Video observations inside conduits of erupting geysers in Kamchatka, Russia, and their geological framework: Implications for the geyser mechanism

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ABSTRACT

Several models have been proposed to explain periodic eruptions of geysers. In essence, the models all use two principally different types of geyser plumbing configurations, dealing with two different physical mechanisms. Here we present data on direct video observations of interior conduit systems for four erupting geysers in Geyser Valley, Kamchatka, Russia. The video footage reveals highly contorted water-filled conduits that periodically discharge voluminous parcels of steam bubbles during eruptions. These observations do not favor the models that use the most popular long vertical conduit type of plumbing, where eruptions are caused by sudden flashing of superheated water into steam. In contrast, our data fit the models using the less-explored type of plumbing, where pressurized steam gradually accumulates in an underground cavity (bubble trap) and periodically erupts through a water-filled, highly contorted conduit with the configuration of an inverted siphon. Hydrodynamic calculations show that such a plumbing configuration produces periodic eruptions when the volume of the bubble trap exceeds the volume of the conduit connecting it to the ground surface. Conduits of the studied geysers were developed from erosion by ascending geothermal water in landslide deposits; chaotic internal structures of the deposits facilitated the formation of conduit systems with highly contorted configurations of the bubble trap type. We suggest that geyser fields are rare on Earth because they require the combination of hydrothermal discharge and geological formations having specific mechanical properties and structures (that facilitate the generation of highly contorted conduits).

INTRODUCTION

Geysers are a variety of boiling springs characterized by quasi-cyclic intermittent discharge; eruptions of water and steam are separated by clearly defined quiescent intervals (White, 1967; Rinehart, 1980; Wang and Manga, 2009). Geyser eruptions commonly consist of three successive phases: an initial sluggish overflow of water, a vigorous liquid-dominated discharge (fountaining), and a steam-dominated discharge of progressively decreasing intensity (this last phase is not always present).

While ordinary boiling springs (perpetual spouters) are numerous and occur in many places on Earth, geysers are rare. In total, fewer than 1000 geysers are known to exist worldwide (Bryan, 1995), and most of them are located in three large geyser fields: Yellowstone (Wyoming, United States), Geyser Valley (Kamchatka, Russia), and El Tatio (Chile). Investigations of geysers were facilitated for many decades by the presumption that changes in the periodicity of geyser eruptions were linked to ongoing tectonic deformation, and that these changes might be used to forecast earthquakes (Ingebritsen and Rojstaczer, 1993; Rojstaczer et al., 2003). Some researchers have considered geysers as simplified analogs of volcanoes, suggesting that their investigations could help illuminate mechanisms of volcanic eruptions (Droznin, 1982; Kieffer, 1982; Kedar et al., 1996). Spontaneous transitions to cyclic intermittent discharge (geysering) have also been observed in some critical artificial systems, such as nuclear power plants and rocket engines (Lu and Watson, 2005).

Several physical models have been proposed to explain the periodic discharge of geysers. Detailed overviews of these models were given by Allen and Day (1935), Iwasaki (1962), and Lu and Watson (2005). A key component of these models is the assumed configuration of the geyser plumbing system. Very limited field data exist on geyser plumbing, and the models have relied on two different plumbing configurations envisaged in the first half of the 19th century. Mackenzie (1811) suggested a type of geyser plumbing system that includes a large subterranean cavity connected to the ground surface by a highly contorted conduit with the configuration of an inverted siphon (Fig. 1A; Fig. DR1A in the GSA Data Repository[1]). The cavity works as a trap for steam bubbles rising from below; it has an impermeable roof and gradually accumulates notable volumes of pressurized steam that periodically erupt through the water-filled conduit. This bubble trap type of plumbing is rare in current geyser models (Iwasaki, 1962; Kagami, 2010; Nechayev, 2012).

