Climate-induced variations of geyser periodicity in Yellowstone National Park, USA

Shaul Hurwitz
U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025, USA
Ashish Kumar
Department of Statistics, Stanford University, Stanford, California 94305, USA
Ralph Taylor
Henry Heasler
National Park Service, Yellowstone Center for Resources, Yellowstone National Park, Wyoming 82190, USA

ABSTRACT

The geysers of Yellowstone National Park, United States, attract millions of visitors each year, and their eruption dynamics have been the subject of extensive research for more than a century. Although many of the fundamental aspects associated with the dynamics of geyser eruptions have been elucidated, the relationship between external forcing (Earth tides, barometric pressure, and precipitation) and geyser eruption intervals (GEIs) remains a matter of ongoing debate. We present new instrumental GEI data and demonstrate, through detailed time-series analysis, that geysers respond to both long-term precipitation trends and to the seasonal hydrologic cycle. Responsiveness to long-term trends is reflected by a negative correlation between the annual averages of GEIs and stream flow in the Madison River. This response is probably associated with long-term pressure changes in the underlying hydrothermal reservoir. We relate seasonal GEI lengthening to snowmelt recharge.

Keywords: geyser, climate, Yellowstone, time-series analysis, hydrothermal processes, periodicity, Old Faithful.

INTRODUCTION

Multiyear and seasonal cyclic variations in the hydrosphere can induce large-scale deformation of the continental crust (Blewitt et al., 2001) and slow slip in subduction zones (Lowry, 2006), may modulate earthquake occurrence (Christiansen et al., 2005; Heki, 2001; Saar and Manga, 2003), and correlate with volcanic eruptions (Mason et al., 2004). Geysers, which are intermittently discharging hot springs or fountains driven by steam and non-condensable gas, should potentially also respond to these cyclic variations, because one of the major controls on their dynamics is the influx of water (Ingebritsen and Rojstaczer, 1993). A systematic investigation of climate-induced changes on geyser dynamics has never been performed for three main reasons. First, geysers are rare; fewer than 1000 exist worldwide (Bryan, 1995); second, "Geysers are exceedingly complex hot springs, no two of which are alike" (White and Marler, 1972, p. 5825); and third and most important, continuous (year round) and long-term data on geyser eruption intervals (GEIs), the most common parameter used to quantify geyser dynamics, were lacking until recently.

Physical models of geyser eruption dynamics (Fournier, 1969; Ingebritsen and Rojstaczer, 1993, 1996; Kedar et al., 1998; Kieffer, 1989, 1984; Rinehart, 1980) are primarily based on observations and measurements at the Upper Geyser Basin in Yellowstone National Park (Fig. 1), particularly in Old Faithful Geyser (Birch and Kennedy, 1972; Hutchinson et al., 1997; Jaggar, 1898; Kedar et al., 1996; Kieffer, 1984; Rinehart, 1980) (Fig. 1). A geyser eruption occurs when the temperature in the geyser conduit exceeds the boiling point; at that time, a pressure-release wave propagates through the water column, causing widespread boiling and forcing liquid water and steam up and out of the conduit. The GEI of a geyser reflects a narrow balance between the supply of water into a shallow subsurface reservoir, an intense source of heat, and rock permeability (Ingebritsen and Rojstaczer, 1993). Because of this delicate balance, and because eruptive intervals are significantly influenced by neighboring and distant geysers

