Chapter 10

Geysers

Abstract Geysers, springs that intermittently erupt boiling water, appear to be especially sensitive to earthquakes. As they are a surface manifestation of geothermal systems, their response to earthquakes provides a window into how earthquakes change hydrothermal systems and processes. The most common approach to document responses to earthquakes is to identify changes in the interval between eruptions. Sustained changes in eruption intervals may be caused by changes in permeability. Confirming what processes lead to changes at geysers is hampered by limited reliable, quantitative multi-parameter data sets.

10.1 Introduction

Geysers are springs that intermittently erupt mixtures of steam and liquid water (White 1967). They may be periodic or irregular, and their eruption behavior can change over time. A key outstanding question is “what processes, both internal and external to the geyser, influence the duration and volume of an eruption and the interval between eruptions” (Hurwitz and Manga 2017)? Earthquakes are one of those external influences.

Geysers are rare, with less than 1000 worldwide, and this number is decreasing owing to geothermal development of the hydrothermal systems they tap (Bryan 2005). Their rarity reflects the special conditions needed to create a geyser: a supply of heat that is large enough to boil water close to Earth’s surface, and a plumbing system that has the right geometry to permit episodic discharge. Other gases such as CO₂ may play a role in their eruption (Hurwitz et al. 2016; Ladd and Ryan 2016). Despite being rare, they are of interest for understanding the connection between earthquakes and water because they provide a window into how earthquakes affect hydrothermal systems. They may also serve as a model for understanding the processes that trigger the eruption of magmatic volcanoes and hydrothermal explosions. Figure 10.1 shows pictures of some geysers caught in the act of erupting, including some of those discussed in this chapter.

Fig. 10.1 Photos of geysers: **a** Lone Star geyser, Yellowstone National Park, **b** Great Geysir and Strokkur geysers, Iceland, and **c** Upper geyser basin, El Tatio, Chile. Photo **a** from S. Hurwitz USGS and **b** and **c** from the authors

Changes in the behavior of geysers are usually characterized by the interval between eruptions, hereafter abbreviated IBE, since this is the easiest attribute of eruptions to document. The volume erupted can be difficult to impossible to measure. The duration can also be tricky to define: some geyser eruptions begin with minor eruptions called preplay events (Kieffer 1989), and eruptions often taper off gradually. Geyser eruptions can be periodic (constant IBE), irregular, have a biomodal distribution of IBE, or exhibit chaotic features (Ingebritsen and Rojstaczer 1996).

10.1.1 *Response of Geysers to Earthquakes*

Geysers have long been known to be especially sensitive to earthquakes, as manifested by changes in the IBE. Examples include a geysering well in California, USA (Silver and Vallette-Silver 1992) and natural geysers in Yellowstone National Park,

USA (e.g., Marler 1964; Rinehart and Murphy 1969; Hutchinson 1985; Husen et al. 2004; Hurwitz et al. 2014).

There is no systematic pattern to responses after earthquakes. Among the many Yellowstone geysers that have been documented to respond to earthquakes, the IBE decreases at some and increases at others (Husen et al. 2004; Hurwitz et al. 2014). Figure 10.2 shows the IBE at two Yellowstone geysers and how they responded

Fig. 10.2 **a** Response of Daisy Geyser in Yellowstone to the M 7.9 Denali earthquake located 3100 km from the geyser. DFE indicates the time of the Denali earthquake in Alaska, USA. The grey curve is raw data and the black curve is smoothed data. Times under the curves show median eruption intervals before and after the earthquake and are averaged over weeks or days (the latter in parentheses) (from Husen et al. 2004). **b** A longer time series for Daisy geyser and Old Faithful geyser showing that the pool geyser (Daisy) that responded to the 2002 Denali earthquake also varies seasonally, and that Old Faithful did not respond to either the earthquake or vary over the course of a year. The red lines show earthquakes with the largest ground motions in Yellowstone National Park (from Hurwitz et al. 2014)

to 2002 M7.9 Denali earthquake in Alaska, 3100 km away from the geysers. The IBE changed suddenly after the earthquake and then recovered to its pre-earthquake value over a time period of months. In other cases, the IBE appears to change more gradually (Fig. 10.3). Interestingly, some geysers that responded to large earthquakes in 1959 and 1983 did not respond to the 2002 Denali earthquake (Husen et al. 2004).

