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Authors

Hurwitz, Shaul
Manga, Michael

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The Fascinating and Complex Dynamics of Geyser Eruptions

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Shaul Hurwitz^{1,*} and Michael Manga^{2,*}

¹US Geological Survey, Menlo Park, California 94025; email: shaulh@usgs.gov

²Department of Earth and Planetary Science, University of California, Berkeley, California 94720; email: manga@seismo.berkeley.edu

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*Authors contributed equally to all aspects of this review.

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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.

Keywords

[choked flow](#), [phase separation](#), [multiphase flow](#), [conduit](#), [sinter](#), [hydrothermal](#)

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, 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, Jagger 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?
 - .

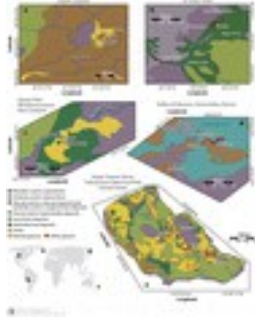
- 5 How is heat transformed to mechanical energy to drive the multiphase and
 - . multicomponent eruptions?

- 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 SiO₂-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.

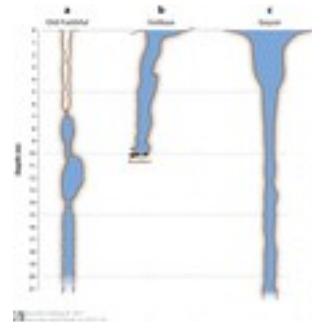


There are several observations that imply that the volumes of geyser reservoirs and fracture complexes are significantly larger than the volumes of water discharged during a single eruption. Some of the relevant observations include the following: (a) Fluorescein dye experiments in 1951 and 1959 at Geysir Flat, Whakarewarewa, in New Zealand (Lloyd 1975) imply a very direct and 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 m³ (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 m³.

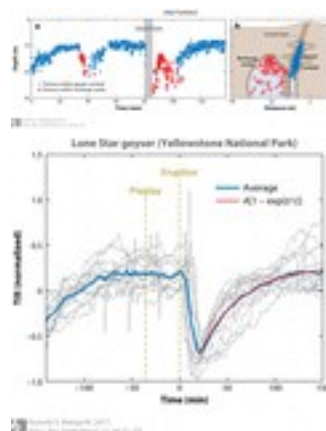


Video observations made in the conduit of Old Faithful geyser in the summer of 1992 (<https://www.youtube.com/watch?v=8luNCFUnvBw>) to a depth of nearly 13 m (Hutchinson et al. 1997) reveal an irregular, elongated fissure-like channel with fractured walls lined with white silica sinter (Figure 5a). The 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 5b; 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 5c), 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 fracture or some other interconnected channels. The glacial deposits 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 6b). 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 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%.

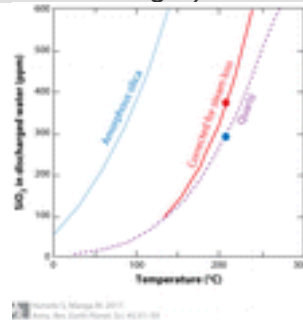
The major anion in most geyser waters is chloride, and the major cation is sodium (Table 1). The major anion in Lake Bogoria geysers is bicarbonate (HCO_3^-) (Renaut et al. 2008). Whereas chloride and sulfate concentrations vary by more than an order of magnitude between geyser fields, the range of silica (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 ($\sim 86^\circ\text{C}$) (Figure 1b; 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).



[CLICK TO VIEW](#)

Table 1

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



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 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 CO₂ derived from magma and N₂ 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 thermomechanical models to quantify various

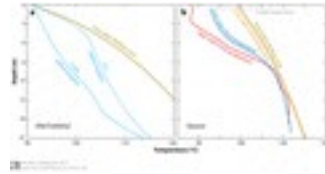
aspects of the geysering process. We first review observational constraints for processes in the reservoirs and conduits that deliver water to the surface, and then we describe the processes that influence the visible surface eruption.

4.1. Subsurface Processes

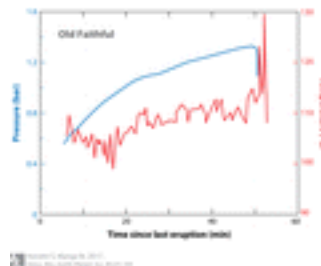
Inspired mainly by observations made in Geysir (“spout”) and to a lesser extent in Strokkur (“churn”) in Iceland (Figure 1), two early conceptual models sought to explain the main features of geysers. Mackenzie (1811) proposed that eruptions are caused by the increasing pressure exerted by the expansion 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 9a); Geysir, in Iceland (Figure 9b); 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 9a). The maximum temperature in the conduit of Geysir occurs several meters below the top of the water column (Figure 9b). 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 (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 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 $\sim 200^{\circ}\text{C}$) 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).