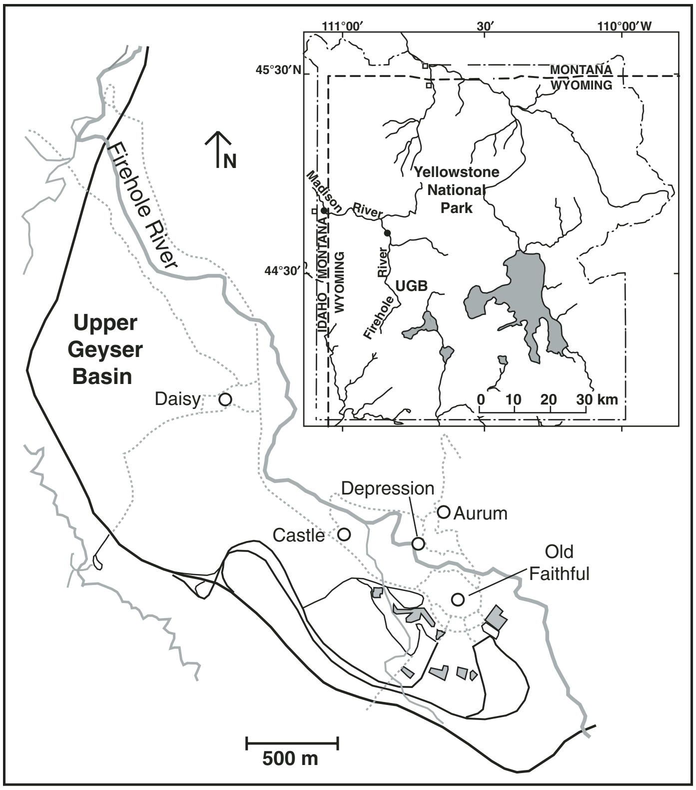

Figure 1. Map of Upper Geyser Basin (UGB) showing locations of geysers mentioned in this study (open circles). Inset: Map of Yellowstone National Park, showing U.S. Geological Survey stream gages on the Firehole and Madison Rivers (filled circles).

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(Rojstaczer et al., 2003), eruption times of only a few geysers in Upper Geyser Basin are predicted by park rangers. The nonlinear GEI pattern of Old Faithful, the most famous geyser, serves as a prime example in statistics textbooks (Chatterjee et al., 1995; Dekking et al., 2005).

The search for possible correlations between external forces and GEIs has attracted scientists for decades (Rinehart, 1972; Rojstaczer et al., 2003; White, 1967; White and Marler, 1972), because such a correlation might permit quantitative inference on the forces controlling geyser eruptions. Nevertheless, the existence of correlations remains controversial. In a recent experiment conducted at several geysers in the Upper Geyser Basin, the influence of Earth tides on GEIs was undetected and the possible effect of atmospheric pressure variations was found to be small (Rojstaczer et al., 2003). In contrast, there is clearly a relationship between large earthquakes and GEIs (Husen et al., 2004; Hutchinson, 1985; Manga and Brodsky, 2006; Rinehart, 1972). This relation is complex, because not all geysers respond to a given earthquake, and of those that do, some eruption intervals lengthen whereas others shorten (Husen et al., 2004).

DATA

Newly available continuous data on GEIs, based on instrumental measurements with a temperature sensor in the geyser outflow channels, have allowed us to search for a possible correlation between the interannual and intraannual hydrological cycle and GEIs. We analyze data from four geysers in the Upper Geyser Basin (Fig. 1) for which instrumental data are available for 1997 or 1998 through 2006 (http://www.geyserstudy.org), and for which the time series is sufficiently complete to permit formal quantitative analysis.

There is a longer time series For Old Faithful. Data from 1937–1956 and 1997–2002 are based on visual observations by park rangers (Stephens, 2002), and the data from 2003–2006 are based on year-round measurements by a temperature sensor.

For the interannual analysis of Daisy, Castle, Aurum, and Depression Geysers, we used data only from 1 July to 30 September because prior to 2003 data from non-summer months are either missing or incomplete (many gaps). The Old Faithful analysis is based on ranger observations for 1997–2002 (Stephens, 2002) and instrumental data from 1 July to 30 September for 2003–2006.

In the extreme climate conditions of Yellowstone, instrument malfunction is inevitable, especially in the winter months. In cases, this leads to unrecorded geyser eruptions, which in the time series leads to an overly long apparent GEI. In very few cases the false detection of an eruption was noted. To overcome artifacts of instrumental problems, we applied a rigorous criterion to remove outliers from all GEI data sets; data were filtered by removing any interval value that is greater than double or less than half of the previous and consecutive eruption intervals.

STATISTICAL ANALYSIS

To explore for links between multiyear trends of geyser periodicity and other hydrologic processes, we calculate coefficients of cross correlation between the arithmetic mean of GEIs each year and the average annual water discharge in the Madison River. We use data from the Madison River (http://waterdata.usgs.gov/wy/nwis/uv/?site_no = 06037500&agency_cd = USGS) rather than the Firehole River, which drains the Upper Geyser Basin (http://waterdata.usgs.gov/mt/nwis/nwisman/?site_no = 06036905&agency_cd = USGS), because data from the Firehole River are available only from 2002. The high degree of cross correlation (coefficient of 0.99) between the daily water discharges in the Firehole and Madison Rivers for the period 2002–2006 suggests that this approach should introduce negligible error.

