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Thermal and Seismic Indications of Old Faithful Geyser's Inner Workings

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Recent temperature measurements within Old Faithful combined with earlier seismic data provide a fairly broad knowledge of the mechanics of the geyser's action. The geyser tube, which is surprisingly deep, probably deeper than 175 meters, fills suddenly shortly after an eruption. Initially the water in the whole tube superheats, but the upper 60 meters soon cools as the boiling works its way downward. Finally, the hotter water below the 60-meter level rises to the top fairly rapidly, again superheating the water in the upper regions, causing the eruption to start. The boiling rapidly cascades downward, thrusting water from the reservoir to continue the eruption.

INTRODUCTION

Old Faithful Geyser in Yellowstone National Park, described first by the Washburn party in 1870, performs with remarkable regularity. Its visually observable behavior has been extensively recorded and described and the nature of its inner workings much speculated upon; but almost nothing has been known by direct interior probing about its structure, water supply, and heat source. The first attempt to obtain temperatures within Old Faithful made by *Allen and Day* [1935] was not successful. Using a thermometer attached to a 40-meter-long line, they reported that the line was affected by a 'strong horizontal circulation' and the thermometer could not be recovered. *Graton et al.* [1949] were more successful; using six thermocouples of short-time constant strung in tandem, they obtained records of temperature versus time to a depth of 21 meters through several eruptions of Old Faithful. They concluded that the most likely depth for initiation of an eruption is within the uppermost 4.5 meters of water, since throughout most of the quiet period, temperatures were everywhere well below the boiling curve. They also observed a strong circulation pattern within the geyser tube.

Further studies began in 1965, when seismometers were placed on the geyserite cone of Old Faithful [*Rinehart,* 1965; *Nicholls and Rinehart,* 1967] revealing a seismic signature relative to the circulation and heating of the water within the geyser.

The present temperature study was undertaken primarily to establish temporal and spatial patterns of heating and water circulation within the geyser and, by so doing, to explain its performance.

OBSERVATIONS

The seismic signature of Old Faithful has been well established by emplacing a vertical Hall Sears HS-10 seismometer on the cone of the geyser and recording the signals. The relation of the signals to the temperature measurements will be discussed later. During the January 1968 Yellowstone Field Research Expedition, extensive temperature measurements were made inside of the geyser tube. These measurements, coupled with the previous seismic observations, have revealed much about the inner workings of the geyser. It was not practically possible to record temperatures and seismic signals simultaneously, but fortunately the pattern of the geyser's performance is so regular that information obtained at one time can be unambiguously related to that obtained at another.

The temperatures were measured by lowering a single thermistor by cable down the throat of the geyser and leaving it at a fixed depth during several eruptions. The cable was attached to a single-channel Instrument Corporation of America Model 400 pen recorder operated most of the time at a paper speed of 2.5 cm/min and other times at 7.6 cm/min.

The geyser tube proved to be much deeper than the 30 meters originally anticipated, and in the end it was believed that a measurement was made at the extreme depth of 175 meters. Lack of cable prevented going still deeper.

There is some ambiguity as to the actual depths reached. First, the geyser tube may not stand vertical, in which case the depths quoted here are slant depths. Second, the cable may have been balling up at the bottom of a much shallower tube. The apparent straight-downward pull on the cable at all times and the general freedom of motion were such as to convince an experimenter that the weighted thermistor and attached cable were freely falling at all times. Further, the temperature patterns show progressive changes that seem most likely associated with changes in depth. In particular, the pattern changed markedly between the 60- and the 90-meter level, the range in levels at which the sediments merge into more solid rock in the surrounding terrain [*Fenner*, 1936].

The thermistor was weighted with a modified brass plumb bob and had a time constant of a few seconds and a temperature resolution of 0.5°C. Simultaneous readings at several levels were not possible with the single thermistor, although it would have been highly desirable. Again the great regularity of the geyser's behavior permits records taken at different times to be meaningfully related.

