries about the Enceladus geysers, including their energy source, their eruption duration and interval, and their longevity. Violent boiling of liquid water may allow the salt to be incorporated into the erupted ice particles (Spencer & Nimmo 2013). The abundances of CO_2 and CH_4 are higher than their solubility in liquid water, suggesting a different source of some of the gas, possibly the decomposition of clathrates (Kieffer et al. 2006). Like Earth's geysers (Karlstrom et al. 2013, Munoz-Saez et al. 2015b), the eruption velocity at the vent appears to be choked to the speed of sound (Nimmo et al. 2014). A space mission designed specifically to sample and characterize the plumes would reduce uncertainty in the measurements and could allow the various hypotheses about the sources of mass and energy to be distinguished.

8. FUTURE STUDIES

Almost a century and a half after the geological survey led by Ferdinand V. Hayden in what would later become Yellowstone National Park, one of his conclusions still remains pertinent: "What remains to be done is to start a series of close and detailed observations protracted through a number of consecutive years, with a view to determine, if possible, the laws governing geyseric action" (Hayden 1883, p. XXIII). Here we suggest some potential areas for future study.

First, high-resolution imaging of geysers' subsurface structure and four-dimensional (space and time) representation of bubble cavitation (phase change) processes should be obtained in order to distinguish between conceptual models. This requires dense arrays of instruments. In addition, better age constraints on geyser formation, growth, and eruptive history need to be provided. Weed (1912, p. 27) stated that "the cone is not only a measure of a geyser's age and activity, but it tells in a way the nature of the eruption," and Allen & Day (1935, p. 151) stated that "attempts to measure the rate at which siliceous sinter is deposited have all led to the conclusion that it must be very slow." It will also be important to incorporate realistic steam-water relative permeabilities for flow in rough-walled rock fractures into eruption models. Laboratory experiments have shown that the sum of the water and gas relative permeabilities is much less than one at intermediate saturations, implying that multiphase flow in fractures is dominated by significant retention of the wetting phase (liquid water) and persistent instabilities with cyclic pressure and flow rate variations (Persoff & Pruess 1995, Bertels et al. 2001).

More than three decades ago, Kieffer (1984) proposed that insights gleaned from geyser studies could be used to improve the interpretation of signals recorded at volcanoes and to test or even improve physical models of volcanic processes. With the many observations made since, both inside and outside the geyser conduit, insights from geysers could be applied to reevaluate the interpretation of deformation and seismic signals recorded at magmatic volcanoes.

Finally, it has been demonstrated that a variety of natural phenomena (e.g., earthquakes and landslides) and anthropogenic processes (e.g., geothermal energy development) (e.g., Scott & Cody 2000, Barrick 2007, Steingisser & Marcus 2009, Saptadji et al. 2016) can change geyser eruption intervals or terminate geyser activity. Therefore, continuous and long-term records of geyser eruption durations and intervals using temperature sensors in outflow channels (Hurwitz et al. 2008, 2014) or infrasound (Johnson et al. 2013) should be collected. These data can guide the protection and preservation of the unique and diverse geysers on Earth.

9. SUMMARY

Geysers have "become a familiar symbol of the western lands of the United States and their national parks" (Kieffer 1989, p. 18); their "behavior had attracted tourists as well as learned men, and legion is the number of notes and descriptions of Geysir from the seventeenth century up to the present day" (Barth 1940, p. 27). The millions of people who watch geysers erupt each year are attracted by the power and size of the eruptions and fascinated by their episodicity. Geysers capture our imagination, as described more than two centuries ago by Sir George Steuart Mackenzie after a visit to Geysir, in Iceland:

> Here description fails altogether. The Geyser did not disappoint us, and seemed as if it was exerting itself to exhibit all its glory on the eve of our departure. It raged furiously, and threw up a succession of magnificent jets, the highest of which was at least ninety feet. At this time I took the sketch from which the engraving is made: but no drawing, no engraving, can possibly convey any idea of the noise and velocity of the jets, nor of the swift rolling of the clouds of vapour, which were hurled, one over another, with amazing rapidity. (Mackenzie 1811, p. 224)

In Section 1 we highlighted several open questions about how and why geysers erupt. Some of these questions were singled out as needing further study in order to provide even qualitative answers, including the age and evolution of geysers and the landforms they create as well as why geysers change eruption patterns and vanish. Nevertheless, progress has been made, and we end by revisiting these questions along with a summary of our current understanding.