Bunsen (1847) suggested that highly contorted plumbing with a steam-accumulating cavity is not critical for a geyser; given a specific combination of heat and water supply conditions, a boiling spring with a simple long vertical conduit (Fig. 1B; Fig. DR1B) could display

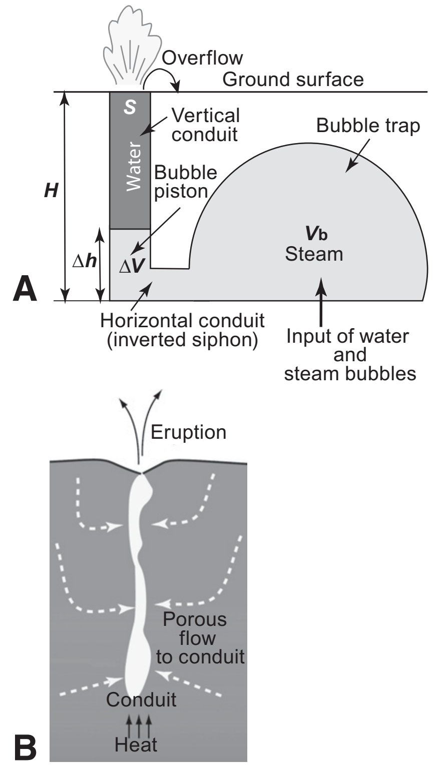

Figure 1. Modern representations of two principal types of geyser plumbing. A: Mackenzie's (1811) bubble trap configuration shows moment when accumulating steam has completely displaced water from bubble trap and starts to enter vertical conduit. *H* and *S* correspond to length and area cross section, respectively, of vertical conduit; V_b—volume of bubble trap; Δh—height of bubble piston and corresponding decrease of water column height in conduit. B: Bunsen's (1847) long vertical conduit configuration (Wang and Manga, 2009). Original 19th century drawings are in Figure DR1 (see footnote 1).

[1]GSA Data Repository item 2013078, Figure DR1 (original drawings of two principal types of geyser plumbing suggested in the 19-th century), Figure DR2 (simplified geological map of Geysernaya River area), Figure DR3 (photos and drawing of the landslide deposit exposed in the Geysernaya River valley wall), and Videos DR1–DR6 (video clips of the footage inside the geyser conduits), is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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periodic eruptions. The conduit must be narrow (or have constrictions) and long enough to allow the infilling water to reach a superheated state; hydrostatic pressure in the lower part of the conduit prevents boiling, while the small diameter of the conduit retards convection. Geyser eruptions in such systems are caused by sudden flashing of superheated water into steam when hydrostatic pressure drops (due to overflow of water from the conduit) after boiling initiates. This long vertical conduit type of plumbing is used in many modern geyser models (e.g., White, 1967; Steinberg et al., 1982; Kieffer, 1984; Ingebritsen and Rojstaczer, 1993; Saptadji, 1995; Sugrobov et al., 2009). Although some of the plumbing configurations include a variety of chambers (e.g., Steinberg et al., 1982, their figure 1), this chamber opens directly into the vertical conduit, and thus cannot trap rising bubbles and accumulate a sizable volume of pressurized steam.

The experimental setups used to date to test each type of plumbing configuration reproduced satisfactorily the pulsatory action of natural geysers (Honda and Terada, 1906; Iwasaki, 1962; Steinberg et al., 1982; Saptadji, 1995; Lasic, 2006). However, the bubble trap configuration had one significant problem; i.e., its geometrical complexity. There was no geological explanation for the nonfortuitous formation of multiple, closely spaced geysers with the necessarily contorted conduits, as takes place in geyser fields (Le Conte, 1878). In contrast, long vertical conduits can easily develop along vertical fissures that are common in rocks. Moreover, the observations of periodic geyser-like discharges from some artificial geothermal wells (White, 1967; Sugrobov et al., 2009), along with video (Hutchinson et al., 1997) of the inside of the uppermost part of the channel of the Old Faithful Geyser in Yellowstone National Park, have provided support for a simpler long vertical conduit configuration, and led to its frequent use in modern geyser models.