The vertical red lines in Fig. 10.2 show the time of other large teleseismic and regional events. None changed the eruptions of Daisy and Old Faithful geysers. The Denali earthquake produced the largest peak dynamic stresses during this time period, enhanced by directivity effects. Dynamic stresses less than 0.02 MPa have not changed the eruptions of any geysers in Yellowstone (Hurwitz et al. 2014).

Fig. 10.3 Response of Old Faithful geyser to regional earthquakes shown in panel (a). For all three earthquakes, panel (b), the eruption interval appears to increase. The change in eruption interval may be gradual, panel (c), unlike Daisy geyser (Fig. 10.2). The dashed curve indicates a time period without data (from Hurwitz et al. 2014)

The most remarkable feature of the response of geysers to earthquakes is the distance from the epicenter at which they show a sensitivity. They respond to earthquakes that produce static strains $<10^{-7}$ and dynamic strains $<10^{-6}$ (Hutchinson 1985; Silver and Vallette-Silver 1992). The Denali earthquake that changed the eruptions of Daisy geyser (Fig. 10.2) has a peak dynamic stress of 0.14 MPa and energy density of $10^{-3.5}$ J/m³ (Hurwitz et al. 2014). Some geysers thus respond to earthquakes at distances far greater than that for changes in stream discharge (Chap. 7) and the occurrence of liquefaction (Chap. 11), and distances similar to the most sensitive water wells (Chap. 6).

10.1.2 *Response of Geysers to Other Sources of Stress*

Geysers may respond to longer term changes in tectonic stress or regional deformation. For example, the reactivation of dormant Steamboat Geyser in Yellowstone in 2018, the tallest active geyser, has been attributed to regional uplift produced by fluid ascent and accumulation (Wicks et al. 2020), though this conclusion is contested (Reed et al. 2021).

The response of geysers to non-seismic and non-tectonic strains has been the subject of many studies, and conclusions are not consistent. Some of the inconsistencies may be the result of errors and gaps in eruption catalogs (Nicholl et al. 1994). Earth tides (Rinehart 1972a, b) and barometric pressure variations (White 1967) have been reported to influence geyser eruptions in Yellowstone. Rojstaczer et al. (2003), in contrast, found that Yellowstone geysers are not sensitive to Earth tides and barometric pressure variations—strains typically smaller than 10^{-7} . This is comparable to and larger than the static strains generated by earthquakes that changed eruption intervals.

Figure 10.2 has data for tens of thousands of eruptions providing an opportunity to identify responses. Old Faithful is not sensitive to barometric pressure changes or solid Earth tides, but the pool geyser, Daisy geyser, is sensitive to surface temperature and wind speed. Munoz-Saez et al. (2015a) recorded thousands of eruptions of a small geyser in El Tatio, Chile, and found no sensitivity to air temperature, atmospheric pressure, or tides. The sensitivity of pool geysers to environmental conditions makes sense: enhanced heat loss during winter or by wind increases the time needed for water to reach boiling conditions.

Geysers also respond to hydrological changes. Figure 10.2 shows seasonal variations of IBE for Daisy geyser. Hurwitz et al. (2008) document clear seasonal variations in IBE and a response to long term trends in precipitation. The latter observation indicates that recharge to the geyser plumbing system influences IBE.

10.2 Mechanisms

In order to understand how earthquakes can influence geysers it is first necessary to understand how and why geysers erupt. We thus first review published models for the processes that operate within geysers and then identify how earthquakes might influence these processes.

10.2.1 *How Do Geysers Work?*

The evolution of a geyser eruption provides insights and constraints into the processes that lead to their eruption. Geyser eruptions begin with the discharge of water at temperatures below the boiling point; this is followed by a fountain dominated by liquid which progressively becomes more steam-rich before ending with a quiet phase (White 1967; Karlstrom et al. 2013). Bubbles and steam play a central role in transferring heat to warm water in the conduit and in driving the eruption (Kieffer 1989; Adelstein et al. 2014).

Here we focus on intermittency as this is the property that is documented to change after earthquakes. Three different types of models have been proposed to explain why geysers are intermittent.