1. **Why do some springs discharge continuously and others (geysers) erupt intermittently? Why are geysers rare?** Geological setting matters. Geysers form in regions with sufficient water supply; quaternary rhyolite eruptions (the source of silica and heat); glacial, landslide, or hyaloclastite deposits, which provide an optimal fracture network; and a relatively low permeability cap (e.g., hydrothermal cemented deposits), which impedes the ascent

of fluids. Together, these features create reservoirs that allow hot water to accumulate and then be discharged in discrete events.

2. **How old are geysers? How long does it take their mounds and cones to grow? What causes them to change eruption patterns and vanish?** The major geyser fields on Earth were formed following the last glaciation (<14,000 years ago). Geysers are transient features with periods of activity and dormancy that are affected by earthquakes, changes in water recharge rates, erosion of their cones and/or mounds, and slow silica deposition in flow channels and reservoirs.
3. **Why do some geysers erupt periodically and others at irregular intervals?** Regularity is promoted by reservoirs that are deep enough that they do not sense surface weather changes and large enough that external strains are of little consequence. Geysers influence each other, and hence hydraulically isolated geysers should be the most regular.
4. **Why do only a few geysers erupt to heights of tens of meters?** Eruptions are driven by the energy change associated with the decompression of hot water. Deep, large chambers lead to a greater energy change and provide more water, hence creating larger and longer eruptions.
5. **How is heat transferred to mechanical energy to drive the multiphase and multi-component eruptions?** The ascent and eruption of water unload the conduit and deeper reservoir and promote boiling. The enthalpy change from near-adiabatic decompression provides the energy source for the eruption. The ejection speed of water from the vent, however, may be limited by the flow choking at the sound speed of the liquid + vapor mixture.
6. **What processes, both internal and external to the geyser, influence duration and volume of an eruption and the interval between eruptions?** Many geysers appear to have some form of subsurface cavity that allows steam to accumulate between eruptions. Its release creates preplay or large eruptions. As these cavities are well below the surface and are large, most geysers are not particularly sensitive to changes at Earth's surface. Pool geysers, however, in which the volume of water that must be heated is in contact with the atmosphere, are most sensitive to surficial factors such as changes in wind speed and temperature.

DISCLOSURE STATEMENT

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LITERATURE CITED

Abedini AA, Robinson JE, Muffler LJP, White DE, Beeson MH, Truesdell AH. 2015. *Database for the geologic map of Upper Geyser Basin, Yellowstone National Park, Wyoming*. Data Ser. 911, Volcano Sci. Cent., US Geol. Surv., Reston, VA. doi: 10.3133/ds911

Adelstein E, Tran A, Munoz-Saez C, Shteinberg A, Manga M. 2014. Geyser preplay and eruption in a laboratory model with a bubble trap. *J. Volcanol. Geotherm. Res.* 285:129–35

Alexandrov DV, Bashkirtseva IA, Ryashko LB. 2016. Analysis of noise-induced eruptions in a geyser model. *Eur. Phys. J. B* 89:62

Allen ET, Day AL. 1935. *Hot springs of the Yellowstone National Park*. Publ. 466, Carnegie Inst., Washington, DC

Anderson LW, Anderegg JW, Lawler JE. 1978. Model geysers. *Am. J. Sci.* 278:725–38

Barrick KA. 2007. Geyser decline and extinction in New Zealand—energy development impacts and implications for environmental management. *Environ. Manag.* 39:783–805

Barth TFW. 1940. Geysir in Iceland. *Am. J. Sci.* 238:381–407

Běhounková M, Tobie G, Čadek O, Choblet G, Porco C, Nimmo F. 2015. Timing of water plume eruptions on Enceladus explained by interior viscosity structure. *Nat. Geosci.* 8:601–4

Belousov A, Belousova M, Nechayev A. 2013. Video observations inside conduits of erupting geysers in Kamchatka, Russia, and their geological framework: implications for the geyser mechanism. *Geology* 41:387–90

Bercovici D, Michaut C. 2010. Two-phase dynamics of volcanic eruptions: compaction, compression and the conditions for choking. *Geophys. J. Int.* 182:843–64

Bertels SP, DiCarlo DA, Blunt MJ. 2001. Measurement of aperture distribution, capillary pressure, relative permeability, and in situ saturation in a rock fracture using computed tomography scanning. *Water Resour. Res.* 37:649–62

Birch F, Kennedy GC. 1972. Notes on geyser temperatures in Iceland and Yellowstone National Park. *Am. Geophys. Union Monogr.* 16:329–36

