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Variability in geyser eruptive timing and its causes: Yellowstone National Park

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[1] Field data from Upper Geyser Basin, Yellowstone, indicate that geyser frequency is less sensitive to elastic deformation than might be surmised from a review of the literature. Earth-tide influences are not identifiable in any of the geysers we monitored. Though atmospheric-pressure influences are observed, only long-period variations on the order of 5 mBars or greater seem to influence geyser frequency. Long-distance interconnections between geysers are common and add to the difficulty of identifying strain influences. Additional variations in geyser periodicity may be governed by the internal dynamics of the geysers rather than external influences. *INDEX TERMS:* 8424 Volcanology: Hydrothermal systems (8135); 1878 Hydrology: Water/energy interactions; 1829 Hydrology: Groundwater hydrology. **Citation:** Rojstaczer, S., D. L. Galloway, S. E. Ingebritsen, and D. M. Rubin, Variability in geyser eruptive timing and its causes: Yellowstone National Park, *Geophys. Res. Lett.*, *30*(18), 1953, doi:10.1029/2003GL017853, 2003.

1. Introduction

[2] Geysers are extremely rare hydrothermal features on the Earth's land surface. Perhaps less than 1000 exist worldwide, of which 200–500 occur in Yellowstone National Park [*Rinehart*, 1980; *Bryan*, 1995]. Numerical simulations suggest that their existence depends upon a combination of rock properties, thermal and hydrologic conditions rarely found in nature [*Ingebritsen and Rojstaczer*, 1993, 1996]. However, the characteristic behavior of geysers, intermittent discharge of water driven by steam or noncondensable gas, has also been observed on the ocean floor [*Tryon et al.*, 1999], and is analogous to any intermittent eruptive phenomena such as volcanic eruptions on Earth and other planetary bodies [*Kieffer*, 1989]. Hence, understanding geyser behavior can yield insight into many self-organized, intermittent processes in nature that result from localized inputs of energy and mass.

[3] Our initial interest in this topic was prompted by indications that geyser eruptive frequency could be changed by seismicity [*Marler and White*, 1977; *Hutchinson*, 1985; *Silver and Vallette-Silver*, 1992]. Given the magnitude of deformation induced by seismicity, there are other influences on eruptive timing that can be expected to be of equal or greater influence. Potential external influences on eruptive frequency, in addition to seismicity, include caldera resurgence and deflation, Earth tides [*Rinehart*, 1972], barometric pressure [*White*, 1967], availability of meteoric recharge [*White and Marler*, 1972] and wind [*Weir et al.*, 1992], particularly for interconnected pool geysers. However, analyses of eruptive timing and its influences based on field observations have been sparse and somewhat contradictory [*Rinehart*, 1972; *White and Marler*, 1972].

[4] Much of the ambiguity surrounding external controls on geyser frequency stems from a lack of definitive data. Despite extensive casual observation, time series of geyser-eruption frequency that are complete enough to permit formal analyses have been extremely rare. Even records of well-known geysers, such as Old Faithful, contain significant errors and gaps [*Nicholl et al.*, 1994].

2. Results

[5] We collected high-quality geyser-frequency time series from a number of geysers in an effort to understand in detail how and why geyser eruptive interval changes over time (raw geyser-frequency data available upon request: contact Steven Ingebritsen, seingebr@usgs.gov). The data that we rely on here come from six natural geysers in the Upper Basin in Yellowstone National Park (Big and Little Anemone, Daisy, Old Faithful, Plume, and Riverside; Table 1). We restricted our measurements to geysers that were known to be strongly periodic, and with eruptive intervals that were short relative to the period of monitoring. The results here have implications for the efficacy of geysers as strainmeters and provide some context for the results previously reported for pre-seismic behavior of a well-known artificial geyser in Calistoga, California [*Silver and Vallette-Silver*, 1992].

[6] Over the time period monitored, the character of the geysers' principal intervals ranged from unimodal to multimodal (Figure 1). None of the geysers examined, however,

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Table 1. Geysers Examined and Nature of the Time Series

Geyser	Time Series Length (days)	Method Used	Time Resolution (seconds)
Big Anemone	17	TV	15
Daisy	49 (1996) 101 (1997)	TV TDC	15 120
Little Anemone	17	TV	15
Old Faithful	101	TDC	60
Plume	14	TV	15
Riverside	101	TDC	120

Distances between these geysers range from a few m (Big Anemone to Little Anemone) to 1.6 km (Old Faithful to Daisy). TDC indicates that eruption time was inferred from increases in temperature in the drainage channel of the geysers; TV indicates that it was inferred from temperature changes in the geyser vent.

pass a Chi-square goodness-of-fit test for Gaussian distribution at the 90% confidence level. Old Faithful, which is generally considered to be bi-modal [*Bryan*, 1995], actually has a more complex character over the time period of monitoring.