- (1) Ingebritsen and Rojstaczer (1993, 1996) develop a numerical model for ground-water flow and heat transport in an idealized geyser system that consists of a conduit and surrounding matrix. They show that the observed sequence of events at a geyser can occur periodically for specific combinations of heat flow, conduit and matrix permeabilities, and conduit length.
- (2) Steinberg et al. (1982a, b, c) present a model for geysers in which eruption is driven by the nucleation of steam bubbles in a superheated fluid. The IBE in this case is governed by the time it takes to achieve this degree of superheating. Hurwitz and Manga (2017) note that there is no strong evidence for superheating in natural geysers.
- (3) Many geysers appear to have cavities beneath the conduit feeding the eruption, observed directly with video cameras (e.g., Belousov et al. 2013), imaged seismically (e.g., Vandemeulebrouck et al. 2013; Wu et al., 2017) or inferred from ground deformation (e.g., Vandemeulebrouck et al. 2014; Ardid et al. 2019). These “bubble traps” can accumulate water at the boiling point and then initiate and sustain an eruption for an extended period of time. Geyser eruptions can influence nearby geysers indicating that the plumbing systems are not isolated to a single geyser (e.g., Munoz-Saez et al. 2015b) (Fig. 10.4).

Fig. 10.4 Schematic illustration of a geyser illustrating the plumbing system below the surface. The surface manifestation of hydrothermal systems can include fumaroles (all vapor), hot springs (continuous discharge), and geysers (episodic eruption). Direct observations of Hutchinson et al. (1997) and Belousov et al. (2013) confirm that the main vent of geysers consists of a complex network of conduits with multiple constrictions. Bubble traps have been proposed to be required for geysers (Belousov et al. 2013) however geysering wells would appear to contradict this assertion (Rudolph et al. 2012) (from Hurwitz and Manga 2017 after Lloyd 1975)

10.2.2 Mechanisms for Altering Eruptions

Changes in eruption interval can be caused by changes in permeability of the conduit and/or surrounding matrix. As the permeability of the conduit is very high, changes in the matrix that governs conduit recharge are more likely (Ingebritsen and Rojstaczer 1993). That recharge influences IBE is highlighted by the climate sensitivity of

geysers (Hurwitz et al. 2008; Hurwitz et al. 2020). Changes in conduit length by reopening blocked and preexisting fractures is an alternative possibility (Ingebritsen et al. 2006). The mechanisms by which the permeability changes or fractures get unblocked remain unclear, but as with hydrological responses reviewed previously, it is likely that dynamic strains cause such changes. For example, the static stress changes from the Denali earthquake in Yellowstone were less than 10 Pa (Husen et al. 2004), far too small to have an impact, whereas the dynamic stresses were 4 orders of magnitude larger. The gradual post-earthquake changes in IBE can be explained by gradual fracture sealing and reduction of matrix permeability as has been documented at Yellowstone (e.g., Dobson et al. 2003).

Steinberg et al. (1982c) create a laboratory model of a geyser in which nucleation of bubbles in a superheated fluid drives periodic eruptions. They also show that vibrations can trigger eruptions, presumably by lowering the degree of superheating needed to initiate an eruption. This mechanism does not obviously explain why IBE sometimes increases, nor why changes are sustained over multiple eruptions.

Simultaneous measurements of discharge and eruption intervals may provide the key information to test models and identify the origin of seismic responses. It may be possible to distinguish between these two end members with additional measurements. In the first case, increased matrix permeability will lead to faster recharge and hence an increase in the mean discharge, though the magnitude of changes depends on details of the conduit and matrix properties (Ingebritsen and Rojstaczer 1996). Measuring discharge is not easy. The duration of eruption can be used as proxy for discharge, assuming choked flow conditions apply throughout the eruption (Kieffer 1989) but not all geysers reach those conditions nor are they sustained throughout an eruption (e.g., Karlstrom et al. 2013). Measurements at Old Faithful, Yellowstone (Kieffer 1989), the Calistoga geyser, California (Shteinberg 1999), Crystal Geyser, Utah (Gouveia and Friedman 2006) and lab models (Shteinberg 1999) are consistent with IBE scaling with the duration of the previous eruption for some geysers. Other geysers, however, have more complex relationships between eruption intervals: Eibl et al. (2020) found that Strokkur geyser, Iceland (Fig. 10.1) has a predictable waiting time for an eruption, but that the duration and pattern of subsequent eruptions are not predictable. Regardless of the regularity of eruptions, however, if the IBE is dominated by nucleation, then the mean discharge will be unaffected—changes in the IBE will be accompanied by equivalent changes in the amount of fluid erupted.

10.3 Conclusions About Geysers

Of the hydrological responses reviewed thus far, geysers stand out because some are extremely sensitive to seismic waves. The property of geysers used to document these changes is the interval between eruptions (IBE). With this one measure alone, it is challenging to distinguish between hypotheses about the origin of changes in the IBE.