Bissig P, Goldscheider N, Mayoraz J, Surbeck H, Vuataz FD. 2006. Carbogaseous spring waters, coldwater geysers and dry CO_2 exhalations in the tectonic window of the Lower Engadine Valley, Switzerland. *Eclogae Geol. Helv.* 99:143–55

Bloss FD, Barth TFW. 1949. Observations on some Yellowstone geysers. *Geol. Soc. Am. Bull.* 60:861–86

Brilliantov NV, Schmidt J, Spahn F. 2008. Geysers of Enceladus: quantitative analysis of qualitative models. *Planet. Space Sci.* 56:1596–606

Brown RH, Kirk RL, Johnson TV, Soderblom LA. 1990. Energy sources for Triton's geyser-like plumes. *Science* 250:431–35

Bryan TS. 2008. *The Geysers of Yellowstone*. Boulder: Univ. Press of Colorado. 4th ed.

Bunsen R. 1847. Physikalische Beobachtungen ueber die hauptsaechliche Geysir Islands. *Poggendorffs Ann. Phys. Chem.* 72:159–70

Campbell KA, Guido DM, Gautret P, Foucher F, Ramboz C, Westall F. 2015. Geyserite in hot-spring siliceous sinter: window on Earth's hottest terrestrial (paleo)environment and its extreme life. *Earth-Sci. Rev.* 148:44–64

Casarosa C, Latrofa E, Shelginski A. 1983. The geyser effect in a two-phase thermosyphon. *Int. J. Heat Mass Trans.* 26:933–41

Cody AS, Lumb JT. 1992. Changes in thermal activity in the Rotorua geothermal field. *Geothermics* 21:215–30

Cortecci G, Boschetti T, Mussi M, Lameli CH, Mucchino C, Barbieri M. 2005. New chemical and original isotopic data on waters from El Tatio geothermal field, northern Chile. *Geochem. J.* 39:547–71

Cros E, Roux P, Vandemeulebrouck J, Kedar S. 2011. Locating hydrothermal acoustic sources at Old Faithful Geyser using Matched Field Processing. *Geophys. J. Int.* 187:385–93

Cross J. 2010. A model of a geyser that erupts in series. *GOSA Trans.* 11:123–30

Davis B. 2012. Observations of small model geysers with variable plumbing. *GOSA Trans.* 12:159–72

Dowden J, Kapadia P, Brown G, Rymer H. 1991. Dynamics of a geyser eruption. *J. Geophys. Res.* 96(B11):18059–71

Droznin V, Bakhtiyarov V, Levin V. 1999. Temperature measurements in the Velikan Geyser Basin (Valley of Geysers, Kamchatka). *Volcanol. Seismol.* 21:67–78

Emter D. 1997. Tidal triggering of earthquakes and volcanic events. In *Tidal Phenomena*, ed. H Wilhelm, W Zurm, HG Wenzel, pp. 295–309. New York: Springer

Foley D. 2006. Dating castle geyser: preliminary results and broad speculations on the geologic development of geysers and hydrothermal systems in Yellowstone National Park, Wyoming, USA. *Trans. Geotherm. Res. Counc.* 30:413–17