[7] Variations in eruptive interval are significantly influenced by neighboring and distant geysers (Figure 2). Eruptions at one geyser presage a lengthening of eruptive interval at another over distances as large as 1.5 km (the distance between Daisy and Plume or Old Faithful). These causal relationships indicate that the reservoir(s) supplying water to the geysers generally are connected by highly permeable pathways. Every geyser was significantly influenced by at least one other monitored geyser during each period of observation. Assuming that diffusion of fluid pressure is responsible for the communication, dimensional analysis of the diffusion equation [e.g., *Bird et al.*, 1960] provides a lower bound on the permeability of the reservoir(s):

$$k > r^2(\alpha + n\beta)\mu/4t \qquad (1)$$

where k is permeability, r is the radial distance between geysers, α is rock compressibility, n is porosity, β is water compressibility, μ is water viscosity, and t is time. For a geyser 1.5 km distant to affect the timing of another geyser, the minimum permeability of the reservoir must be on the order of 10^{-11} m^2, assuming a rock compressibility of 1×10^{-10} Pa^{-1}, water at 200°C, and a propagation time of 10 minutes. This value of permeability is comparable to that observed in unaltered volcanic rocks in Hawaii (lower bound of 10^{-10} m^2 [*Ingebritsen and Scholl*, 1993]) and the Oregon Cascades (10^{-11} m^2 [*Manga*, 1996]).

[8] Examination of the power spectra (Figure 3) yields information about the potential for rock deformation to influence geyser eruption interval. Others have speculated that Old Faithful and Riverside respond to deformation induced by Earth tides [*Rinehart*, 1972] and to either pool-pressure variations or elastic deformation induced by variable atmospheric pressure (loading) at Daisy [*Bryan*, 1995]. In contrast, our data indicate no response to Earth tides at any of the geysers and no indication of a barometric response at diurnal or higher frequencies.

[9] While diurnal and semi-diurnal variations in eruptive interval that can be unequivocally attributed to Earth tides or barometric pressure are absent in the observed geysers, longer period changes in barometric pressure (~5 mBars or greater) have an observable influence on geyser behavior (Figure 2) at Big Anemone, Plume, Riverside, and possibly the last six weeks of observation at Old Faithful (Old Faithful after Feb. 25 in lower panel of Figure 2). There is no consistent sign to the correlations. The influence of barometric pressure appears to be highly localized in that a geyser that is insensitive to atmospheric pressure can be influenced by the eruption of a geyser that is sensitive to barometric pressure. This is even true for the relationship between Big Anemone and Little Anemone, geysers less than 4 m apart. The absence of a consistent sign in the response and its highly localized nature suggests that the long-period barometric response represents a sensitivity to

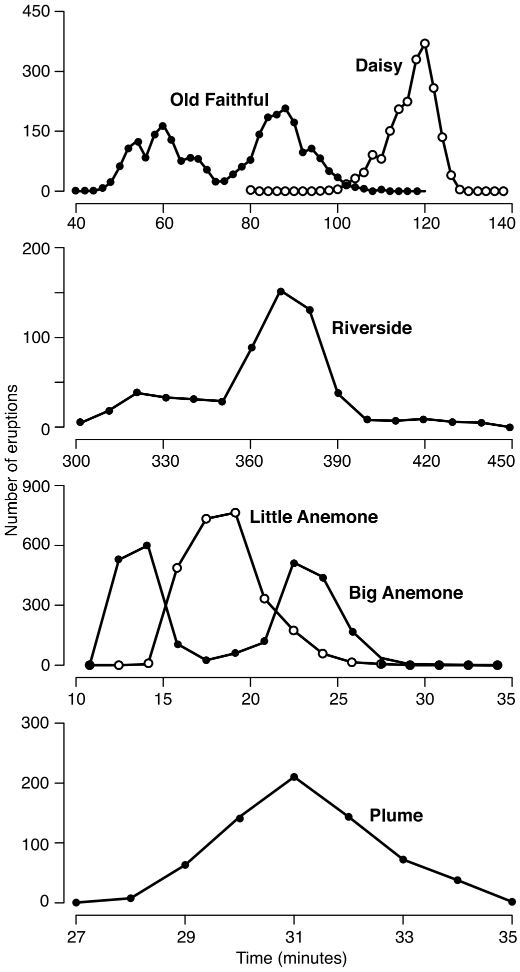
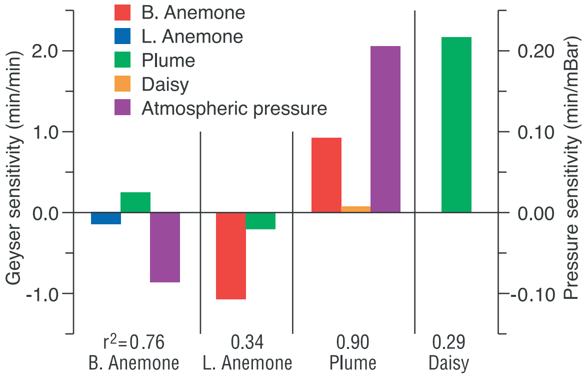