A total of twenty-eight intervals were successfully monitored: six at 15 meters, seven at 23 meters, seven at 30 meters, four at 60 meters, three at 90 meters, and one at 175 meters.

On three or four occasions the plumb bob was hurled from the geyser during an eruption by the uprushing water, but most of the time it remained below ground level, although probably not always at the depth it had been placed.

Temperature-Time Curve

The temperature-time curve was essentially the same down to the 60-meter level, and it more or less retraced itself from eruption to eruption. Below this depth pronounced changes occurred in the shape of the curve. A typical upper level curve taken at 30-meter depth is shown in Figure 1. Following an eruption the temperature remains constant at about 93°C for several minutes. This constancy in temperature would indicate that the thermistor is not immersed in water, but rather it is bathed in rising condensing steam. The boiling point of water at the elevation (2204 meters) of Old Faithful is 93°C. Exactly how long the temperature remains constant governs the time to the next eruption.

After a few minutes, the temperature rises abruptly to about 98°C, the abruptness of the rise suggesting that the thermistor suddenly becomes surrounded by hot water at this temperature. The temperature of the water then increases gradually to about 105°C, taking 10 to 20 min to do so. After this, it begins to cool, reaching in a few minutes a temperature of about 95° or 96°C.

Two or three minutes before the eruption the temperature begins to rise and shortly after the eruption starts, it goes up to 107° to 112°C.

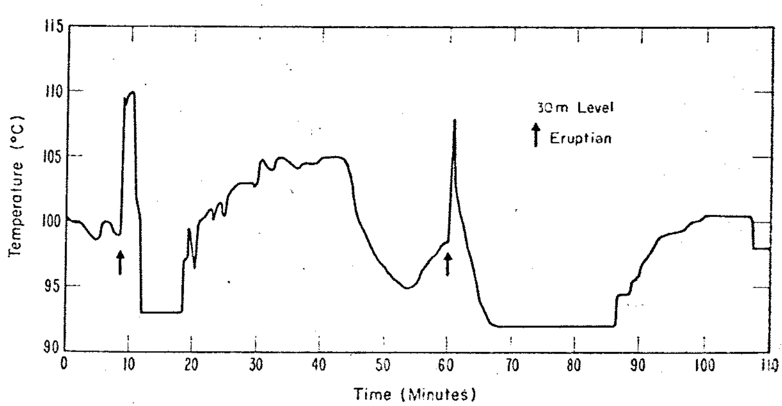

Fig. 1. Temperature-time curve at 30-meter depth. Record taken January 13, 1963.

The temperature decreases uniformly during the eruption, dropping finally to 93°C when the eruption is complete.

The appearance of the temperature-time curve changes significantly between the 60- and 90-meter depth. (See Figure 2.) The water at 90 meters remains at a temperature of about 105° or 106°C during most of the interval, there being no cooling phase. The rise in temperature preceding the eruption begins 5 to 10 min ahead of the eruption, earlier than the 1 or 2 min observed at the 15- to 60-meter depths. At the beginning of the eruption the temperature reaches 120°C, which is 8 to 10 degrees hotter than at the levels closer to the surface.

Superimposed on this constant temperature from 90 meters downward is a 1° to 2°C periodic variation of about 1 min. Somewhat similar rapid fluctuations were observed at 175 meters and in one instance at 15 and 60 meters. These fluctuations must indicate fairly regular upward and downward movement of water masses.

Only one complete record was obtained at 175 meters (Figure 3). It differs markedly from the records taken at other levels. For about 20 min following the eruption, the temperature rises gradually at a rate of about one-half of a degree per minute, except for the short period immediately following the eruption when the temperature remained constant at 93°C. The steady rise is interrupted by a great surge of extremely hot water, greater than 140°C, followed by a surge of cold water, which in turn is followed by another surge of extremely hot water; this rapid circulation all takes place in about 5 min. The curve finally levels off at 115°C, except for periodic excursions 5°C up and down. The temperature does not rise either as eruption time approaches or when the eruption is occurring.