Forrester JD, Thune HW. 1942. A model geyser. *Science* 95:204–6
Fournier RO. 1969. Old Faithful: a physical model. *Science* 163:304–5
Fournier RO. 1981. Application of water chemistry to geothermal exploration and reservoir engineering. In *Geothermal Systems*: *Principles and Case Histories*, ed. L Rybach, LJP Muffler, pp. 109–43. Chichester, UK: Wiley
Fournier RO. 1985. The behavior of silica in hydrothermal solutions. *Rev. Econ. Geol.* 2:45–61
Fukutomi TA. 1942a. New mechanism of the geyser I. *Bull. Seismol. Soc. Jpn.* 14:157–74
Fukutomi TA. 1942b. New mechanism of the geyser II. *Bull. Seismol. Soc. Jpn.* 14:189–202
Furushima Y, Nagao M, Suzuki A, Yamamoto H, Maruyama T. 2009. Periodic behavior of the bubble jet (geyser) in the Taketomi submarine hot springs of the southern part of Yaeyama archipelago, Japan. *Mar. Technol. Soc. J.* 43:13–22
Giggenbach WF. 1988. Geothermal solute equilibria. Derivation of Na-K-Mg-Ca geoindicators. *Geochim. Cosmochim. Acta* 52:2749–65
Giggenbach WF, Glover RB. 1992. Tectonic regime and major processes governing the chemistry of water and gas discharges from the Rotorua geothermal field, New Zealand. *Geothermics* 21:121–40
Glennon JA, Pfaff RM. 2004. The operation and geography of carbon dioxide-driven, cold-water "geysers." *GOSA Trans*. 9:184–92
Hague A. 1889. Soaping geysers. *Science* 8:382–84
Hales AL. 1937. Convection currents in geysers. *Geophys. J. Int.* 4:122–31
Han WS, Lu M, McPherson BL, Keating EH, Moore J, et al. 2013. Characteristics of CO_2-driven cold-water geyser, Crystal Geyser in Utah: experimental observation and mechanism analysis. *Geofluids* 13:283–97
Hansen CJ, Esposito L, Stewart AIF, Colwell J, Hendrix A, et al. 2006. Enceladus' water vapor plume. *Science* 311:1422–25
Hayden FV. 1883. Twelfth annual report of the United States Geological and Geographical Survey of the Territories: a report of progress of the exploration in Wyoming and Idaho for the year 1878, Part II: Yellowstone National Park. Ann. Rep., US Geol. Surv., Washington, DC
Howald T, Person M, Campbell A, Lueth V, Hofstra A, et al. 2014. Evidence for long timescale ($>10^3$ years) changes in hydrothermal activity induced by seismic events. *Geofluids* 15:252–68
Hung RJ, Shyu KL. 1992. Constant reverse thrust activated reorientation of liquid hydrogen with geyser initiation. *J. Spacecr. Rockets* 29:279–85
Hurwitz S, Clor LE, McCleskey RB, Nordstrom DK, Hunt AG, Evans WC. 2016. Dissolved gases in hydrothermal and geyser eruptions at Yellowstone. *Geology* 44:235–38
Hurwitz S, Hunt AG, Evans WC. 2012. Temporal variations of geyser water chemistry in the Upper Geyser Basin, Yellowstone National Park, USA. *Geochem. Geophys. Geosyst.* 13:Q12005
Hurwitz S, Kumar A, Taylor R, Heasler H. 2008. Climate-induced variations of geyser periodicity in Yellowstone National Park, USA. *Geology* 36:451–54
Hurwitz S, Sohn RA, Luttrell K, Manga M. 2014. Triggering and modulation of geyser eruptions in Yellowstone National Park by earthquakes, earth tides, and weather. *J. Geophys. Res. Solid Earth* 119:1718–37
Husen S, Taylor R, Smith RB, Healser H. 2004. Changes in geyser eruption behavior and remotely triggered seismicity in Yellowstone National Park produced by the 2002 M 7.9 Denali Fault earthquake, Alaska. *Geology* 32:537–40
Hutchinson RA. 1985. Hydrothermal changes in the Upper Geyser Basin, Yellowstone National Park, after the 1983 Borah Peak, Idaho, earthquake. *Proc. Worksh. XXVIII Borah Peak*, *Ida. Earthq*., Open-File Rep. 85-290, ed. RS Stein, RC Bucknam, pp. 612–24. Menlo Park, CA: US Geol. Surv.
Hutchinson RA, Westphal JA, Kieffer SW. 1997. In situ observations of Old Faithful Geyser. *Geology* 25:875–78
Huybers P, Langmuir C. 2009. Feedback between deglaciation, volcanism, and atmospheric CO_2. *Earth Planet. Sci. Lett.* 286:479–91
Ingebritsen SE, Rojstaczer SA. 1993. Controls on geyser periodicity. *Science* 262:889–92
Ingebritsen SE, Rojstaczer SA. 1996. Geyser periodicity and the response of geysers to small strains in the Earth. *J. Geophys. Res.* 101(B10):21891–907
Ingersoll AP, Ewald SP. 2011. Total particulate mass in Enceladus plumes and mass of Saturn's E ring inferred from Cassini ISS images. *Icarus* 216:492–506

Jaggar TA Jr. 1898. Some conditions affecting geyser eruption. *Am. J. Sci.* 5:323–33

Jellinek AM, Manga M, Saar MO. 2004. Did melting glaciers cause volcanic eruptions in eastern California? Probing the mechanics of dike formation. *J. Geophys. Res.*109:B09206

Johnson JB, Anderson JF, Anthony RE, Sciotto M. 2013. Detecting geyser activity with infrasound. *J. Volcanol. Geotherm. Res.* 256:105–17

Johnston MJS, Mauk FJ. 1972. Earth tides and the triggering of eruptions from Mount Stromboli, Italy. *Nature* 239:266–67

Jones B, Renaut RW, Torfason H, Owen RB. 2007. The geological history of Geysir, Iceland: a tephrochronological approach to the dating of sinter. *J. Geol. Soc.* 164:1241–52