Here we report on our direct video observations of geyser conduits in the Geyser Valley (Kamchatka Peninsula, Russia), the second-largest geyser field on Earth. Previous researchers have described the geyser activity, water chemistry, temperature distributions in several geysers, and areal geology of the Geyser Valley (e.g., Ustinova, 1955; Droznin, 1982; Leonov et al., 1991; Nechayev, 2000; Sugrobov et al., 2009). Our goals were to determine the plumbing configurations of the geysers, their geological framework, and the driving mechanism for periodic eruptions.

OBSERVATIONS OF GEYSERS IN KAMCHATKA

Video Observations Inside Geyser Conduits

To investigate geyser plumbing systems, we lowered a video camera (with thermal and water insulation) into the conduits of four geysers. These included Velikan and Bol'shoy (the largest geysers in the field), ejecting ~20 m^3 and 15 m^3 of liquid water to heights of 25 and 15 m, respectively, with rather stable periods of ~5 h and 1 h. We also investigated Vanna and Kovarny, small geysers with irregular regimes, ejecting ~10 L of water to heights of as much as 2 m, with periods of several minutes. We were able to access to 2 m into connected horizontal conduits. Video was transmitted to the surface, observed in real time, and recorded (for selected video clips from a total of 10 h of video, see the Data Repository).

Despite significant differences in scale and eruption regime, all of the studied geysers have strikingly similar plumbing system configurations (Fig. 2). They consist of a vertical upper conduit 1–10 m deep, having an approximately oval cross section of ~0.4–2 m. Several sinter-covered rounded boulders were on the bottom of each vertical conduit in a formation resembling a fluvial pothole. Water and steam jets probably whirled the boulders during early eruptions of the geysers, causing them to grind out and enlarge the upper vertical conduits. At the bottom, each vertical conduit is connected at approximately a right angle with a relatively narrow horizontal conduit with an irregular cross section of ~0.3–1 m (Videos DR1 and DR4), and with lengths exceeding 0.5–2 m (distal parts of the horizontal conduits were not visible). Thus, we have found that conduits of the studied geysers are notably different from long vertical tubes or fissures; instead, they become horizontal at several meters depth.

The hydrodynamic processes observed inside the conduits are similar in all four of the studied geysers. After an eruption and an initially violent filling, the upper vertical conduit gradually fills with nonboiling water, which flows in from the connected horizontal conduit. When the vertical conduit is completely filled, it overflows. Late in the overflow phases of the Bol'shoy, Vanna, and Kovarny geysers (due to safety concerns, we did not film inside Velikan during the late overflow and fountaining), relatively small volume parcels of steam bubbles from the deeper level of the plumbing system begin to pass along the ceiling of the horizontal conduit into the lower part of the vertical conduit (Videos DR1, DR2, DR4, and DR5). Upon entering the cooler water in the lower part of the vertical conduit, these steam parcels immediately condense and collapse. These initial steam injections gradually (~15, 1, and 0.5 min for Bol'shoy, Vanna, and Kovarny, respectively) increase the water temperature in the upper conduit until a point when no further significant condensation occurs. At this moment, one or several large-volume parcels of steam bubbles burst violently through the horizontal conduit into the upper vertical conduit, where they expand greatly and eject the conduit-infill water into the atmosphere (corresponding to a fountaining phase of the geyser eruption; Videos DR3–DR5). During the fountaining phase, the explosion-like expansion of the steam parcels in the upper vertical conduit completely masks the fact that the steam was initially ejected from the horizontal conduit; even geysers having short vertical conduits discharge water upright.