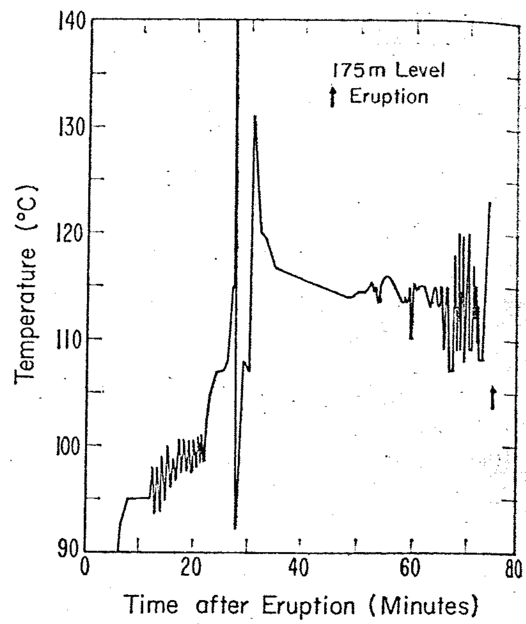

Fig. 3. Temperature-time curve at 175-meter depth. Record taken January 15, 1968.

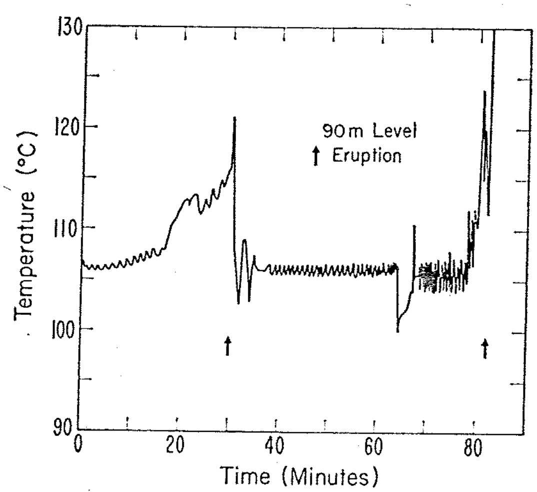

Fig. 2. Temperature-time curve 90-meter depth. Record taken January 15, 1968.

Filling

Each eruption either partially or completely empties the geyserite tube, which must fill again before the next eruption. Previous seismic records correlate well with the temperature-time profiles. The play of water during an eruption is either short (about 2 min) or long (about 4 min), although intermediate lengths of play are not uncommon. Long plays occur about twice as frequently as short plays. The length of play is usually an indication of a long or short interval to the time of the next eruption. The interval between the time of the last eruption and the time of filling (plotted in Figure 4 against the interval between the two eruptions) is closely related to the length of play going before it, and this in turn is necessarily closely

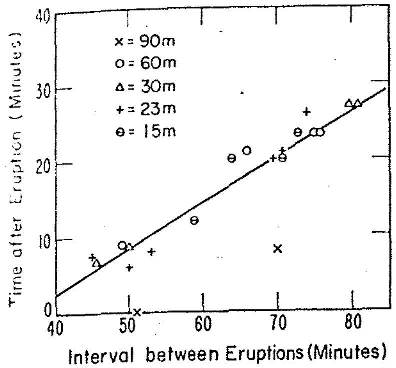

Fig. 4. Time after eruption at which tube fills as function of interval between eruptions. Depths of thermistor are indicated by respective symbols.

correlated with the time to the next eruption. The relationship is linear.

From the appearance of the temperature-time profiles, the ones shown in Figures 1, 2, and 3 plus others not shown, a short play empties the tube down to 60 meters but not to 90 meters, whereas a long play empties it down to 90 meters and perhaps to 175 meters if the single recording made at this depth is typical.

All the temperature data indicate that the tube fills quickly and that the water entering the tube is superheated a few degrees with respect to the ambient boiling point at the surface. Perhaps the substantial surge of hot water observed at the 175-meter level about 25 to 30 min into the interval (Figure 3) is typically indicative of filling.

