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Short communication

Measuring pressure in the source region for geysers, Geyser Valley, Kamchatka

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A B S T R A C T

Liquid water and steam that erupt at geysers are provided from deeper reservoirs, whose location, geometry and pressure are in general poorly known. Here we report measurements at two geysers from a field experiment in Geyser Valley, Kamchatka, designed to measure pressure in the reservoir providing water to the geysers. Water level in the geyser conduit was controlled, and the recharge to the geyser conduit was measured by monitoring the discharge needed to maintain the controlled water level. Recharge is not constant, but depends on water level in the geyser. From the relationship between water level in the conduit and recharge to the conduit, we can estimate the hydraulic head in the reservoir that supplies water to the geyser. Hydraulic head in the two studied reservoirs is within a couple of meters of the elevation of the geyser vents and the adjacent rivers. Pressures in the reservoirs are low enough that the reservoirs should not be prone to hydrothermal explosions, and explain why flooding of geysers in Geyser Valley terminated their eruptions.

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1. Introduction

Geysering, the episodic eruption of water, is an uncommon phenomenon. The rarity of geysers reflects an unusual combination of water supply, heat flux, and subsurface geometry — hot springs form if the flux of water is too large relative to that of heat, and fumaroles form if there is too much heat. Not surprisingly, then, geysers respond to changes in both subsurface and surface hydrology. The decrease in the number of active geysers (Bryan, 2005) is the result of geothermal development (Barrick, 2007) which reduces subsurface pressures and temperatures. Geysers also respond to changes in local surface hydrology such as water level in streams, or changes in climate such as droughts or floods (Hurwitz et al., 2008). The importance of external influences on geysering was highlighted by the disappearance of many of the geysers in Kamchatka's Geyser Valley following their burial by a landslide and river water impounded by that landslide (Kiryukhin et al., 2012).

The source of water and geometry of the plumbing system that feed geysers are in general poorly known, leading to contrasting conceptual models for why geysers erupt: Are they driven by decompression boiling at the surface (e.g., Bunsen, 1847) or the accumulation of steam at depth (e.g., Mackenzie, 1811; Belousov et al., 2013)? Are eruption intervals controlled by conduit and reservoir geometries (e.g., Steinberg et al., 1981a; Belousov et al., 2013) or by the permeability of the geyser conduit (e.g., Ingebritsen and Rojstaczer, 1993, 1996)? To better understand eruption evolution and the plumbing of geysers, recent studies have used downhole cameras to image geyser conduits (e.g., Hutchinson et al., 1997; Belousov et al., 2013), seismic and self-potential measurements to image the progression of eruptions (e.g., Kieffer, 1984; Kedar et al., 1996; Legaz et al., 2009; Cros et al., 2011; Vandemeulebrouck et al., 2013a), ground deformation to characterize the water source (e.g., Rudolph et al., 2012), and imaging and acoustic measurements to characterize eruption dynamics (e.g., Karlstrom et al., 2013).

There are a variety of approaches to identifying the source of waters that erupt: geothermometers can be used to estimate the temperature of deep geothermal reservoirs (e.g., Fournier, 1989), stable isotopes can be used to identify the recharge location of water (e.g., Hurwitz et al., 2012; Kiryukhin et al., 2012), and radiogenic isotopes such as tritium can be used to constrain when erupted water is recharged (e.g., Hurwitz et al., 2012). Quantifying the fluid pressures that play a role in the mechanics of the eruptions, however, is more challenging because of the unsteady nature of the eruptions and their high temperatures.

Here we report on an active field experiment performed in 1990 designed to identify the source of the water providing most of the recharge for two geysers in Geyser Valley, Kamchatka. We decided to analyze the previously unpublished data collected in this experiment because 1) a recent study by Kiryukhin et al. (2012) suggested a potential for hydrothermal eruptions, and 2) we would like to understand why recent flooding of some of the geysers in June 2007 caused their disappearance. We also hoped to obtain new insights into the geysering process. We show that recharge to these geysers is not constant but depends on the water level in the geyser conduit. Extrapolation of the data indicates that recharge should drop to zero if water level rises to a height that is within two meters of the water level in adjacent rivers and the

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vent of the geysers. The implied pressure in the reservoir providing water to the geysers is thus not much greater than hydrostatic, implying limited overpressure and hydrothermal explosion potential, at least in the immediate vicinity of the geysers. Water level changes from flooding would be sufficient to stop recharge to the geyser conduit, at least in the short term.