If eruptions are controlled by properties of the geyser plumbing system, because changes in IBE are sustained over multiple eruptions, permanent changes must occur in this plumbing system. Ingebritsen and Rojstaczer (1996) argue changes most likely occur in the recharge to the geyser conduit which is governed by matrix permeability. If IBE is instead controlled by the ability of bubbles to nucleate in a supersaturated system, then it is possible that the earthquake created lower energy nucleation sites that permit eruption at smaller supersaturations.

One challenge in identifying the sensitivity of geysers to external forcing is a limited amount of reliable, quantitative data. Our present ability to monitor geysers with temperature loggers, video, and seismic instrumentation should allow the requisite data sets to be collected and expanded.

References

- 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* 285:129–135
- Ardid A, Vera E, Kelly C, Manga M, Munoz-Saez C, Maksymowicz A, Ortega-Culaciati F (2019) Geometry of geyser plumbing inferred from ground deformation. *J Geophys Res Solid Earth* 124:1072–1083. <https://doi.org/10.1029/2018JB016454>
- 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* 41:387–390
- Bryan TS (2005) Geysers: what they are and how they work, 2nd edn. Mountain Press Publishing, Missoula, Montana, p 69
- Dobson PF, Kneafsey TJ, Hulen J, Simmons A (2003) Porosity, permeability, and fluid flow in the Yellowstone geothermal system, Wyoming. *J Volcanol Geotherm Res* 123:313–324
- Eibl EPS, Hainzl S, Vesely NIK et al (2020) Eruption interval monitoring at Strokkur Geyser, Iceland. *Geophys Res Lett* 47:e2019GL085266. <https://doi.org/10.1029/2019GL085266>
- Gouveia FJ, Friedmann SJ (2006) Timing and prediction of CO₂ eruptions from Crystal Geyser, Utah. <https://doi.org/10.2172/897988>
- Hurwitz S et al (2020) Yellowstone's Old Faithful Geyser shut down by a severe thirteenth century drought. *Geophys. Res. Lett.* 47, e2020GL089871.
- Hurwitz S, Kumar A, Taylor R, Heasler H (2008) Climate-induced variations of geyser periodicity in Yellowstone National Park, USA. *Geology* 36:451–454
- 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* 119:1718–1737
- Hurwitz S, Clor LE, McCleskey RB, Nordstrom DK, Hunt AG, Evans WC (2016) Dissolved gases in hydrothermal and geyser eruptions at Yellowstone. *Geology* 44:235–238
- Hurwitz S, Manga M (2017) The fascinating and complex dynamics of geyser eruptions. *Ann. Rev Earth Planet Sci* 45:31–59. <https://doi.org/10.1146/annurev-earth-063016-015605>
- Husen S, Taylor R, Smith RB, Heasler H (2004) Changes in geyser eruption behavior and remotely triggered seismicity in Yellowstone National Park induced by the 2002 M 7.9 Denali fault earthquake. *Geology* 32:537–540
- Hutchinson RA (1985) Hydrothermal changes in the upper Geyser Basin, Yellowstone National Park, after the 1983 Borah Peak, Idaho, earthquake. In Stein RS, Bucknam RC, USGS Open File Report 85-0290A:612–624