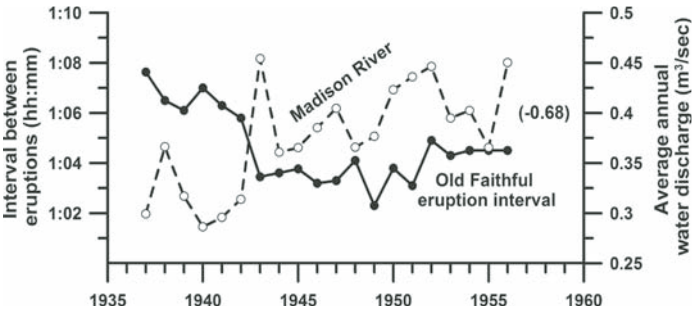

Figure 2. Multiyear mean Madison River discharge (dashed curve and open circles) and Old Faithful eruption intervals (solid curve and filled circles) for the period 1937–1956. Old Faithful data are based on Yellowstone National Park ranger observations (Stephens, 2002). Number in parentheses is coefficient of cross correlation between the two time series.

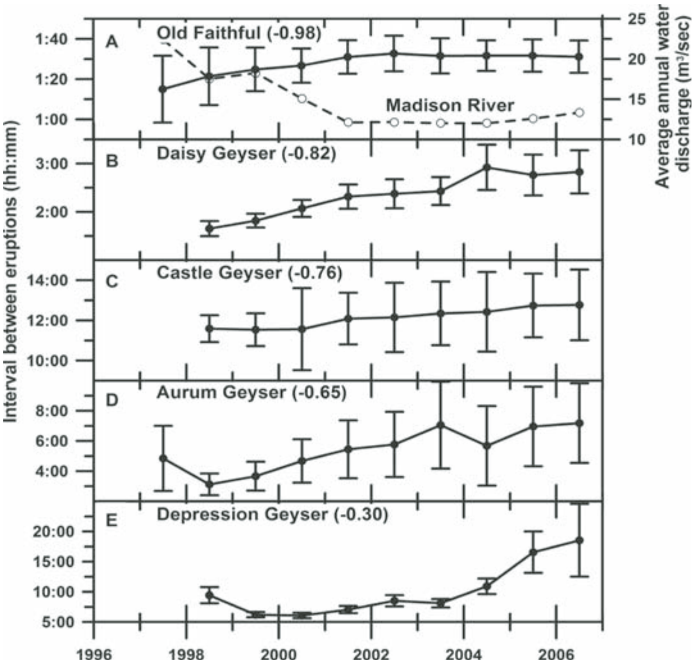

Figure 3. Multiyear average eruption intervals and 2σ error bars. A: Old Faithful Geyser. B: Daisy Geyser. C: Castle Geyser. D: Aurum Geyser. E: Depression Geyser. Except for Old Faithful data, average intervals are for period from 1 July to 30 September. Average annual water discharge in the Madison River (dashed line and empty circles) is also shown in A. Numbers in parentheses are coefficients of cross correlation between multiyear river discharge and geyser eruption intervals (GEI).

The GEI interannual temporal trends of the five analyzed geysers correlate negatively with the trend of the Madison River discharge (Figs. 2 and 3); as mean annual water discharge in the river decreases, the GEIs lengthen. The long-term cross correlation between Old Faithful's annual average GEI and Madison River discharge is especially significant; for the period between 1937 and 1956, for which park ranger observations are available (Stephens, 2002), the coefficient of cross correlation is –0.68, and for the period between 1967 and 2006 it is –0.98. The 1959 Hebgen Lake, 1975 Central Plateau, and 1983 Borah Peak earthquakes induced lengthening of Old Faithful's GEI that lasted for several years (Hutchinson, 1985). Thus in years following a major earthquake any climate-induced control on Old Faithful's GEI could be masked. There are similar relations between the Madison River discharge and the shorter-term records of Daisy, Castle, Aurum, and Depression Geysers GEIs, and similarly high values of cross correlation (Fig. 3), supporting the notion of a basin-wide