2. Setting

Geyser Valley in Kamchatka is the world's second largest geyser field, with around 200 geysers (Bryan, 2005). The geological and hydrogeological setting of Geyser Valley are described by Kiryukhin et al. (2012).

Our measurements were made at two geysers mapped in Fig. 1, named Bannyi and Pearl (English translation of "Zhemchuzhnyi"). At Bannyi, the interval between eruptions is typically about 40 min, with a 20 minute eruption and 20 minute rest period. At Pearl, eruptions occur every 3.5 to 4 hours, with a 10 minute eruption duration.

On July 3, 2007 a landslide dammed the Geysernaya River, and the landslide and lake of impounded water buried 23 geysers, including Bannyi (Sugrobov et al., 2009).

3. Measurement technique

Immediately after eruption, the geyser conduit was artificially flooded with cold water. This ensures that the geyser does not erupt while measurements are being made, and that its conduit is filled with a single phase fluid so that the presence of two phases (gas and liquid) does not complicate interpretations. After the experiment, geyser behavior returned to normal: that is, the active experiment does not have any long-lasting effect on geyser dynamics.

The water in the conduit was then maintained at a fixed elevation h_0 using either a float valve (Pearl) or a siphon (Bannyi), as illustrated in Fig. 2. Elevation is defined relative to the elevation of the brim of the geyser cone (defined to be $h = 0$). Water that was removed to maintain the fixed water level is termed "recharge", water that would otherwise continue filling the conduit. Recharge into the conduit is diverted through a hose and into a bucket so that the water level in the conduit is fixed. Recharge is measured by recording the time it takes to obtain a measured amount of water.

4. Results

Fig. 3 plots three examples of data showing the relationship between time and volume of water discharged at the surface. The slope in Fig. 3 is thus the rate of "recharge" to the geyser system. For a given water level h_0, recharge is a constant (at least after the first few minutes), implying an approximately constant pressure at depth and that the pressure distribution in the geyser system was effectively at steady state during the measurement.

Fig. 4 shows the relationship between water level and recharge. If we assume that recharge is linearly proportional to the hydraulic head difference across the geyser system, $h_r - h_0$, then we can fit measurements of water level and recharge with a linear equation and identify the water level at which recharge would becomes zero.

There are a few complications in trying to extrapolate our measurements to the water level at which recharge would drop to zero and hence estimate the hydraulic head h_r in the source of water for the geyser. First, we have a small number of measurements at each geyser, limited by the ability to fill the conduit and to measure discharge. Second, the density of water within the geyser system varies with temperature and hence the water level for zero discharge will overestimate