A frequently observable aspect of the seismic signature of Old Faithful is a short series of substantial long-period movements, approximately 0.1 cps, lasting for a minute or so (Figure 5) [*Rinehart*, 1965]. These movements may be repeated a few minutes later, but then cease entirely. Occasionally this motion is accompanied by audible booming. It is reasonable to assume that these seismic and acoustic disturbances originate from the movements of subterranean waters at the time of filling, suggesting that the contents of an underground freshly filled reservoir are quickly transferred to the geyser tube proper.

Heating and Circulation

Once the geyser tube is filled, the water, originally at a temperature of 98°C, begins to heat up and after 10 to 15 min reaches a more or less constant temperature at 105°C down to the 60-meter level. There are two external manifestations of this change. At about the time the tube fills, several minutes after an eruption, the quiet lazy venting of steam from the geyser opening that follows the eruption is replaced by a continuing series of intermittent vigorous puffs of steam. At the same time, short high-frequency (20 to 50 cps) pulses of seismic energy of the type shown in Figure 6 begin to appear. The growth, collapse, and bursting of large steam bubbles within the column of water probably generate these seismic pulses.

A cumulative distribution of the number of

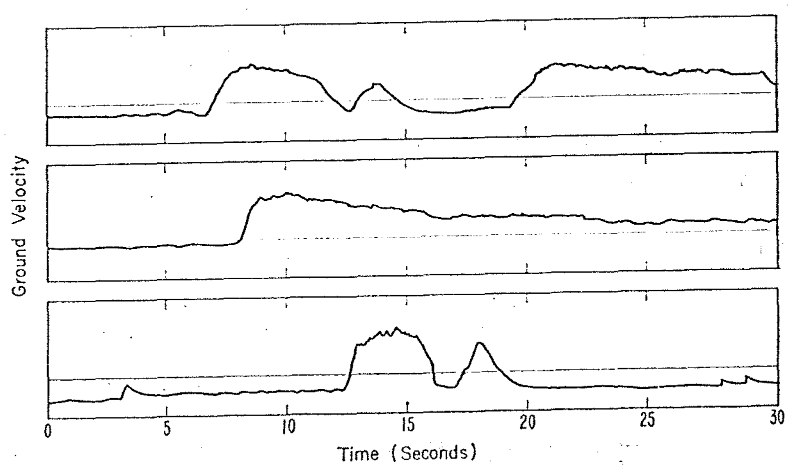

Fig. 5. Long-period seismic movements. Arbitrary vertical scale.

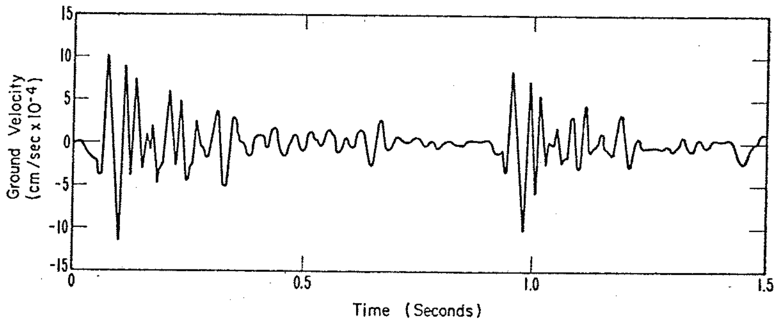

Fig. 6. Seismic high-frequency pulses generated by Old Faithful.

seismic signals as a function of time is shown for four successive eruptions in Figure 7. The rate varies from 50 to about 90 per minute. The total number of pulses per interval ranges from 1500 to 1800. Data taken from plots such as these indicate that the time at which the pulses start and the time of presumed filling correlate closely, as can be seen in Figure 8, where the time after the eruption at which seismic pulses begin is plotted against the interval of time between successive eruptions. Superimposed on Figure 8 is the straight line of Figure 4, which relates the time at which the temperature starts to rise, or the time of filling, to the interval between eruptions. The line from Figure 3 fits very well the points in Figure 8, suggesting that the time of filling and commencement of seismic pulses are concurrent.