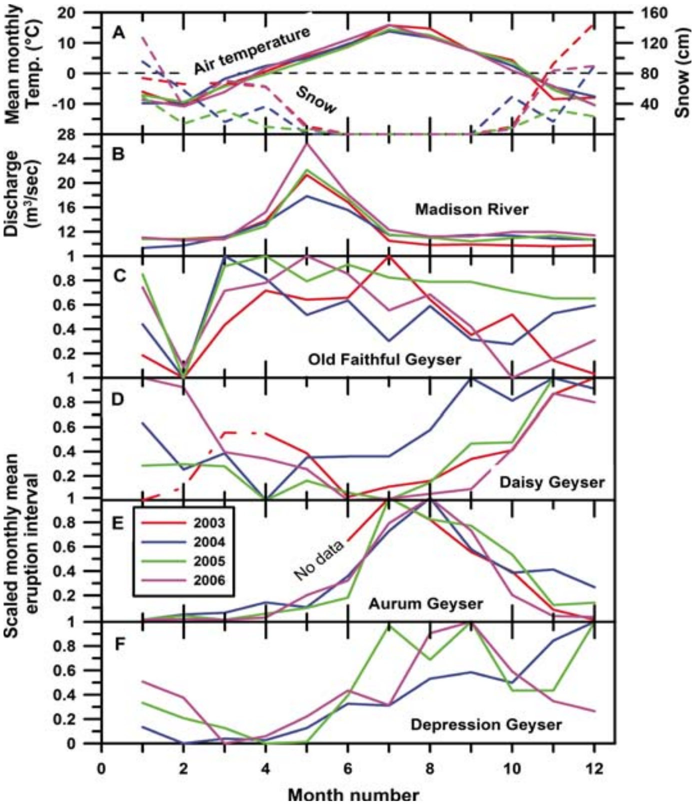

Figure 4. A: Average monthly air temperature and snowfall in Old Faithful (http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwDI~StnSrch~StnID~20023004). B: Average monthly Madison River discharge. C: Average monthly Old Faithful scaled geyser eruption intervals (GEIs). D: Average monthly Daisy Geyser scaled GEI. E: Average monthly Aurum Geyser scaled GEI. F: Average monthly Depression Geyser scaled GEI. Dash-dot segment for Daisy Geyser in 2003 represents continued response to November 2002 Denali earthquake in Alaska (Husen et al., 2004).

process. The computed cross-correlation coefficients for these data are two orders of magnitude greater than the coefficients calculated using 100 randomly generated time series of equal length.

To test for a seasonal signal, we calculated the monthly average GEIs of four geysers with sufficient year-round instrumental data to permit formal analysis (Fig. 4). Analysis of daily and weekly GEI data resulted in a rather noisy time series, mainly because of data gaps. The maximum seasonal peak-to-peak amplitudes of monthly averages (difference between shortest and longest intervals) are 2.7, 45, 258, and 687 minutes for Old Faithful, Daisy, Aurum, and Depression, respectively. Since the GEI of Old Faithful has a relatively narrow distribution around the mean, the data were filtered to include only intervals in the range of 85–105 min to enhance the signal-to-noise ratio. This filtering eliminated 15% of the intervals from the data set, mainly the short intervals. It should be noted that Old Faithful's GEI displays a bimodal distribution with very few observations intermediate in length (Kieffer, 1984). However, the percentage of short GEIs has decreased recently and accounted for only 2.6% (in 2004) to 4.5% (in 2003) of the total annual eruptions between 2003 and 2006.

We scaled the monthly average values for each year between 0 (month with shortest intervals) and 1 (month with longest interval) (Fig. 4). We then computed the cross correlation between the monthly average GEI for each year and the monthly average discharge of the Madison River and searched for the phase shift (with 1 month resolution) that results in the highest degree of cross correlation (Table 1). For the four years studied, the phase shifts that result in the highest degree of cross correlation are 10–11, 6, 2–3, and 3–5 months for Old Faithful, Daisy, Aurum, and Depression, respectively (with two exceptions in bold labels in Table 1). However, the cross-correlation coefficients for Old Faithful at zero phase shift are also relatively high (highest in 2006), suggesting that interval lengthening might be synchronous with peak Madison River discharge.

TABLE 1. CALCULATED LAG TIMES AND CROSS CORRELATIONS

	2003		2004		2005		2006	
Geyser	ϕ (months)	r^2	ϕ (months)	r^2	ϕ (months)	r^2	ϕ (months)	r^2
Old Faithful	0	0.37	0	0.29	0	0.24	0	0.6
	2	**0.7**						
	11	0.37	10	0.54	11	0.36	11	0.49
Daisy	0	–0.28	0	–0.39	0	–0.36	0	–0.34
	6	0.81	6	0.75	6	0.88	6	0.51
Aurum	0	0.26	0	–0.09	0	–0.24	0	–0.07
	2	0.87	3	0.93	2	0.79	3	0.88
Depression	n/a		0	–0.22	0	–0.45	0	–0.28
	n/a		**2**	**0.81**				
			5	0.59	3	0.47	4	0.77

Note: Calculated phase shift (ϕ) between monthly mean geyser eruption interval and the Madison River discharge and the computed coefficients of cross correlation (r^2) for no phase shift ($\phi = 0$) and for the shift that results in the highest degree of correlation.