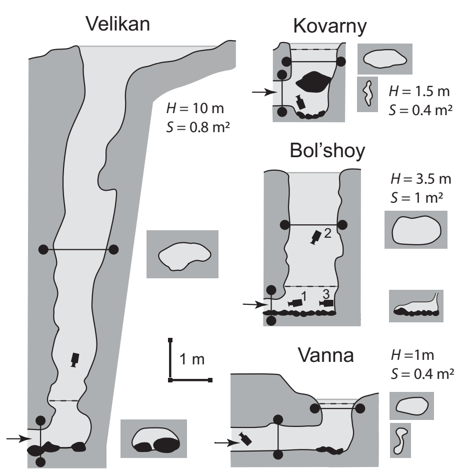

Figure 2. Plumbing schematics for studied geysers based on video observations. Boulders are depicted in black; arrow—horizontal conduit; dashed line—posteruption water level; camera symbol—positions from which video clips were shot. *H* and *S* correspond to approximate length and average area cross section, respectively, of vertical conduits.

The fountaining phases of Velikan and Bol'shoy expel ~80%–90% of the water volume stored in the upper vertical conduits, and then mostly pure steam is ejected from the horizontal conduits through a thin layer of water left in the bottom of the vertical conduits (Video DR6): this corresponds to a steam-dominated phase of the eruptions. The fountaining phases of Vanna and Kovarny are short-lived; they eject only ~5%–10% of the water stored in the vertical conduits, and their eruptions have no steam-dominated phases. In summary, we have observed periodic discharge of voluminous parcels of steam through highly contorted water-filled conduits; the process characteristic of the geyser models using a bubble trap type of plumbing (Iwasaki, 1962; Kagami, 2010).

Geology of the Host Rocks and Plumbing of Extinct Geysers

The plumbing systems of the studied geysers were developed in a rock formation that is well exposed around the geyser vents, as well as in the walls of the Geysernaya River canyon, which drains the area. The formation is composed of deposits of several voluminous landslides (debris avalanches) of Holocene age, which originated from the steep slopes of Gornoye Plato (Fig. DR2). The landslides displaced a former Pleistocene deposit of a caldera lake, represented by variously layered, moderately cemented, silicic pumice tuffs. The landslide deposits have a chaotic structure composed of irregular domains (debris avalanche blocks) of the displaced tuffs, as much as 5 m across (Fig. 3A; Fig. DR3A). Tuff inside the blocks was deformed and shattered to various degrees during the landslide emplacement. Originally, the landslide deposits were friable and composed of very poorly sorted sandy gravel with angular tuff fragments as much as 0.5 m across. Later, the material was partly cemented, and partly turned into dense clay by hydrothermal alteration processes that made it poorly permeable to water and steam.

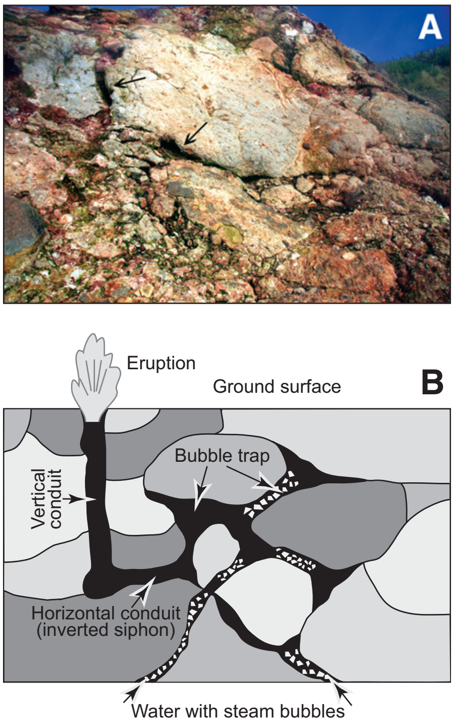

Figure 3. A: Landslide deposit hosting conduits of extinct geysers. Arrows indicate largest conduits formed along contorted contacts of debris avalanche blocks (additional pictures of paleoplumbing are in Fig. DR3; see footnote 1). Largest block is 5 m across. B: Suggested geyser plumbing. Debris avalanche blocks are in various shades of gray.