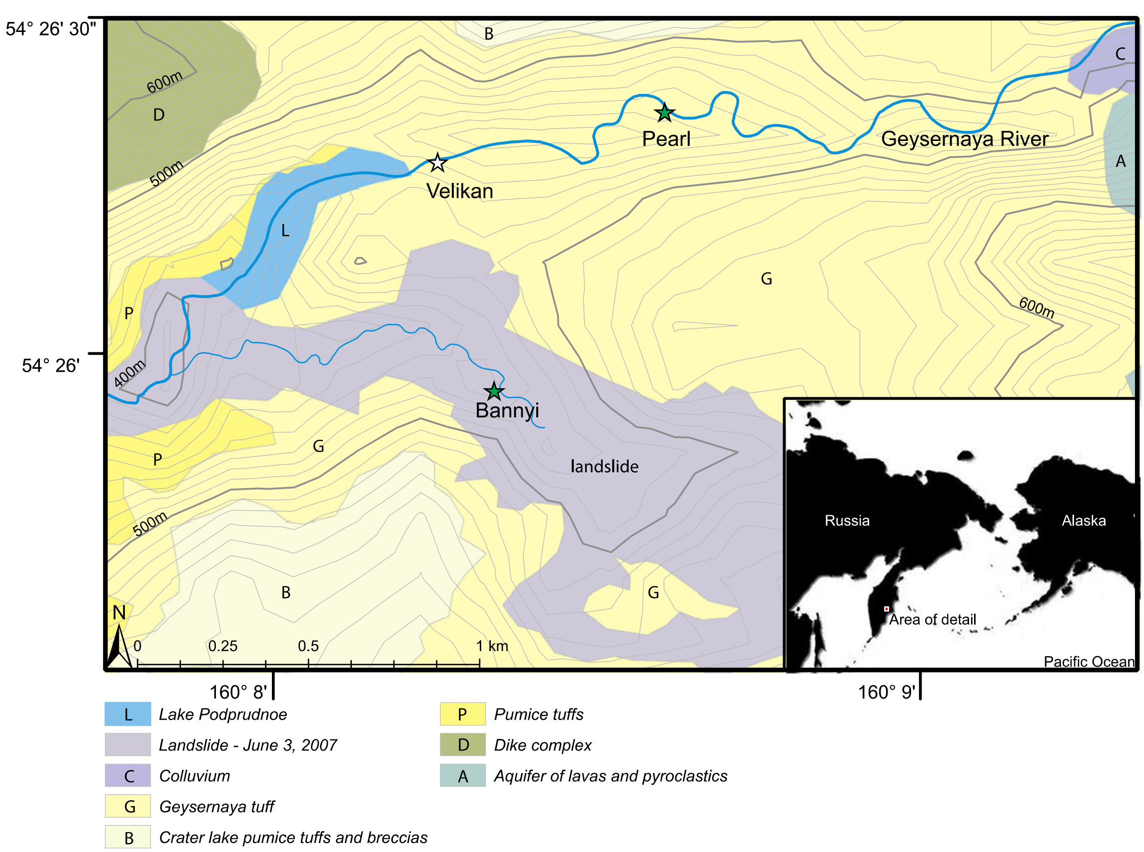

Fig. 1. Map showing location of Bannyi and Pearl geysers, Kamchatka. Topography from Shuttle Radar Topography Mission (SRTM). Geological map and units from Kiryukhin et al. (2012).

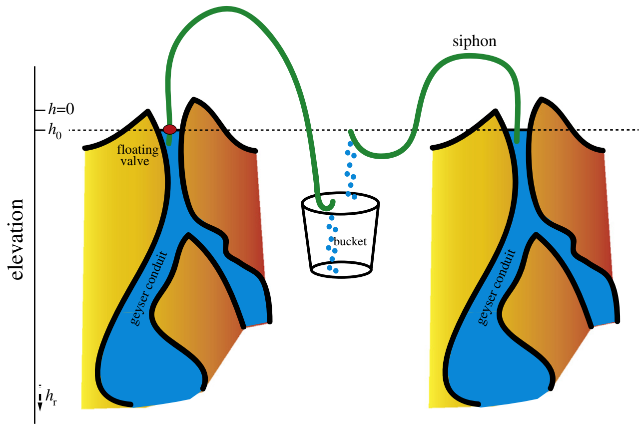

Fig. 2. Illustration of experimental procedure for measuring recharge and controlling water level. After an eruption the conduit is artificially flooded with cold water. Water level is then maintained with either a floating valve (left) that opens when water level reaches h_0, or with a siphon (right). Discharged water is collected in a bucket, and the recharge is obtained by measuring the weight of water collected and the time to collect that water.

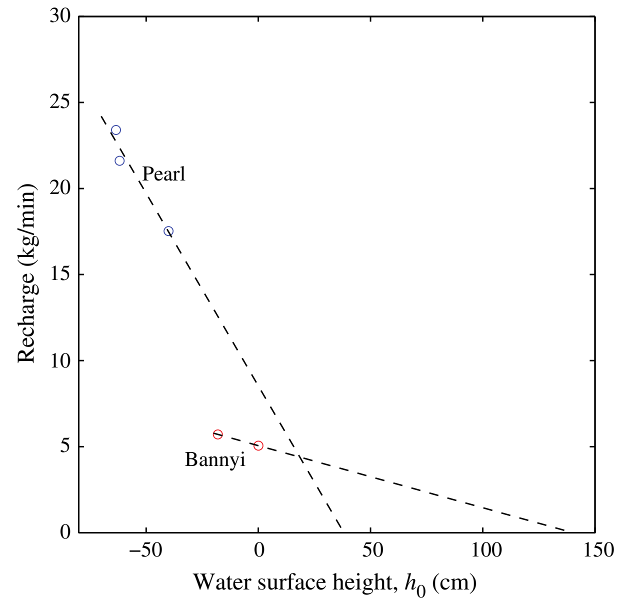

Fig. 4. Recharge as a function of water level h_0. The extrapolation of recharge to 0 gives an estimate of the hydraulic head h_r in the reservoir refilling the geyser.

the hydraulic head at depth because deeper water is warmer and less dense. Third, our extrapolation assumes a linear relationship, which only holds for non-turbulent flows and small enough Reynolds numbers. Assuming a cross-sectional area for the conduit of 0.01 m^2, the recharge in Fig. 4 implies velocities less than 0.03 m/s and Reynolds numbers less than 3×10^3 (this may be an upper bound — Belousov et al. (2013) measured conduit diameters >0.3 m, hence cross section areas >0.1 m^2 at other geysers in Geyser Valley). At such values discharge will be nearly proportional to the head difference. Inertial effects and turbulence would cause the extrapolation in Fig. 4 to underestimate the head in the water source.

