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In situ observations of Old Faithful Geyser

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ABSTRACT

In a series of experiments from 1983 to 1993, four probes were carefully lowered into Old Faithful Geyser, Yellowstone National Park, Wyoming. At different times, these probes variously recorded pressure-temperature-time conditions (to nearly 22 m depth), and video probes showed the conduit geometry and processes of recharge (to 13 m depth). Temperatures recorded were, within experimental error, the same as those recorded in 1942, with a peak bottom temperature (*T*) of 118 °C. Processes observed include fog formation in the upper levels of the conduit owing to wind and entrainment of cool air; "bank storage" of hot water that splashes to high levels, cools, and recharges; recharge of cooler ground water into the conduit; superheated steam expansion into the conduit (T = 129.5 °C); periodic temperature fluctuations; and exsolution of bubbles of noncondensable gas, which we propose are CO_2.

INTRODUCTION

Lack of observational data about the geometry and initial conditions in geysers prior to eruption has precluded verification of hypotheses about the triggering mechanisms for eruptions and the fluid dynamics of mass and heat balances during and between eruptions. Observations can help with quantification of geyser dynamic theory and can provide answers to the questions asked by millions of tourists who visit geysers. Observations of properties and processes can provide a database for understanding fluid and thermodynamic conditions in epithermal veins and possible relationships of fluid flow conditions in multiphase, multicomponent systems to the geochemistry of mineral deposition (Barton et al., 1977; Henley and Ellis, 1983; Kieffer, 1989). Geysers are also used as analogues for planetary volcanism, and observations may provide constraints on theories for multiphase flow in hydrothermal systems (Ingebritsen and Rojstaczer, 1993, 1996), and in volcanoes on the Earth and on the planetary bodies Io and Triton (Kieffer, 1982).

We describe here the preliminary results of measurements with two types of probes that we lowered into Old Faithful Geyser in Yellowstone National Park, Wyoming. With these probes we were able to obtain pressure (P) and temperature (T) measurements to the base of the accessible conduit at ~22 m as well as video observations of conduit geometry and hydrologic processes down to the base of a chamber ending at 14 m depth. The probes were designed to be of minimal diameter (cables less than 13 mm everywhere; the largest component, the insulated video camera, was 50 mm) and geometrically smooth to minimize the probability of jamming in the conduit. Seven years (1976–1983) of conservative noninvasive observations of the characteristics of the plume, of the seismicity, and of the geochemistry of the water were relied upon to optimize the design of the probes. All experiments were done with prior approval of the National Park Service, with the assistance and monitoring by park rangers, and with no damage to the conduit or the ground surface surrounding the geyser.

EXPERIMENTS

In 1984 a probe was designed to measure pressure and temperature simultaneously during recharge intervals. We were able to obtain measurements during periods associated with eight eruptions in April 1984 and six in October 1984. The probe consisted of a string of eight stations. At each station, temperature was measured with a solid state sensor (National LM335) in April, or with a chromel-alumel thermocouple in October. Pressure was measured with a bubble manometer (Craig, 1983) that used dry nitrogen gas in Teflon tubes with 1.5 mm bores. The measured time-constant response of the pressure sensors was from 2 s for the shortest tubes (shallowest depth) to 4 s for the longest (deepest depth). The measured time constant of response of the thermocouples was less than 1 s. Calibration was done in the laboratory. The calibration was field checked when the temperature sensors were in steam in the empty conduit where the temperature is the boiling point at the barometric pressure. Each of the 16 sensors at the eight stations was sampled and digitally recorded in sequence every 5.12 s.

In 1992 we obtained a very small video camera (Elmo EM-102BW), and by placing it into a vacuum-insulated metal housing with water and ice cooling, we were able to obtain "Hi-8" tape-recorded video data between eruptions that allowed us to view and measure the conduit. The field of view was 55°, and maximum viewing distances were about 2 m. Video observations were made on September 28, 1992, and September 27, 1993, typically 26 to 40 min into a recharge cycle and 12 to 62 min prior to an eruption. On each descent, even only 14 min after a long eruption, water was visible at the 13.7 m level or above. After long eruptions water is less than 2 m deep in the accessible vent, and after a short eruption, water is immediately visible and wildly boiling at the 12 m level.

Because of the rapid motions, especially spinning, of the camera, the prints from individual frames of the video data such as shown in this paper are relatively difficult to interpret compared to the video data. Selected parts of the conduit video are available through the authors.

CONDUIT GEOMETRY RESULTS

The conduit is an irregular, elongated fissure-like channel oriented along an east-trending fracture (Fig. 1). Our reference zero level was at 7367 ft (2245.5 m) elevation (Muffler et al., 1982). The walls of the conduit as deep as we viewed are lined with white silica sinter like that seen on the surface.