We also observed a complex network of sinter-lined paleoconduits and chambers of extinct geysers exposed by river erosion in the studied outcrops (Fig. 3A; Fig. DR3A). Some conduits and chambers are hollow caverns, and some are composed of coarse gravel with openwork texture (Fig. DR3C); both were developed by ascending hydrothermal water that elutriated friable clastic material. Hot water found its way along contacts between debris avalanche blocks of different permeability. The highly irregular contacts between adjacent blocks provided an environment that favored the formation of conduit systems with highly contorted configurations. In many cases, they have configurations of the bubble trap type (Figs. DR3A and DR3B).

CONDITIONS FOR PERIODIC DISCHARGE OF STEAM FROM THE BUBBLE TRAP

The mechanics of a geyser with the bubble trap plumbing configuration are, in essence, the gradual accumulation of pressurized steam and its periodic outbreak through the water-filled conduit. When water containing steam (or any other gas) bubbles ascends along a highly contorted conduit, the bubbles separate from the water and accumulate in a bubble trap structure, while the residual bubble-free water discharges to the ground surface (overflows). After some time, steam fills the entire volume of the bubble trap, $V_{b,}$ and starts to percolate in the conduit (Fig. 1A). At this moment, the pressure of the steam in the bubble trap is equal to the hydrostatic pressure in the conduit base plus atmospheric pressure: $\rho gH + P_{atm}$ (where ρ is the average density of the water column, g is the acceleration of gravity, H is the vertical conduit height, and P_{atm} is the atmospheric pressure).

When the volume of the steam then increases by a small value, ΔV, by the addition of steam bubbles from below, the equivalent volume starts to percolate in the vertical conduit (forming a bubble piston). The total volume of steam in the system becomes $V_b + \Delta V$. Correspondingly, the volume of water in the conduit also decreases (the displaced water overflows) by the same value, $\Delta V = S\Delta h$, where S is the area of the conduit cross section, and Δh is the height of the bubble piston and the corresponding decrease of the water column height in the conduit. Accordingly, the water pressure in the vertical conduit on the boundary with steam decreases by a value of $\Delta P_c = \rho g\Delta V/S$.

As a result, the pressure P of steam in the system bubble piston and the bubble trap starts to decrease. The process is very fast, and in a first approximation can be considered adiabatic. According to adiabatic law, $PV_b^\gamma = A$ = constant, where γ is the specific heat ratio or adiabatic index. Hence, the decrease in steam pressure in the bubble trap strongly depends on its volume, V_b; if V_b is large enough, the pressure decreases more slowly than the hydrostatic pressure in the conduit decreases. Hence, positive feedback appears that causes progressive intensification of the steam outburst that expels water from the vertical conduit, and the fountaining phase of the eruption starts (for simplification we neglect extra boiling caused by a pressure drop in the bubble trap; obviously, extra boiling intensifies the eruption process). When enough water stored in the vertical conduit is expelled, the rest of the pressurized steam leaves the bubble trap (steam-dominated phase). After that, the new geyser cycle commences.

The volume of the bubble trap necessary to produce periodic eruptions can be estimated. When steam starts to percolate in the vertical conduit, the pressure drop ΔP_b in the bubble trap is

$$\Delta P_b = \frac{dP_b}{dV_b}\Delta V = -\frac{A\gamma}{V_b^{\gamma+1}}\Delta V. \quad (1)$$

The instability appears if $\Delta P_b < \Delta P_c$:

$$\rho g/S > A\gamma/V_b^{\gamma+1}. \quad (2)$$

Using the fact that the pressure of steam in the bubble trap in this initial moment is equal to the hydrostatic pressure in the base of the vertical conduit plus atmospheric pressure, the value of A can be found by $\rho gH + P_{atm} = A/V_b^\gamma$, so $A = V_b^\gamma(\rho gH + P_{atm})$.