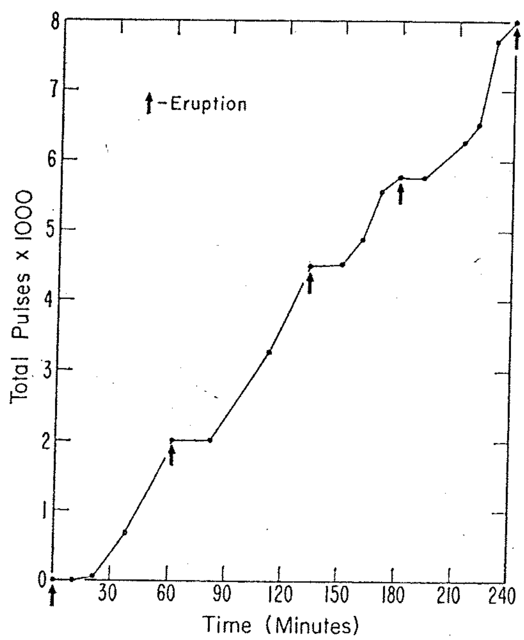

Fig. 7. Cumulative distribution of high-frequency seismic pulses of type shown in Figure 6. Record taken May 18, 1967.

Considerable circulation occurs after the seismic signals start, particularly at the 90- and 175-meter levels. Hot and cold fronts recorded by the thermistor pass every minute or so during the early phases of heating and represent temperature fluctuations of 1° to 2°C. A vigorous steam puff was often accompanied by a drop in temperature of 2° to 3°C, especially when the thermistor was at the 30-meter level, indicating that a hot steam bubble and its associated hot water had replaced cooler water at the surface, which then sank.

Boiling

The drop in temperature, down to the 60-meter level, which begins 30 to 50 min into the interval, suggests a change in the pattern of boiling. Previous observations of both seismic and steam activity have shown a lull in both activities at about this juncture.

The suspicion is that the drop in temperature is indicative of steady-state boiling gradually working its way down from the top. From 40 to 60 min into the interval the tube, to a depth of at least 60 meters, is in a constant state of agitation. This suspicion is further substantiated by an increase in high-frequency background noise (Figure 9) in the seismic signal, a characteristic of vigorously boiling hot springs. The bumping that superimposes itself on the vigorous boiling is associated with steam bubbles now being formed at greater depths, perhaps 90 to 180 meters.

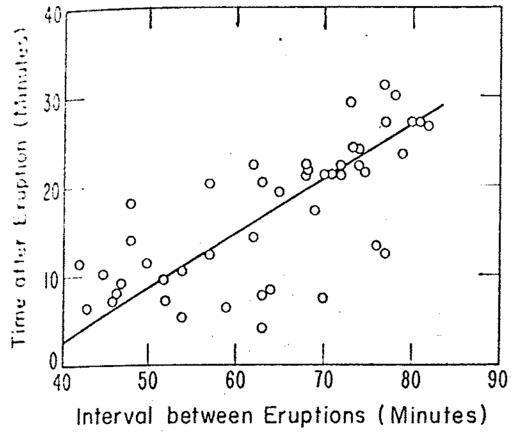

Fig. 8. Time after eruption of beginning of seismic pulses of type shown in Figure 6 as function of interval between eruptions. Straight line is taken from Figure 4.

Eruption

Finally the column of water erupts catastrophically, discharging large quantities of water to a height of 30 to 45 meters for from 2 to 5 min. Seismic signals have, as a rule, stopped about 2 min before the eruption. The temperature at the 90-meter level has been rising for 5 to 10 min before the eruption; at the upper levels, only 1 to 2 min before the eruption.