Kagami H. 2010. An extended dynamic model of a geyser induced by an inflow of gas (2): effects of various shapes and repeated expansions and contractions in an underground watercourse. *Data Sci. J.* 9:IGY110–20

Karlstrom L, Hurwitz S, Sohn RA, Vandemeulebrouck J, Murphy F, et al. 2013. Eruptions at Lone Star Geyser, Yellowstone National Park, USA. 1. Energetics and eruption dynamics. *J. Geophys. Res. Solid Earth* 118:4048–62

Kedar S, Kanamori H, Sturtevant B. 1998. Bubble collapse as the source of harmonic tremor at Old Faithful Geyser. *J. Geophys. Res.* 103(B10):24283–99

Kedar S, Sturtevant B, Kanamori H. 1996. The origin of harmonic tremor at Old Faithful geyser. *Nature* 379:708–11

Kieffer SW. 1977. Sound speed in liquid-gas mixtures: water-air and water-steam. *J. Geophys. Res.* 82:2895–905

Kieffer SW. 1984. Seismicity at Old Faithful Geyser; an isolated source of geothermal noise and possible analogue of volcanic seismicity. *J. Volcanol. Geotherm. Res.* 22:59–95

Kieffer SW. 1989. Geologic nozzles. *Rev. Geophys.* 27:3–38

Kieffer SW, Lu X, Bethke CM, Spencer JR, Marshak S, Navrotsky A. 2006. A clathrate reservoir hypothesis for Enceladus' south polar plume. *Science* 314:1764–66

Kirk RL, Brown RH, Soderblom LA. 1990. Subsurface energy storage and transport for solar-powered geysers on Triton. *Science* 250:424–29

Kiryukhin AV, Rychkova TV, Dubrovskaya IK. 2012. Formation of the hydrothermal system in Geysers Valley (Kronotsky Nature Reserve, Kamchatka) and triggers of the Giant Landslide. *Appl. Geochem.* 27:1753–66

Kiryukhin AV, Rychkova TV, Dubinina EO. 2015. An analysis of hydrogeological behavior in the Geyser Valley, Kronotskii nature reserve, Kamchatka after the disaster of June 3, 2007. *J. Volcanol. Seismol.* 9:1–16

Krug von Nidda C. 1836. On the mineral springs of Iceland. *Edinb. New Philos. J.* 22:99–100

Ladd B, Ryan MC. 2016. Can CO_2 trigger a thermal geyser eruption? *Geology* 44:307–10

Lasic S. 2006. Geyser model with real-time data collection. *Eur. J. Phys.* 27:995

Le Conte J. 1878. Geysers and how they are explained. *Pop. Sci. Mon.* 12:407–17

Leonov VL. 2009. Geological structure and history of Geysers Valley. In *Geysers Valley—Pearl of Kamchatka*, ed. VM Sugrobov, NG Sugrobova, VA Droznin, GA Karpov, VL Leonov, pp. 35–39. Petropavlovsk-Kamchatsky, Russ.: Kamchatpress (in Russian)

Linde AT, Sacks IS. 1998. Triggering of volcanic eruptions. *Nature* 395:888–90

Lloyd BF. 1975. *Geology of Whakarewarewa Hot Springs*. Wellington, NZ: Gov. Print.

Lowenstern JB, Hurwitz S, McGeehin JP. 2016. Radiocarbon dating of silica sinter deposits in shallow drill cores from the Upper Geyser Basin, Yellowstone National Park. *J. Volcanol. Geotherm. Res.* 310:132–36

Lu X, Kieffer SW. 2009. Thermodynamics and mass transport in multicomponent, multiphase H_2O systems of planetary interest. *Annu. Rev. Earth Planet. Sci.* 37:449–77

Lu X, Watson A, Gorin AV, Deans J. 2005. Measurements in a low temperature CO_2-driven geysering well, viewed in relation to natural geysers. *Geothermics* 34:389–410

Lynne BY, Campbell KA, Moore J, Browne PRL. 2008. Origin and evolution of the Steamboat Springs siliceous sinter deposit, Nevada, USA. *Sediment. Geol.* 210:111–31

Mackenzie GS. 1811. *Travels in the Island of Iceland*. Edinburgh: Archibald Constable & Co.