GEYSER PERIODICITY AND THE HYDROLOGIC CYCLE

We propose a conceptual model that accounts for the long-term (decadal) and seasonal patterns of GEIs. Multiyear variability is controlled by pressure changes in the 200–215 °C reservoirs (Fournier, 1989) that feed the geyser. In years with high precipitation, the pressure in the reservoir increases, geyser conduits are replenished faster by hot water, boiling is achieved in a shorter time, and GEIs are shorter. Seasonal lengthening of intervals following peak river discharge results from percolation of cold recharge from the ground surface. Cooling of the geyser conduits, which causes lengthening of the intervals, may be controlled by geyser conduit dimensions; faster when the volume is smaller (Aurum and Depression), and slower as the volume increases (Daisy and Old Faithful). The much larger peak-to-peak amplitudes in the Aurum and Depression time series, compared with Old Faithful, also suggest a greater effect of cooling by meteoric recharge. Thus, GEIs respond to two competing processes; sourcing of hot water from the bottom and cold water from the top, consistent with models of geyser dynamics (Fournier, 1969; White, 1967; White and Marler, 1972).

Other processes that might cause the different phase shifts displayed by the geysers are small differences in geyser conduit permeability that have a profound effect on eruption intervals (Ingebritsen and Rojstaczer, 1993, 1996); the formation of ice sheets and cryogenic silica deposits at the ground surface (Channing and Butler, 2007), which may inhibit recharge of cold meteoric water; and entrainment of extremely cold air in winter months (Fig. 4A) (Hutchinson et al., 1997).

In summary, our statistical analysis indicates that geysers respond to both long-term precipitation trends and to the seasonal hydrologic cycle. Based on these observations, we propose that an extended period of drought in the region should result in GEI lengthening and perhaps even cessation of geysering. In years with high precipitation, the GEI should be more frequent.

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REFERENCES CITED

Birch, F., and Kennedy, G.C., 1972, Notes on geyser temperatures in Iceland and Yellowstone National Park, *in* Heard, H.C., et al., eds., Flow and fracture of rocks: American Geophysical Union Geophysical Monograph 16, p. 329–336.

Blewitt, G., Lavallee, D., Clarke, P., and Nurutdinov, K., 2001, A new global mode of earth deformation: Seasonal cycle detected: Science, v. 294, p. 2342–2345, doi: 10.1126/science.1065328.

Bryan, T.S., 1995, The geysers of Yellowstone (third edition): Niwot, University Press of Colorado, 463 p.

Channing, A., and Butler, I.B., 2007, Cryogenic opal-A deposition from Yellowstone hot springs: Earth and Planetary Science Letters, v. 257, p. 121–131, doi: 10.1016/j.epsl.2007.02.026.

Chatterjee, S., Handcock, M.S., and Simonoff, J.S., 1995, A casebook for a first course in statistics and data analysis: New York, John Wiley & Sons, 328 p.

Christiansen, L.B., Hurwitz, S., Saar, M.O., Ingebritsen, S.E., and Hsieh, P., 2005, Seasonal seismicity at western United States volcanic centers: Earth and Planetary Science Letters, v. 240, p. 307–321, doi: 10.1016/j.epsl.2005.09.012.

Dekking, F.M., Kraaikamp, C., Lopuhaä, H.P., and Meester, L.E., 2005, A modern introduction to probability and statistics. Understanding why and how: London, Springer-Verlag, 486 p.

Fournier, R.O., 1969, Old Faithful; a physical model: Science, v. 163, p. 304–305, doi: 10.1126/science.163.3864.304.

Fournier, R.O., 1989, Geochemistry and dynamics of the Yellowstone National Park hydrothermal system: Annual Review of Earth and Planetary Sciences, v. 17, p. 13–53, doi: 10.1146/annurev.ea.17.050189.000305.

Heki, K., 2001, Seasonal modulation of interseismic strain buildup in northeastern Japan driven by snow loads: Science, v. 293, p. 89–92, doi: 10.1126/science.1061056.