The thermistor was thrown out completely on a few occasions during the eruption, and at other times it was undoubtedly displaced by the uprushing water. It was usually repositioned properly within minutes after an eruption. There is, therefore, considerable ambiguity in the meaning of temperatures recorded during and shortly after an eruption.

At the upper levels the temperatures during an eruption rose to about 107° to 112°C, and at the lower levels, to about 120°C. Typically, the temperatures that rose abruptly at the time or shortly after the eruption began decayed more or less uniformly for the duration of the discharge. A high-resolution record taken at 23 meters is reproduced in Figure 10. An anticipated dependence of temperature on the length of the preceding interval or the length of play was not corroborated, but, in general, the higher the temperature was, the more spectacular was the eruption.

Two observations suggest strongly that the eruption mechanism is a downward cascading of the rapid conversion of superheated water into steam. First, during an eruption the water gushes out in distinct bursts. For example, nine major thrusts of water were clearly discernible during one 5-min play. Second, whereas the water in the tube is superheated with respect to the ambient boiling point at the mouth of the geyser, the water temperature at depth is far below the boiling point curve that must be applied to a vertical column of water. For example, at a depth of 60 meters the boiling point is about 204°C. Stepwise release of the hydrostatic head enables some of the water to flash to steam; the pressure of the steam hurls out the surrounding hot water.

If at the time of cascading the temperature in the lower regions is lower than might be expected, cascading stops short of the bottom and the play is short; when the temperature is comparatively high at these depths, cascading works itself down much farther and the play is long. The two cases are illustrated in Figure 11 by time-temperature curves taken at 60 meters for successive long and short intervals.

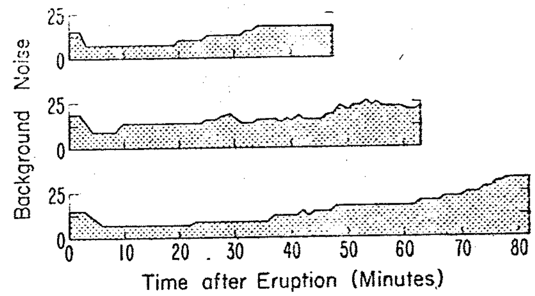

Fig. 9. Background noise in Old Faithful. Arbitrary vertical scale.

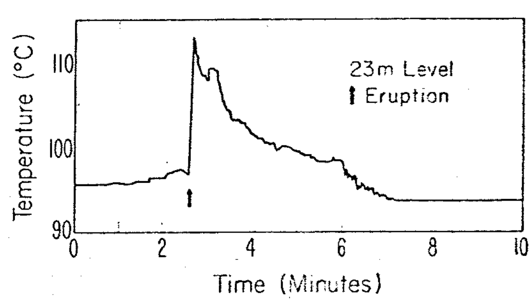

Fig. 10. High-resolution record of temperature at 23 meters during an eruption. Record taken January 12, 1968.

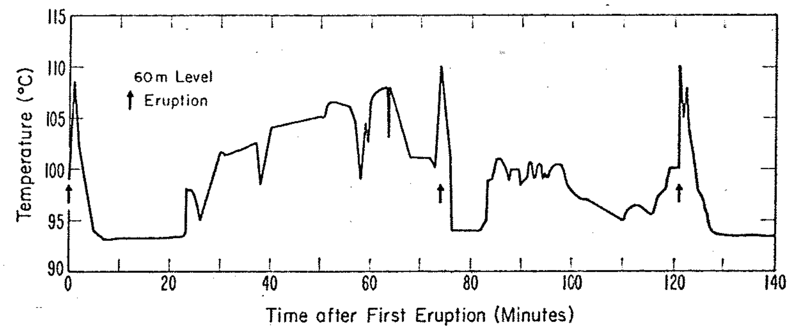

Fig. 11. Temperatures at 60 meters during two successive intervals. Record taken January 14, 1968.