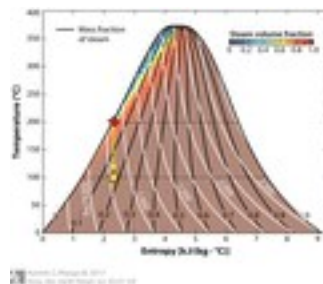
As water from the reservoir ascends through the conduit and decompresses, some of its thermal energy is converted to kinetic energy. For example, Kieffer (1989) proposed that at Old Faithful, isentropic decompression of water in the conduit initially at 116°C (measured at a depth of 21–22 m) into a 0.8-bar 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 $204 \pm 4^\circ\text{C}$ (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 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 $20.8 \pm 4.1 \text{ m}^3$, a reservoir temperature of $160\text{--}170^\circ\text{C}$, and eruptions every 3 h, the calculated average heat output is $1.4\text{--}1.5 \text{ MW}$ (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, CO₂-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 CO₂-driven geysers because they capture some of the processes that would arise if CO₂ 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 CO₂ 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 (CO₂-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 CO₂ is much smaller than that of steam, ascent of cold CO₂ 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 CO₂ in water increases with increasing pressure, ascent of CO₂-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 CO₂ 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 CO₂ 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

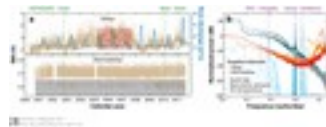
The regularity of some geysers is among their most compelling features. This attribute raises the question, What causes variations in the interval between eruptions (IBE)? Because geysers transport fluids and require a narrow range of thermodynamic and hydrogeological conditions to erupt, processes that 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 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 (CO₂), methane (CH₄), and ammonia (NH₃) (Hansen et al. 2006); the solid particles are mostly water ice, but may contain ~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 CO₂ and CH₄ 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 multicomponent 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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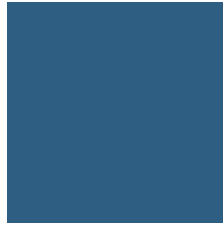
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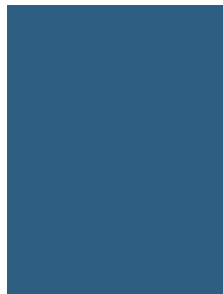
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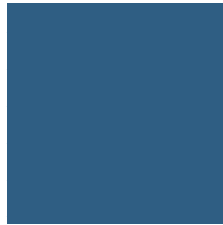
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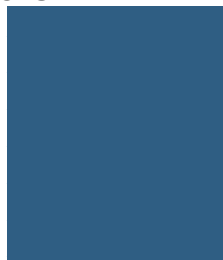
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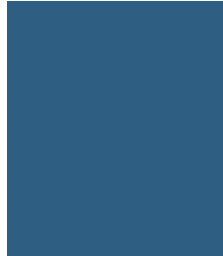
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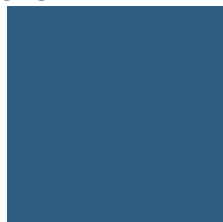
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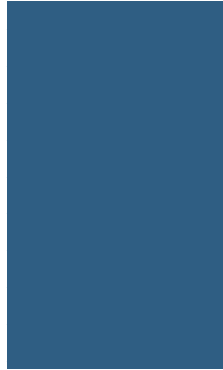
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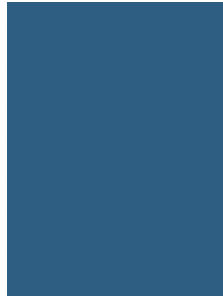
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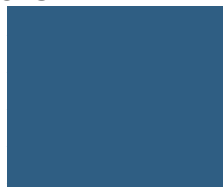
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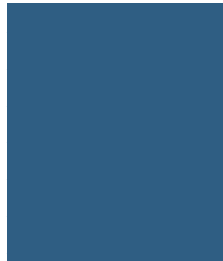
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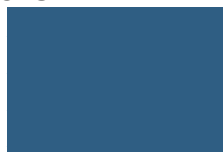
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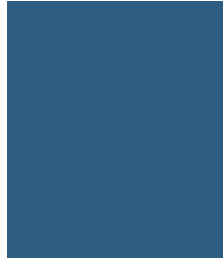
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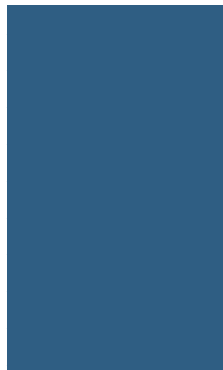
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