At 5.5 m depth (Fig. 2), the walls are broken with near-vertical fractures. This depth is about the shallowest level that the wildly boiling water stands in the conduit just before an eruption. We infer that this depth is near the top of the local water table in this area. For this paper, we use the words *water table* to designate the time-dependent, multicomponent (H_2O, CO_2; see below), multiphase (liquid, gas, solid matrix) interface. The top of the sinter mound around the vent is 3.6 m above the surroundings and so this water table would be 1.9 m below the general surface level.

At 6.8 m below the surface, the fissure width narrows to 11 cm (Fig. 3). Kieffer (1989) proposed that sonic (choked) conditions (mach 1 at 70 m/s) occur in the flow during the first ~30 s of the eruptions. We propose that the choking is at this depth.

Regions of choked flow are important in both the dynamics of flow, and in associated processes of geochemical deposition or erosion. During the first 20–40 s of an eruption, the flow is at maximum flux and is choked at sonic conditions with a sound speed and flow velocity of about 70 m/s

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*Died in an avalanche March 4, 1997, near Heart Lake in Yellowstone National Park.

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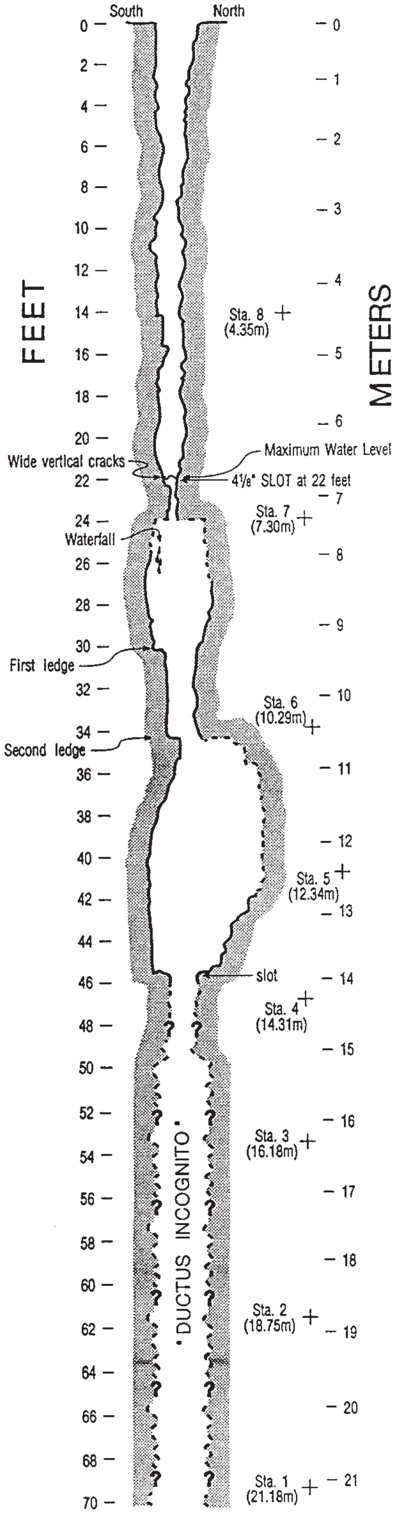

Figure 1. Shape of conduit of Old Faithful Geyser inferred from video observations. Two pressure-temperature probes that we lowered were configured slightly differently from each other, but stations were approximately at positions shown.

(Kieffer, 1989). The mass flux can be determined from conditions in the choked zone. Taking the mean narrowest dimension as 15 cm and the longest dimension as 2 m (estimated from the field-of-view constraints), the cross-sectional area at the choke is 3000 cm^2. The density of the fluid at this point is ~25 kg/m^3 (Kieffer, 1989). From these values, we calculate the peak maximum flux to be ~525 kg/s. This stage lasts only 20–30 s, producing roughly 10 000 to 16 000 kg (~liters) of liquid water, but accounts for most to much of the total discharge; our historical observations indicate that the total discharge for a full eruption ranges between 14 000 and 32 000 L.

The typical waxing and waning of geyser and hot-spring lifetimes ends with silica sealing; at Old Faithful this process is evidenced by the presence of several other older, now dormant sinter mounds near the currently active vent. By analogy with geothermal wells, the constriction at 6.8 m could be the most likely place yet imaged for future sealing of the current Old Faithful conduit.