Manga M, Brodsky E. 2006. Seismic triggering of eruptions in the far field: volcanoes and geysers. *Annu. Rev. Earth Planet. Sci.* 34:263–91

Marinovic N, Lahsen A. 1984. *Hoja Calama: región de Antofagasta*. Carta Geol. Chile No. 58, Escala 1:250.000, Serv. Nac. Geol. Min., Santiago, Chile (in Spanish)

Marler GD. 1951. Exchange of function as a cause of geyser irregularity [Wyoming]. *Am. J. Sci.* 249:329–42
Marler GD. 1954. Does the cold of winter affect the thermal intensity of the hot springs of Yellowstone Park? *Am. J. Sci.* 252:38–54
Marler GD. 1964. Effects of the Hebgen Lake earthquake of August 17, 1959 on the hot springs of the Firehole geyser basins, Yellowstone National Park. *US Geol. Surv. Prof. Pap.* 435:185–98
Marler GD, White DE. 1975. Seismic Geyser and its bearing on the origin and evolution of geysers and hot springs of Yellowstone National Park. *Geol. Soc. Am. Bull.* 86:749–59
Mason B, Pyle DM, Dade WB, Jupp T. 2004. Seasonality of volcanic eruptions. *J. Geophys. Res.* 109:B04206
Mastin LG. 1994. Explosive tephra emissions of Mount St. Helens, 1989–1991: the violent escape of magmatic gas following storms? *Geol. Soc. Amer. Bull.* 106:175–85
Mastin LG. 1995. Thermodynamics of gas and steam-blast eruptions. *Bull. Volcanol.* 57:85–98
Matthews AJ, Barclay J, Carn S, Thompson G, Alexander J, et al. 2002. Rainfall-induced volcanic activity on Montserrat. *Geophys. Res. Lett.* 29:22-1–22-4
Mauk FJ, Johnston MJS. 1973. On the triggering of volcanic eruptions by Earth tides. *J. Geophys. Res.* 78:3356–62
McCall J. 2010. Lake Bogoria, Kenya: hot and warm springs, geysers and Holocene stromatolites. *Earth-Sci. Rev.* 103:71–79
McGuire WJ, Howarth RJ, Firth CR, Solow AR, Pullen AD, et al. 1997. Correlation between rate of sea-level change and frequency of explosive volcanism in the Mediterranean. *Nature* 389:473–76
Muffler LJP, White DE, Beeson MH, Truesdell AH. 1982. *Geological map of upper Geyser Basin, Yellowstone National Park, Wyoming*. Misc. Investig. Map I-1371, Scale 1:4,800, US Geol. Surv., Reston, VA
Munby AE. 1902. A model geyser. *Nature* 65:247
Munoz-Saez C, Manga M, Hurwitz S, Rudolph ML, Namiki A, Wang CY. 2015a. Dynamics within geyser conduits, and sensitivity to environmental perturbations: insights from a periodic geyser in the El Tatio geyser field, Atacama Desert, Chile. *J. Volcanol. Geotherm. Res.* 292:41–55
Munoz-Saez C, Namiki A, Manga M. 2015b. Geyser eruption intervals and interactions: examples from El Tatio, Atacama, Chile. *J. Geophys. Res. Solid Earth* 120:7490–507
Munoz-Saez C, Saltiel S, Nguyen C, Gonnermann H. 2016. Hydraulic and physical properties of modern sinter deposits: El Tatio, Atacama. *J. Volcanol. Geotherm. Res.* 325:156–68
Murray KS. 1996. Hydrology and geochemistry of thermal waters in the Upper Napa Valley, California. *Ground Water* 34:1115–24
Murty TS. 1979. A mathematical model for pre-boiling convection in a geyser vent. *Am. J. Sci.* 279:989–92
Namiki A, Munoz-Saez C, Manga M. 2014. El Cobreloa: a geyser with two distinct eruption styles. *J. Geophys. Res. Solid Earth* 119:6229–48
Namiki A, Ueno Y, Hurwitz S, Manga M, Munoz-Saez C, Murphy F. 2016. An experimental study of the role of subsurface plumbing on geothermal discharge. *Geochem. Geophys. Geosys.* 17:3691–716
Neuberg J. 2000. External modulation of volcanic activity. *Geophys. J. Int.* 142:232–40
Nicholls HR, Rinehart JS. 1967. Geophysical study of geyser action in Yellowstone National Park. *J. Geophys. Res.* 72:4651–63
Nimmo F, Porco C, Mitchell C. 2014. Tidally modulated eruptions on Enceladus: *Cassini* ISS observations and models. *Astron. J.* 148:46
Nishimura T, Ichihara M, Ueki S. 2006. Investigation of the Onikobe geyser, NE Japan, by observing the ground tilt and flow parameters. *Earth Planets Space* 58:21–24
Noguchi K, Aikawa K, Lloyd EF, Simpson B, van der Werff P. 1983. Measurement of the orifice temperature of the Te Horu geyser in Whakarewarewa, New Zealand. *Proc. 4th Int. Symp. Water-Rock Interact.*, pp. 363–66
O'Hara KD, Esawi EK. 2013. Model for the eruption of the Old Faithful geyser, Yellowstone National Park. *GSA Today* 23:4–9
Pasvanoglu S. 1998. Geochemical study of the Geysir geothermal field in Haukadalur, S-Iceland. In *United Nations University Fellows Reports 1998*, ed. LS Georgsson, pp. 281–318. Reykjavík, Icel.: UN Univ. Geotherm. Train. Program
Peale AC. 1884. The world's geyser-regions. *Pop. Sci. Mon.* 25:15