Husen, S., Taylor, R., Smith, R.B., and 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, v. 32, p. 537–540, doi: 10.1130/G20381.1.

Hutchinson, R.A., 1985, Hydrothermal changes in the upper Geyser Basin, Yellowstone National Park, after the 1983 Borah Peak, Idaho, earthquake, *in* Stein, R.S., and Bucknam, R.C., eds., Proceedings of Workshop 28—On the Borah Peak, Idaho, earthquake: U.S. Geological Survey Open-File Report OF 85–0290-A, p. 612–624.

Hutchinson, R.A., Westphal, J.A., and Kieffer, S.W., 1997, In situ observations of Old Faithful Geyser: Geology, v. 25, p. 875–878, doi: 10.1130/0091–7613(1997)025<0875:ISOOOF>2.3.CO;2.

Ingebritsen, S.E., and Rojstaczer, S.A., 1993, Controls on geyser periodicity: Science, v. 262, p. 889–892, doi: 10.1126/science.262.5135.889.

Ingebritsen, S.E., and Rojstaczer, S.A., 1996, Geyser periodicity and the response of geysers to deformation: Journal of Geophysical Research, v. 101, p. 21,891–21,905, doi: 10.1029/96JB02285.

Jaggar, T.A., Jr., 1898, Some conditions affecting geyser eruption: American Journal of Science, v. 5, p. 323–333.

Kedar, S., Sturtevant, B., and Kanamori, H., 1996, The origin of harmonic tremor at Old Faithful geyser: Nature, v. 379, p. 708–711, doi: 10.1038/379708a0.

Kedar, S., Kanamori, H., and Sturtevant, B., 1998, Bubble collapse as the source of tremor at Old Faithful Geyser: Journal of Geophysical Research, v. 103, p. 24,283–24,299, doi: 10.1029/98JB01824.

Kieffer, S.W., 1984, Seismicity at Old Faithful Geyser; an isolated source of geothermal noise and possible analogue of volcanic seismicity: Journal of Volcanology and Geothermal Research, v. 22, p. 59–95, doi: 10.1016/0377–0273(84)90035–0.

Kieffer, S.W., 1989, Geologic nozzles: Reviews of Geophysics, v. 27, p. 3–38, doi: 10.1029/RG027i001p00003.

Lowry, A.R., 2006, Resonant slow fault slip in subduction zones forced by climatic load stress: Nature, v. 442, p. 802–805, doi: 10.1038/nature05055.

Manga, M., and Brodsky, E., 2006, Seismic triggering of eruptions in the far field: Volcanoes and geysers: Annual Review of Earth and Planetary Sciences, v. 34, p. 263–291, doi: 10.1146/annurev.earth.34.031405.125125.

Mason, B.G., Pyle, D.M., Dade, W.B., and Jupp, T., 2004, Seasonality of volcanic eruptions: Journal of Geophysical Research, v. 109, doi: 10.1029/2002JB002293.

Rinehart, J.S., 1972, Fluctuations in geyser activity caused by variations in Earth tidal forces, barometric pressure, and tectonic stresses: Journal of Geophysical Research, v. 77, p. 342–350, doi: 10.1029/JB077i002p00342.

Rinehart, J.S., 1980, Geysers and geothermal energy: New York, Springer-Verlag, 223 p.

Rojstaczer, S., Galloway, D.L., Ingebritsen, S.E., and Rubin, D.M., 2003, Variability in geyser eruptive timing and its causes; Yellowstone National Park: Geophysical Research Letters, v. 30, no. 18, 1953, doi: 10.1029/2003GL017853.

Saar, M.O., and Manga, M., 2003, Seismicity induced by seasonal groundwater recharge at Mt. Hood, Oregon: Earth and Planetary Science Letters, v. 214, p. 605–618, doi: 10.1016/S0012–821X(03)00418–7.

Stephens, L., 2002, Old Faithful Geyser's lengthening intervals: GOSA (Geyser Observation and Study Association) Transactions, v. 7, p. 5–24.

White, D.E., 1967, Some principles of geyser activity, mainly from Steamboat Springs, Nevada: American Journal of Science, v. 265, p. 641–684.

White, D.E., and Marler, G.D., 1972, Fluctuations in geyser activity caused by Earth tidal forces, barometric pressure, and tectonic stresses: Comment: Journal of Geophysical Research, v. 77, p. 5825–5829, doi: 10.1029/JB077i029p05825.

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