At 7.5 m, a small waterfall with an estimated discharge (by comparison with a spray nozzle garden hose) of a few decaliters per minute was observed in both 1992 and 1993 (Fig. 4). Water was also observed descending from near-surface levels in several forms. Individual droplets of water and fairly substantial streams descended vertically from above the camera. Sheets of water also were observed covering the walls, especially after recession of surges. We interpret these as flowback of surge water that did not escape out of the conduit (analogous to bank storage along rivers). When the camera came in contact with sheets of water on the walls during episodes of

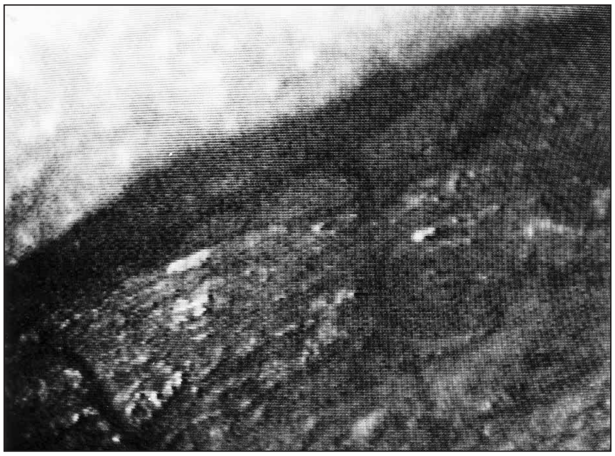

Figure 2. View with camera positioned at 5.5 m, looking downward toward (but not exactly at) the narrowest place in Old Faithful's conduit (running from center left toward upper right). Vertical fracture (1–2 cm wide) on left can also be seen in Figure 3.

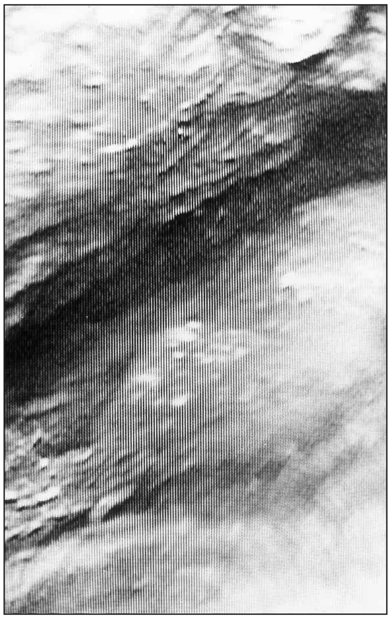

Figure 3. View looking directly down at narrowest place (13 cm wide) in Old Faithful's conduit, at 6.8 m depth. Note beads and bumps of silica sinter.

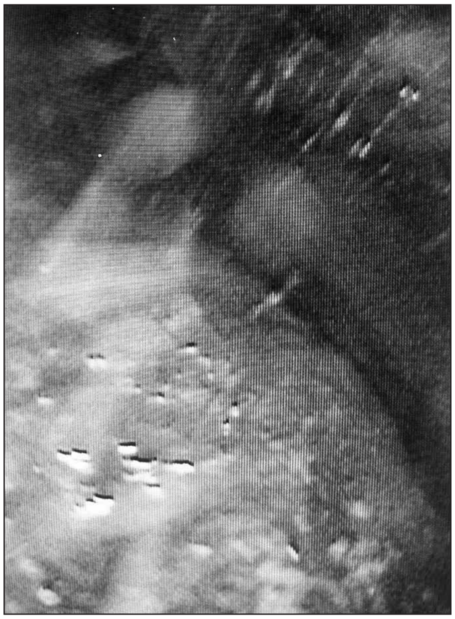

Figure 4. Small waterfall descending into main vent, shown by bright discrete streaks in upper right corner at 7.5 m. Vertically downward is parallel to streaks caused by falling water of waterfall. Brightest spots in lower left are water drops impinging on ledge.

flowback, the thermocouples registered subboiling temperatures. Such water is recycled into the fluid in the conduit and is probably reheated to boiling conditions prior to eruption. The small waterfall may flow from a pool of the bank storage or may be a small influx of ground water.

There are two offsetting ledges protruding from the wall into the conduit. The first, at 9.2 m, is about 15 cm wide and slopes slightly downward toward the axis of the conduit. The second, about 30 cm wide at 10.7 m, slopes only gently toward the conduit. It has a small pool of water trapped on the top surface. The second ledge protrudes beyond the local vertical axis of the conduit along which our probe could descend freely and therefore tends to catch objects that are lowered on cables or wires. It sometimes required several attempts to move sensors past this obstruction.