Figure 1. Histograms determined from the complete time series of each geyser. At all locations, the timing of geyser events was determined by measuring increases in water temperature. Temperature probes were inserted next to the vents of the geysers or in pools adjacent to the geyser. In areas or time periods where tourism prevented direct placement, the temperature probe was inserted in drainage channels less than 10 m from the geyser vent. The time delay between the onset of an eruption and our detection of that eruption was less than 40 seconds at all locations. When examining the time series, it is clear that in all of the records that either the geyser skipped a major eruption interval or the data recording system failed to pick up the eruption 2–5% of the time. It is impossible to determine whether these "skips" represent data error or geyser variability. We *a priori* assume that all of these skips represent data error.

a) Spring 1996



b) Winter 1997

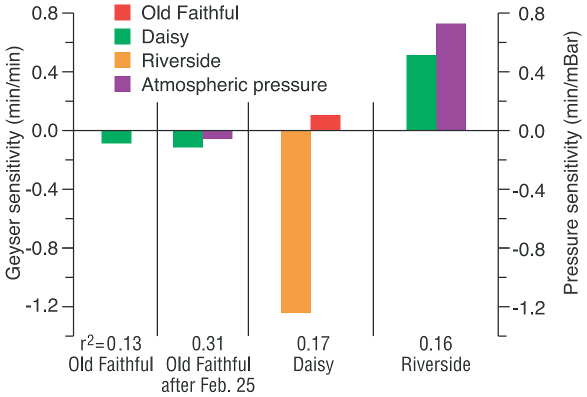


Figure 2. Best-fit linear models for interrelationships between geysers and atmospheric pressure for (a) spring 1996; (b) winter 1997. Big Anemone (upper panel), for example, shows significant influence from nearby geysers Little Anemone (4 m) and Plume (40 m) and is also influenced by long-period atmospheric-pressure variations. In contrast, Daisy (upper panel) is influenced by the relatively distant (1.5 km) Plume Geyser and not by atmospheric pressure. Models were determined by sequential multiple regression with independent parameters discarded if: (1) the p-value for the parameter in the regression was greater than 0.0001; (2) r^2 was less than 0.05 when used as the single independent parameter; or (3) the increase in r^2 associated with inclusion of the additional variable yielded an F statistic with a p-value greater than 0.0001. To examine for interrelationships between geysers, a low-pass finite-impulse response filter with a cutoff frequency of one cycle per day was applied to the geyser eruptive time series. To avoid correlation that might simply be related to similar responses to long-period atmospheric-pressure variations, a zero phase filter determined by regression with the atmospheric-pressure data was used to remove barometric effects in the records when they were present. Linear time trends were also filtered from the time series.

slight fluid pressure variations in the geyser conduit rather than a response to elastic deformation.

3. Discussion

[10] The absence of a statistically significant diurnal and semi-diurnal Earth-tide or atmospheric-pressure signal in any of these geysers suggests that geyser periodicity is insensitive to deformation on the order of less than 20–100 nanostrain given a diurnal amplitude of the atmospheric pressure signal of 1 mBar and assuming a rock compressibility of 10^{-9} to 10^{-10} Pa^{-1}.

[11] This insensitivity to strain has implications for the response of these geysers to earthquakes. For example, the interval between eruptions at Old Faithful was observed to change in response to the Borah Peak earthquake of 1983 (M 7.3) [*Hutchinson*, 1985]. The static strain produced at Yellowstone by Borah Peak is 100 nanostrain using analytical solutions of deformation due to fault shear [*Okada*, 1992] and the focal mechanism of the Borah Peak earthquake derived from geodetic data [*Stein and Barrientos*, 1985]. Unless there is significant frequency dependence in