5. Discussion

The analysis of the field experimental data was motivated by ongoing efforts to assess models presented over the past several years for geyser dynamics, evaluate the recently proposed potential for hydrothermal eruption (Kiryukhin et al., 2012), and to understand why flooded geysers disappeared. We address these topics sequentially.

The 1990 experiment, designed to probe pressure and hydraulic head within the studied geysers, complements previous active experiments at other geysers in Kamchatka. These include experiments to document how adding water at controlled temperatures influences the time to eruption (Steinberg et al., 1978); the effect of increasing the surface area of water in contact with the atmosphere which, owing to enhanced cooling, leads to longer intervals between eruptions (Merzhanov et al., 1990); and using chemical tracers to quantify the relationship between the mass of water that erupts and the total mass of water in the geyser system (Steinberg et al., 1981a). These active, non-destructive experiments revealed the importance of free-convection within the geyser, a conduit process that cannot be studied by observing eruption characteristics alone.

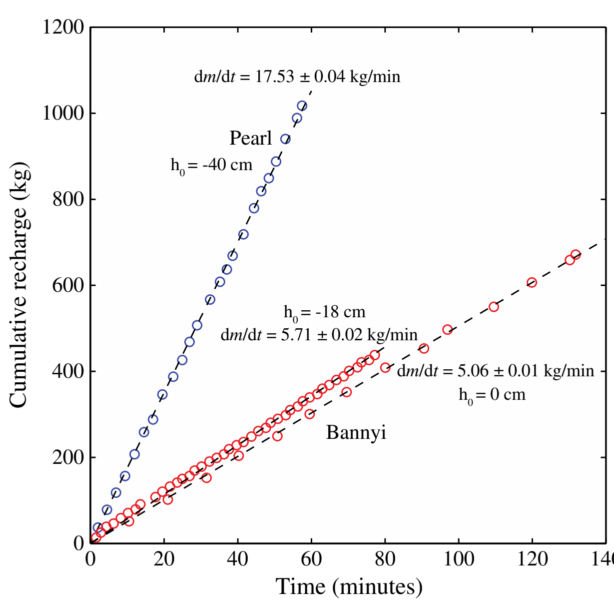

Fig. 3. Cumulative recharge as a function of time for Pearl (blue) and Bannyi (red) for a subset of experiments. Recharge and h_0 are labeled next to their respective curves. Dashed lines are best fits to the data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5.1. Relationship of observations to geyser models

The observation that recharge to the geyser varies with water level in the conduit implies that there is no steady source of recharge at depth, as is sometimes assumed (e.g., Kieffer, 1984; O'Hara and Esawi, 2013). Models for geyser recharge typically assume a combination of recharge of cold water from the surface and shallow depths (Steinberg et al., 1981a; Ingebritsen and Rojstaczer, 1993, 1996) and hotter water from greater depth (Steinberg et al., 1981a). The latter is sometimes assumed to be steady in models (Steinberg et al., 1981b). The present results indicate that any steady, deep recharge makes a small contribution to overall recharge. This inference is consistent with models in which recharge depends on the evolving hydraulic head in the conduit or in reservoirs connected to the conduit (Steinberg et al., 1981a; Kedar et al., 1998; Rudolph et al., 2012).

The water level in the geyser at which recharge would decrease to zero is close to, but somewhat above by 0.5 to 2 m, the water level in the adjacent rivers. This does not mean that river water cannot be a source of recharge to the geyser. Water in the geyser conduit and other reservoirs at depth is hot, so the water level at the top of the geyser is not a direct measure of hydraulic head deeper in the conduit.