Between 10.7 and 12.8 m, the conduit is wider than 1.8 m in all directions. Between 12.8 and 14 m, it narrows to a slot longer than 1.8 m and about 30 cm wide that continues downward to at least 14.6 m, where the wildly boiling water blocks our vision.

Our deepest observations were obtained with the camera at 14 m. The elevation of the nearby Firehole River corresponds to our 14.3 m level (7325 ft elevation; 2233 m). From 14 m we could view water surging up and down in the conduit, transforming nearly explosively from a liquid to a two-phase mixture (observable easily via the video data but not easily shown with photographs), disappearing for a few minutes at a time to unobservable depths greater than 14.6 m, and then reappearing and surging up to at least the 9 m level.

In many cases, as we watched via the camera suspended 1–2 m above the water level while the conduit filled, the water appeared to be jetting nearly horizontally with very high velocity across the camera field of view (again, easily visible in the video data). We believe that these were ejections of superheated boiling water, because the thermocouples attached to the camera often showed temperatures 2–4 °C above the boiling point in the open conduit (92.5 °C) when splashed by this water.

The surging hot water precluded exploration of the geometry or the recharging process in the deeper parts of the conduit. The camera used in 1993 was designed to go underwater. We succeeded in penetrating the top zone of boiling water ~1 m and saw many bubbles rising from below. They were of two types: bubbles of condensable vapor that imploded upon rising into cooler water, inferred to be steam; and bubbles of noncondensable gas about 1–2 cm in diameter. We propose that the noncondensable bubbles are carbon dioxide (Fenner, 1936; White, 1967).

TEMPERATURE RESULTS

The 1984 results from the pressure and temperature sensors supplement these camera observations (Figs. 5 and 6). Traditionally such observations have been interpreted with respect to the reference boiling curve for pure liquid water (Kieffer, 1984; Rinehart, 1974; White, 1967). Interpreted in this way, the data show that the top few meters of water in the conduit are at boiling conditions and that deeper water is consistently a few degrees cooler than the hydrostatic boiling conditions appropriate to the level of water in the conduit as a function of time. A different interpretation is also suggested below.

The hottest temperature consistently recorded was 118 °C at 21.7 m; spikes up to 129.5 °C lasting for 5–10 s were observed a few times at the beginning of an eruption, suggesting that water from deeper than 21.7 m was involved in the eruption. The average maximum temperature measured is in good agreement with that measured by Birch and Kennedy (1972; data obtained in 1949), suggesting that the heat supply to the geyser has not varied substantially over the past half century.

Generalized Sequence of Events

The *P-T* variations with time (Figs. 5 and 6) are extremely complex because of splashing and alternate episodes of one-phase (either steam or liquid) and two-phase (vapor-liquid and/or gas/liquid) flow.

1. Volumes of the conduit are filled with steam at 92–93 °C prior to being submerged in liquid rising from the base and ejected from the sides of the immediate reservoir. The major consistent exception to this process is the volume above ~7.3 m (station 7, Fig. 1), in which entrained air from the surface or blown in by wind can cool the steam and cause local fog formation with temperatures as low as 70 °C.

2. As the recharging fluid rises in the conduit, it is generally at boiling conditions (92 °C) at the surface and within a few meters of the surface, and at sub-boiling conditions by a few degrees at greater depths, according to *P-T* measurements taken as the water rose past individual stations. A consistent exception to these conditions occurs as water rises past ~12 m depth (station 5), where $T = 86$ °C. We interpret this low temperature to indicate recharge from a shallow level, loosely called "ground water" here to draw a contrast with a deep hot geothermal source.

3. As the recharging fluid rises past ~12 m (station 5) in the large chamber between 14 and 10 m (stations 4, 5, and 6), temperature oscillations with a period of ~30 s and with an amplitude of 15 °C occur at station 3 (and, less vigorously, at stations 2 and 1 at depths of ~19 and 21 m; Fig. 6). We interpret these oscillations as convection patterns driven by the temperature inversion in the region between 12 and 16 m (stations 5 and 3).