Persoff P, Pruess K. 1995. Two-phase flow visualization and relative permeability measurement in natural rough-walled rock fractures. *Water Resour. Res.* 31:1175–86

Porco CC, Helfenstein P, Thomas PC, Ingersoll AP, Wisdom J, et al. 2006. Cassini observes the active south pole of Enceladus. *Science* 311:1393–401

Postberg F, Schmidt J, Hillier J, Kempf S, Srama R. 2011. A salt-water reservoir as the source of a compositionally stratified plume on Enceladus. *Nature* 474:620–22

Rawson H, Pyle DM, Mather TA, Smith VC, Fontijn K, et al. 2016. The magmatic and eruptive response of arc volcanoes to deglaciation: insights from southern Chile. *Geology* 44:251–54

Renaut RW, Jones B. 2011. Sinter. In *Encyclopedia of Geobiology*, ed. J Reitner, V Thiel, pp. 808–13. Dordrecht, Neth.: Springer

Renaut RW, Owen RB. 2005. The geysers of Lake Bogoria, Kenya Rift Valley, Africa. *GOSA Trans*. 9:2–16

Renaut RW, Owen RB, Ego JK. 2008. Recent changes in geyser activity at Loburu, Lake Bogoria, Kenya Rift Valley. *GOSA Trans*. 10:4–14

Rinehart JS. 1965. Earth tremors generated by Old Faithful Geyser. *Science* 150:494–96

Rinehart JS. 1969. Thermal and seismic indications of Old Faithful Geyser's inner workings. *J. Geophys. Res.* 74:566–73

Rinehart JS. 1972a. Fluctuations in geyser activity caused by variations in Earth tidal forces, barometric pressure, and tectonic stresses. *J. Geophys. Res.* 77:342–50

Rinehart JS. 1972b. Reply to "Comments on paper by John S. Rinehart, 'Fluctuations in geyser activity caused by Earth tidal forces, barometric pressure, and tectonic stresses.' " *J. Geophys. Res.* 77:5830–31

Rinehart JS. 1980. *Geysers and Geothermal Energy*. New York: Springer-Verlag

Rojstaczer S, Galloway DL, Ingebritsen SE, Rubin DM. 2003. Variability in geyser eruptive timing and its causes: Yellowstone National Park. *Geophys. Res. Lett.* 30:1953

Rudolph ML, Manga M, Hurwitz S, Johnston MJ, Karlstrom L, Wang CY. 2012. Mechanics of Old Faithful Geyser, Calistoga, California. *Geophys. Res. Lett.* 39:L24308

Scott BJ, Cody AD. 2000. Response of the Rotorua geothermal system to exploitation and varying management regimes. *Geothermics* 29:573–92

Sherzer WH. 1933. An interpretation of Bunsen's geyser theory. *J. Geol.* 41:501–12

Shteinberg A, Manga M, Korolev E. 2013. Measuring pressure in the source region for geysers, Geyser Valley, Kamchatka. *J. Volcanol. Geotherm. Res.* 264:12–16

Silver PG, Valette-Silver NJ. 1992. Detection of hydrothermal precursors to large Northern California earthquakes. *Science* 257:1363–68

Soderblom LA, Kieffer SW, Becker TL, Brown RH, Cook AF, et al. 1990. Triton's geyser-like plumes: discovery and basic characterization. *Science* 250:410–15

Sohn RA, Thomson RE, Rabinovich AB, Mihaly SF. 2009. Bottom pressure signals at the TAG deep-sea hydrothermal field: evidence for short-period, flow-induced ground deformation. *Geophys. Res. Lett.* 36:L19301

Saptadji N, O'Sullivan J, Krzyzosiak W, O'Sullivan M. 2016. Numerical modelling of Pohutu geyser, Rotorua, New Zealand. *Geothermics* 64:401–9