Water level h will increase owing to thermal expansion by an amount equal to

$$dh = \int_{h_0}^{d} \alpha \Delta T \cdot dy$$

where y is depth, d is the base of the geyser system, h_0 is the water surface, α is the coefficient of thermal expansion, and ΔT is the increase in temperature within the geyser relative to that in the surroundings at the same depth. Assuming water is heated to an average of 50 °C over a depth interval of 40–80 m, and using a value of α for water of 5×10^{-4} K^{-1} at that temperature, the water surface in the geyser conduit would be 1–2 m above the river, if the head at depth were the same as that in the river.

Based on stable isotopes of O and H, the dominant source of water is not adjacent to the geyser, but at higher elevations where subsurface aquifers are recharged (Kiryukhin et al., 2012). Unfortunately, we have no tritium data to confirm that young water, including river water, makes a small contribution to recharge. But the fact that these geysers are sensitive to seasonal variations in lake level (Kiryukhin et al., 2012) suggests at least a hydraulic connection to local sources. This is also the case at Yellowstone, where the geyser eruption intervals respond to local water levels and vary seasonally (Hurwitz et al., 2008) even though the vast majority of discharged water is not young, locally-derived meteoric water (Hurwitz et al., 2012; Vandemeulebrouck et al., in preparation).

5.2. Potential for hydrothermal explosions

Hydrothermal explosions are short (minutes to hours) eruptions driven by high pressure and high temperature aqueous fluids. Historical explosions are documented in settings with active geothermal systems and prehistoric explosions have occurred in regions with active and fossil hot spring deposits (for a review see Brown and Lawless, 2001; Morgan et al., 2009). The possibility of hydrothermal explosions is a concern for geothermal development and public safety in regions with geothermal systems. Hydrothermal explosions may also create ore-grade mineralization, including gold (Nelson and Giles, 1985).

Kiryukhin et al. (2012) raised the possibility of hydrothermal explosions in Geyser Valley based on a model for fluid transport beneath an impermeable caprock. Observational evidence for high pressures or changing pressures includes the emergence of thermal springs 20–30 m above the elevation of nearby discharge sites. In addition, the June 3, 2007 landslide may have been initiated by a hydrothermal explosion (Kiryukhin et al., 2012), though the steam outbursts observed on the landslide headscarp may have instead been initiated by decompression-boiling caused by mass removal (A. Belousov, personal communication).

The pressures we measure, representative of the part of the subsurface in communication with the geyser on time scales of minutes to hours, are only slightly above hydrostatic. Hydrothermal explosions require fluid pressures that exceed lithostatic pressure plus the tensile strength of rock. The immediate vicinity of the two studied geysers is not likely to generate hydrothermal explosions.

We cannot, however, discount the possibility that high fluid pressure exist elsewhere in the geyser field or in sealed compartments that are isolated from the active geyser system. For example, drilling at Yellowstone National Park found pressures well above hydrostatic (Marler and White, 1975; White et al., 1975). One signature of high reservoir pressure is an approximately constant recharge throughout the geyser cycle. Velikan (Fig. 1), the largest geyser in Kamchatka, does have a nearly constant recharge, as do some Yellowstone geysers (Steinberg et al., 1978). At other Kamchatka geysers, however, recharge varies greatly during the geyser cycle, as we confirmed here (Steinberg et al., 1978).

5.3. Disappearance of geysers

The flooding of geysers by water impounded by the 2007 landslide is analogous to the field experiment, in that cold water is added to the conduit and water level is maintained at a constant value. Flooding above the measured reservoir hydraulic heads, a meter or two above the river level, should terminate eruptions, at least in the short term. Pressures in the larger geothermal system that recharges the geysers, however, should evolve and increase with time. Discharge of geothermal fluids may then occur, perhaps as hot springs rather than geysers if the impounded water can keep the geyser conduit below the boiling point. Indeed, Malyi geyser, now 10 m below lake level, continues to discharge hot water (A. Belousov, personal communication). As lake level falls, geyser activity can resume, as documented in Geyser Valley by Kiryukhin et al. (2012).

6. Summary

By performing an active experiment, we found that water pressures in the reservoirs feeding geyser eruptions are close to hydrostatic, at least in the two examples for which measurements could be made. We infer hydraulic heads in the reservoir of tens of centimeters to 2 m above hydrostatic, with quite of bit of uncertainty owing to the limited data we could collect and the unknown temperature distribution within the geyser. Despite uncertainty, the inferred pressures explain several features of the geysers, including why hydraulic head changes at the surface caused by flooding extinguished them. The near hydrostatic pressures also explain why geysers may be sensitive to local environmental changes such as water levels in surface water.

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