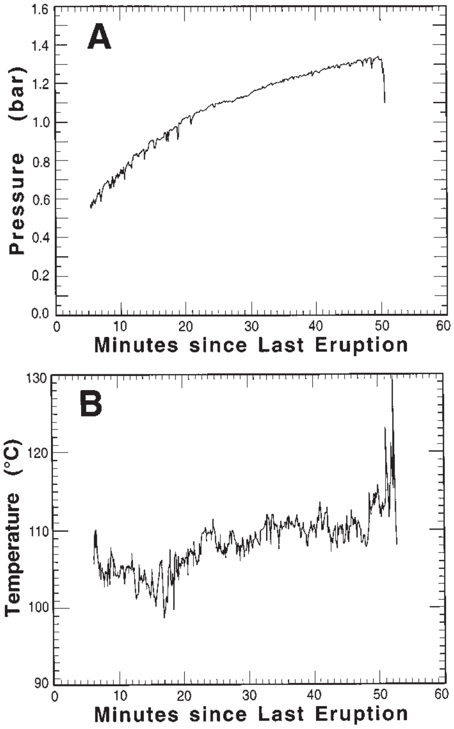

Figure 5. Pressure (A) and temperature (B) vs. time after previous eruption at bottom probe station (no. 1 at 21–22 m into conduit) during October 2, 1984, recharge cycle of Old Faithful. Temperature is highly variable; we believe that all fluctuations are real. Peak temperature, nearly 130 °C, is hotter than observed in conduit at any time during recharge interval and is attained during eruption when hot water from depths below open conduit rushes by temperature probe.

Influence of Firehole River

The temperature anomalies that occur at stations 5, 3, 2, and 1 (corresponding to depths of ~12, 16, 19, and 21 m) as water fills the big chamber are not reflected at 14 m depth (station 4). Because of the coincidence of the location of station 4 with the elevation of the Firehole River, which is only 150 m away, and because of the entrance of cool water only a few meters above this level, we propose that there is a hydraulic relationship between the Firehole River and the geyser at approximately this level. This relationship may be complex, indirect, and time dependent, and the previous sentence is not equivalent

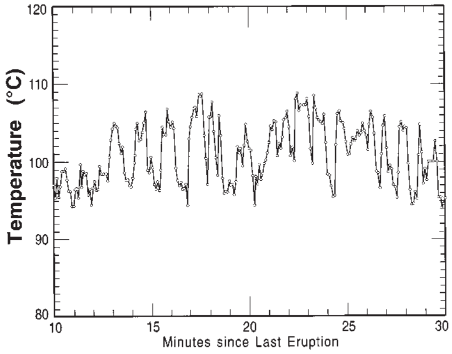

Figure 6. Temperature oscillations recorded October 2, 1984, at station 3 at 16.18 m.

to stating that Old Faithful is recharged by water from the Firehole River. For example, the water from an eruption may recharge the very local time dependent ground water around the vent of Old Faithful. On a longer time scale and at greater distances, this ground-water level may be controlled by the Firehole River. The water recharging from the ground water becomes mixed with the bank-storage water observed falling from higher levels; mixing of the cooler water with the hot geothermal water rising from the bottom of the chamber produces the variable temperatures.

HYPOTHESIS REGARDING THE REFERENCE BOILING CURVE FOR OLD FAITHFUL

In many hot springs, one can observe rising bubbles of noncondensable gas, typically CO_2. We have noted that there are bubbles of noncondensable gas in Old Faithful, and we ask, Is it plausible that these bubbles are CO_2? It is possible to estimate the CO_2 abundance if some simplifying assumptions are made about the geochemical equilibria in Old Faithful. After correction for steam loss during eruption as the temperature falls from 118 to 92 °C, the concentrations of Ca^{++} and K^+ at the bottom of the water column in Old Faithful were measured to be 0.47 ppm, and 19.5 ppm, respectively (unpublished data by Kieffer and Mike Thompson, U.S. Geological Survey, 1978). Assume that water entering the base of the water column is equilibrated with the K-feldspar + $2H^+$ = mica + quartz + $2K^+$ reaction and assume that the CO_2 content is buffered by the calcite + $2H^+$ = Ca^{++} + water + CO_2 reaction (Henley et al., 1984). For this case, the data permit a CO_2 partial pressure of 0.1 to 0.3 bar. The range arises from the uncertainty in the actual Ca^{++} and pH measurements in the Upper Geyser Basin. The pH of the water at the base of the column is estimated to be 7.6, changing to 9 at the surface because of the CO_2 degassing. More detailed calculations using Na^+ for charge balance and varying the assumed pH give CO_2 partial pressures from as low as ~0.003 bar to as high as 0.2 bar. Thus, although we are limited by the available geochemical data, we conclude that the observations to date suggest a significant presence of CO_2.

This discovery implies that any comparisons of *P-T* conditions in Old Faithful should be compared with a reference boiling curve for an H_2O-CO_2 mixture, rather than with the reference boiling curve for pure H_2O. Until the abundance of CO_2 is more precisely known, we cannot say whether the reference boiling curve coincides with the measured *P-T* conditions at depth, or still lies somewhat above them—but not as far as the pure H_2O boiling curve. This is an intriguing problem that could be addressed in the future with *P-T-X* measurements.

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