Spencer JR, Barr AC, Esposito LW, Helfenstein P, Ingersoll AP, et al. 2009. Enceladus: an active cryovolcanic satellite. In *Saturn from Cassini-Huygens*, ed. M Dougherty, L Esposito, S Krimigis, pp. 683–724. Dordrecht, Neth.: Springer

Spencer JR, Nimmo F. 2013. Enceladus: an active ice world in the Saturn system. *Annu. Rev. Earth Planet. Sci.* 41:693–717

Spitale JN, Porco CC. 2007. Association of the jets of Enceladus with the warmest regions on its south-polar fractures. *Nature* 449:695–97

Steinberg AS. 1999. An experimental study of geyser eruption periodicity. *Dokl. Phys.* 44:47–50

Steinberg GS. 1980. The enthalpy of the heat-carrying fluids and the energy of eruption of velican geyser, Kamchatka, U.S.S.R. *J. Volcanol. Geotherm. Res.* 8:267–83

Steinberg GS, Merzhanov AG, Steinberg AS. 1981. Geyser process: its theory, modeling and field experiment. Part 1. Theory of the geyser process. *Mod. Geol.* 8:67–70

Steinberg GS, Merzhanov AG, Steinberg AS, Rasina AA. 1982. Geyser process: its theory, modeling and field experiment. Part 2. A laboratory model of a geyser. *Mod. Geol.* 8:71–74

Steingisser A, Marcus WA. 2009. Human impacts on geyser basins. *Yellowstone Sci.* 17:7–17
Tassi F, Aguilera F, Darrah T, Vaselli O, Capaccioni B, et al. 2010. Fluid geochemistry of hydrothermal systems in the Arica-Parinacota, Tarapaca and Antofagasta regions (northern Chile). *J. Volcanol. Geotherm. Res.* 192:1–15
Thiéry R, Mercury L. 2009. Explosive properties of water in volcanic and hydrothermal systems. *J. Geophys. Res.* 114:B05205
Thorkelsson T. 1928. On the geyser theory. *Philos. Mag.* 5:441–44
Toramaru A, Maeda K. 2013. Mass and style of eruptions in experimental geysers. *J. Volcanol. Geotherm. Res.* 257:227–39
Torfason H. 1985. *The Great Geysir, Geysir*. Reykjavík, Icel.: Conserv. Comm.
Tryon MD, Brown KM, Torres ME, Tréhu AM, McManus J, Collier RW. 1999. Measurements of transience and downward fluid flow near episodic methane gas vents, Hydrate Ridge, Cascadia. *Geology* 27:1075–78
Vandemeulebrouck J, Hurst AW, Scott BJ. 2008. The effects of hydrothermal eruptions and a tectonic earthquake on a cycling crater lake (Inferno Crater Lake, Waimangu, New Zealand). *J. Volcanol. Geotherm. Res.* 178:271–75
Vandemeulebrouck J, Roux P, Cros E. 2013. The plumbing of Old Faithful Geyser revealed by hydrothermal tremor. *Geophys. Res. Lett.* 40:1989–93
Vandemeulebrouck J, Sohn RA, Rudolph ML, Hurwitz S, Manga M, et al. 2014. Eruptions at Lone Star Geyser, Yellowstone National Park, USA. Part 2. Constraints on subsurface dynamics. *J. Geophys. Res. Solid Earth* 119:8688–707
Walter TR, Amelung F. 2007. Volcanic eruptions following $M \geq 9$ megathrust earthquakes: implications for the Sumatra-Andaman volcanoes. *Geology* 35:539–42
Watson ZT, Han WS, Keating EH, Jung NH, Lu M. 2014. Eruption dynamics of CO_2-driven cold-water geysers: Crystal, Tenmile geysers in Utah and Chimayó geyser in New Mexico. *Earth Planet. Sci. Lett.* 408:272–84
Weed WH. 1912. *Geysers*. Washington, DC: Dep. Int.
Weir GJ, Young RM, McGavin PN. 1992. A simple model for Geyser Flat, Whakarewarewa. *Geothermics* 21:281–304
White DE. 1967. Some principles of geyser activity, mainly from Steamboat Springs, Nevada. *Am. J. Sci.* 265:641–84
White DE. 1992. *The Beowawe geysers, Nevada, before geothermal development*. Bull. 1998, US Geol. Surv., Washington, DC
White DE, Marler GD. 1972. Comments on paper by John S. Rinehart, 'Fluctuations in geyser activity caused by earth tidal forces, barometric pressure, and tectonic stresses.' *J. Geophys. Res.* 77:5825–29