- Hutchinson RA, Westphal JA, Kieffer SW (1997) In situ observations of Old Faithful Geyser. *Geology* 25:875–878
- Ingebritsen SE, Rojstaczer S (1993) Controls of geyser periodicity. *Science* 262:889–892
- Ingebritsen SE, Rojstaczer S (1996) Geyser periodicity and the response of geysers to deformation. *J Geophys Res* 101:21891–21905
- Ingebritsen SE, Sanford WE, Neuzil C (2006) *Groundwater in geologic processes*, 2nd edn. Cambridge Univ Press, 341 pp
- Karlstrom L, Hurwitz S, Sohn R, Vandemeulebrouck J, Murphy F, Rudolph ML et al (2013) Eruptions at Lone Star Geyser, Yellowstone National Park, USA: 1. Energetics and eruption dynamics. *J Geophys Res Solid Earth* 118:4048–4062. <https://doi.org/10.1002/jgrb.50251>
- Kieffer SW (1989) Geologic nozzles. *Rev Geophys* 27:3–38
- Ladd B, Ryan MC (2016) Can CO₂ trigger a thermal geyser eruption? *Geology* 44:307–310
- Lloyd BF (1975) *Geology of Whakarewarewa hot springs*. Wellington NZ Government Printing
- Manga M, Brodsky EE (2006) Seismic triggering of eruptions in the far-field: volcanoes and geysers. *Ann Rev Earth Planet Sci* 34:263–291
- Marler GD (1964) Effects of the Hebgen Lake earthquake of August 27, 1959, on the hot spring of the Firehole Geysers basins, Yellowstone National Park. *US Geol Surv Prof Paper* 435-Q:185–197
- Munoz-Saez C, Manga M, Hurwitz S, Rudolph ML, Namiki A, Wang CY et al (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 Geoth Res* 292:41–55. <https://doi.org/10.1016/j.jvolgeores.2015.01.002>
- Munoz-Saez C, Namiki A, Manga M (2015b) Geyser eruption intervals and interactions: examples from el Tatio, Atacama, Chile. *J Geophys Res Solid Earth* 120:7490–7507. <https://doi.org/10.1002/2015JB012364>
- Nicholl MW, Wheatcraft SW, Tyler SW (1994) Is old faithful a strange attractor? *J Geophys Res* 99:4495–4503
- Reed MH et al. (2021) The 2018 reawakening and eruption dynamics of Steamboat Geyser, the world's tallest active geyser. *Proc Nat Acad Sci* 118: e2020943118
- Rinehart JS (1972a) Fluctuations in geyser activity caused by variations in Earth tidal forces, barometric pressure, and tectonic stress. *J Geophys Res* 77:342–350
- Rinehart JS (1972b) 18.6 year tide regulates geyser activity. *Science* 177:346–347
- Rinehart JS, Murphy A (1969) Observations on pre- and post-earthquake performance of old faithful Geyser. *J Geophys Res* 74:574–575
- 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. <https://doi.org/10.1029/2003GL-17853>
- Rudolph ML, Manga M, Hurwitz S, Johnston M, Karlstrom L, Wang CY et al (2012) Mechanics of old faithful Geyser, Calistoga, California. *Geophys Res Lett* 39:L24308. <https://doi.org/10.1029/2012GL054012>
- Sin-Mei Wu, Kevin M. Ward, Jamie Farrell, Fan-Chi Lin, Marianne Karplus, Robert B. Smith (2017) Anatomy of Old Faithful From Subsurface Seismic Imaging of the Yellowstone Upper Geyser Basin. *Geophysical Research Letters* 44 (20):10,240–10,247
- Silver PG, Valette-Silver NJ (1992) Detection of hydrothermal precursors to large Northern California earthquakes. *Science* 257:1363–1368. <https://doi.org/10.1126/science.257.5075.1363>
- Steinberg GS, Merzhanov AG, Steinberg AS (1982a) Geyser process: theory, modeling and field experiment, Part 2. A laboratory models of a geyser. *Mod Geol* 8:61–74
- Steinberg GS, Merzhanov AG, Steinberg AS (1982b) Geyser process: theory, modeling and field experiment, Part 3. On metastability of water in geysers. *Mod Geol* 8:75–78
- Steinberg GS, Merzhanov AG, Steinberg AS (1982c) Geyser process: theory, modeling and field experiment, Part 4. On seismic influence on geyser regime. *Mod Geol* 8:79–86
- Shteinberg AS (1999) An experimental study of geyser eruption periodicity. *Doklady Phys* 44:305–308

- Vandemeulebrouck J, Roux P, Cros E (2013) The plumbing of old faithful Geyser revealed by hydrothermal tremor. *Geophys Res Lett* 40:1989–1993. <https://doi.org/10.1002/grl.50422>
- Vandemeulebrouck J, Sohn RA, Rudolph ML, Hurwitz S, Manga M, Johnston MJ et al (2014) Eruptions at Lone Star Geyser, Yellowstone National Park, USA: 2. Constraints on subsurface dynamics. *J Geophys Res Solid Earth* 119:8688–8707. <https://doi.org/10.1002/2014JB011526>
- White DE (1967) Some principles of geyser activity, mainly from Steamboat Springs, Nevada. *Am J Sci* 265:641–684
- Wicks CW, Dzurisin D, Lowenstern JB, Svarc J (2020) Magma intrusion and volatile ascent beneath Norris Geyser Basin, Yellowstone National Park. *J Geophys Res* 125:e2019JB018208. 10.1029/

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