By replacing A in Equation 2, we obtain the condition of periodic discharge of a geyser:

$$V_b > \gamma(H + P_{atm}/\rho g)S. \quad (3)$$

Equation 3 allows us to estimate the volumes of bubble traps of the studied geysers. For steam $\gamma = 1.4$, P_{atm} can be approximated by the static pressure created by 10 m of water. Hence, the periodic eruptions of steam-driven geysers occur when $V_b > \sim 1.4(H + 10)S$. Geysers with $V_b \gg 1.4(H + 10)S$ obviously have eruptions with well-developed steam-dominated phases (e.g., Velikan and Bol'shoy geysers). Geysers with $V_b \approx 1.4(H + 10)S$ have no steam-dominated phases (e.g., Vanna and Kovarny geysers). Using the parameters of the conduits obtained during our video observations (Fig. 2), we obtain a V_b for Velikan of >22 m^3; for Bol'shoy, >18 m^3; and for Vanna and Kovarny, ~6 m^3.

DISCUSSION

Direct video observations have shown that all four studied geysers of the Geyser Valley have highly contorted conduits, the condition necessary for a water-filled geyser plumbing system to trap rising bubbles and accumulate pressurized steam. The equipment we used did not allow us to penetrate far enough into the horizontal conduits to observe the subterranean cavities as they filled with pressurized steam. However, the paleoplumbing of extinct geysers in the area commonly demonstrates the necessary bubble trap configurations. Combining the observational data on plumbing of modern and extinct geysers, we conclude that geysers of the Geyser Valley have plumbing configurations of the bubble trap type (Fig. 3B).

One important observation is that the first steam parcels start to percolate into the upper vertical conduits a long time before the initiation of the fountaining phase, indicating active boiling low in the plumbing. As such, the fountaining is not the result of a sudden rapid initiation of boiling (flashing), as described by the models using the long vertical conduit plumbing. In our opinion, percolation of the first steam parcels into the upper vertical conduit starts when the bubble trap is completely filled with pressurized steam. The fountaining, however, does not commence at this moment, given that the first steam parcels condense and collapse in relatively cool water, filling the vertical conduit. At first, the collapsing steam parcels gradually increase the water temperature in the vertical conduit, up to the boiling point. Only after that does the accumulated pressurized steam escape from the bubble trap through the upper vertical conduit (corresponding to a fountaining phase). Thus, the observed hydrodynamic processes are easily explainable if the bubble trap plumbing configuration is accepted. Simple hydrodynamic calculations show that the bubble trap starts to discharge steam periodically when its volume notably exceeds the volume of the conduit connecting it to the ground surface.

Geysers in the Geyser Valley are located exclusively where boiling hydrothermal water discharges through the landslide deposits. Outside of the area covered by the landslide deposits, only perpetual spouters and fumaroles are present (Fig. DR2). We suggest that the fragmented landslide deposits, with a strongly heterogeneous, blocky structure, favored the formation of contorted pathways of ascending hydrothermal water. With time, elutriation of fines from the deposits along the contorted fluid pathways formed conduits and chambers, many of which had a bubble trap configuration. This explains the existence of such numerous geysers in the Geyser Valley.

The solitary geysers scattered over Earth (Rinehart, 1980) may have formed by the occasional coincidence of several favorable factors and, perhaps, may have different types of plumbing and mechanics according to the principles of any one of the existing geyser models. However, why are multiple geysers grouped together in relatively small areas in a few locations? We hypothesize that in these areas, besides the necessary hydrothermal conditions, there are specific shallow geological structures or deposits that favor the formation of multiple complex systems of subterranean conduits and cavities, including systems with configurations of the bubble trap type. In the Geyser Valley, the blocky landslide deposits provide such structures. In Yellowstone and El Tatio, these conditions may be provided by glacial moraines covering the hydrothermal areas where the geysers are located (Allen and Day, 1935; Fenner, 1936; Fernandez-Turiel et al., 2003). Moraines are also fragmented, friable deposits that display chaotic, commonly blocky, heterogeneous structures, very similar to those of landslides (Siebert, 1984). Thus the world's three main geyser fields display similar geological features. We suggest that a combination of geological conditions, favoring generation of contorted conduits and chambers, as well as hydrothermal discharge, explains the rarity of large geyser fields on Earth.

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