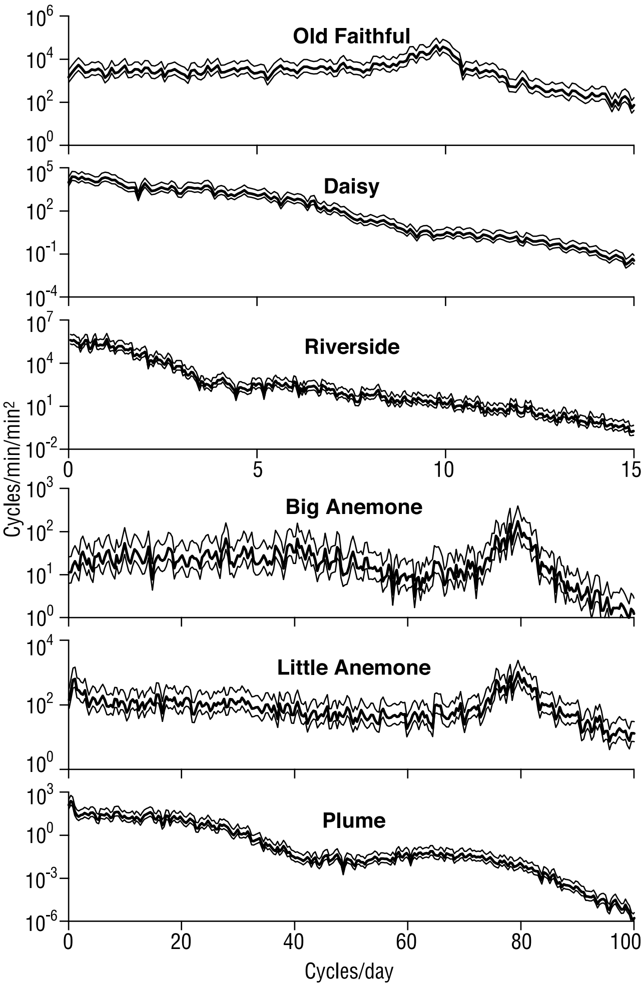


Figure 3. Power spectra (95% confidence intervals in thin black lines) determined from series of eruptive interval versus time, and representing variations about the major eruptive cycles in the data. Units for the y axes are cycles/min/min^2. Power spectra were determined from interpolated times series of eruptive interval versus time. Linear interpolation of these time series was performed at 1-minute intervals for all geysers. The resultant spectra by their nature do not contain any information about the dominant frequencies in eruptive interval, but instead reflect information about variability in those dominant frequencies.

the strain response of the geyser that obscures signals with frequency greater than one cycle per day, it is likely that the response of Old Faithful to earthquakes is due to earthquake-induced changes in the physical state of the geyser rather than a response to the induced elastic strain.

[12] One possible explanation for earthquake-induced timing changes is that the dynamic ground motion produced by these earthquakes is sufficient to alter, at least temporarily, local permeability. Permeability changes induced by seismicity have been inferred in response to the Loma Prieta earthquake [*Rojstaczer and Wolf*, 1992; *Rojstaczer et al.*, 1995] and theoretical modelling [*Ingebritsen and Rojstaczer*, 1993, 1996] indicates that permeability is a key control on eruptive timing. Assuming ground- motion amplitudes similar to the Landers earthquake (1992, **M** 7.3) at distances of 250 km from the epicenter, dynamic stress changes produced by the Borah Peak earthquake are on the order of 5 Bars [*Hill et al.*, 1993]. If such small dynamic stress changes are sufficient to induce permeability changes in the geyser system, then the state of stress in the shallow surface in Upper Geyser Basin is likely in a native state of incipient failure, as has been demonstrated to be the case at a number of localities in the western United States [e.g., *Townend and Zoback*, 2000]. It is worth noting that the Denali earthquake (2002, **M** 7.9) triggered seismicity at Yellowstone, indicating that portions of the upper crust there are in such a native state [*Husen et al.*, 2002].

[13] The field data suggest that geysers are likely not as sensitive to elastic deformation as might be surmised from a review of the literature. Adding to the difficulty of identifying strain influences are variations in geyser periodicity that are not driven by external influences, but appear to be governed by the internal dynamics of the geysers. Even Old Faithful, which is often viewed by the public at large as a strongly periodic geyser, has significant variability in its interval (Figure 1).

[14] The variability due to internal dynamics points to problems with ascribing observed changes in geyser character to tectonic strain. While changes in geyser periodicity synchronous with major earthquakes, like those observed at Old Faithful, are likely not coincidental, identifying tectonically induced changes requires that these events are synchronous with a period of otherwise relative quiescence in geyser eruptive variability. Our observations suggest that, in general, geyser behavior is uncoupled from small elastic strains comparable in magnitude to those associated with earthquakes. Changes in geyser periodicity preceding major tectonic events, like those inferred at Calistoga geyser [*Silver and Vallette-Silver*, 1992], cannot be expected in the geysers that we observed.

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