Records of the intervals between eruptions that have been analyzed indicate that on the average a long play following a short play (short interval) is slightly, but significantly, longer by about 12 sec than a long play following a long play (long interval). This difference could be expected since the unejected water remaining at the depths has had the benefit of being heated during two intervals when the preceding play is short.

Summary and Conclusions

The present temperature measurements combined with earlier seismic data provide for the first time a reasonably complete broad record of the inner workings of Old Faithful Geyser. A plausible system is illustrated in Figure 12. Following an eruption the geyser tube, which extends down to at least 175 meters, fills suddenly and begins to heat. Soon boiling works its way down from the top, causing much of

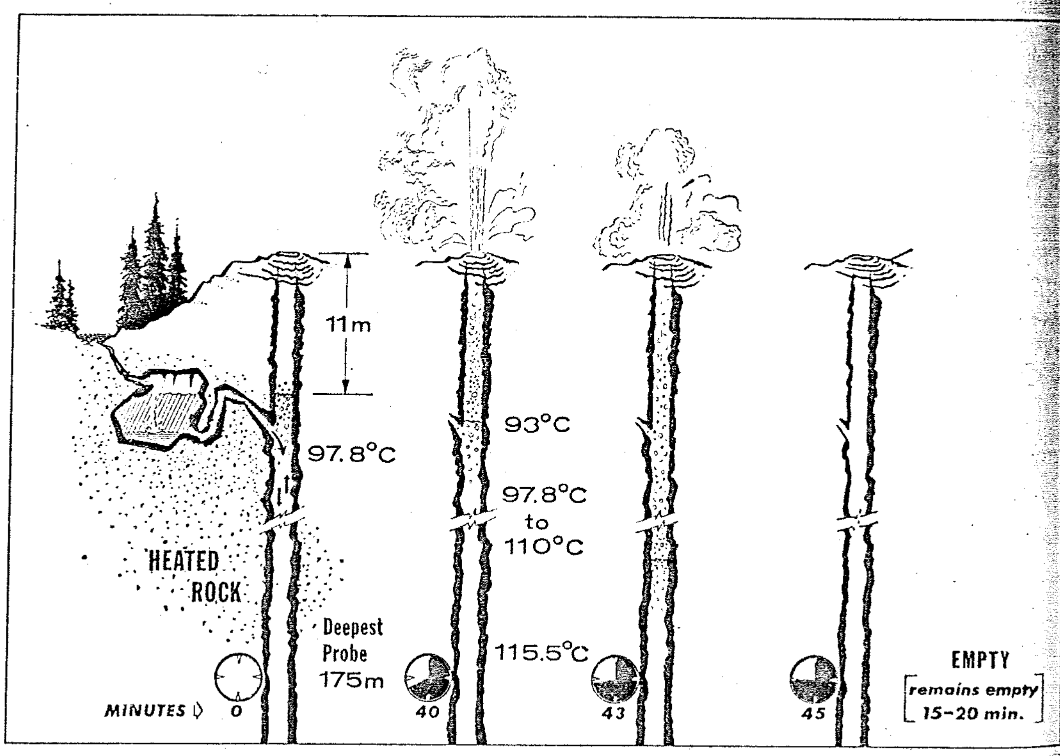

Fig. 12. Possible underground structure and mechanism of Old Faithful.

the column of water to cool down several degrees. During this time considerable mixing of hot and cooler water takes place. Rapid heating occurs just before an eruption. The eruption itself is a series of violent water ejections that are triggered and fed by the boiling action cascading downward.

Details of the reservoir system and the mechanics of filling are not yet clear. Filling occurs much sooner after a short than after a long play, but the reason for this is not understood. The partially filled tube remaining after a short play could conceivably influence the time at which siphoning from one reservoir to another takes place.

Acknowledgments. In conclusion I wish to acknowledge the very great help of Mrs. Anabeth Murphy, who reduced most of the data, the extremely helpful cooperation of the Yellowstone National Park officials, and the opportunity Dr. Vincent Shaeffer gave me to participate in his National Science Foundation supported January 1968 Yellowstone Field Research Expedition.

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