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HEAT FLOW FROM NATURAL GEYSERS

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SUMMARY

A natural geyser is a mechanism that extracts heat from the earth. Trapped meteoric water is heated and then thrown clear of its reservoir as hot water or steam, carrying heat with it. There are two basic types of geysers: columnar, discharging quantities of hot water; and pool, in which the eruption consists of a series of detonating steam explosions. Results of temperature measurements made deep within several geysers permit calculation of their respective approximate rates of heat extraction. Old Faithful, which discharges large quantities of water, extracts heat at the approximate rate of $1.34 \cdot 10^6$ cal./sec. Narcissus, an explosive type geyser, develops power at the approximate rate of $3.3 \cdot 10^3$ cal./sec, and Solitary, another explosive geyser, at the rate of $6.4 \cdot 10^3$ cal./sec.

INTRODUCTION: DESCRIPTION OF GEYSERS

A natural geyser is a mechanism that extracts heat from the earth. Meteoric water, trapped in porous rocky reservoirs close to the surface of the earth, is heated and some is then thrown clear of this reservoir in the form of hot water or steam.

There are two basic types of geysers: columnar, and pool. In a columnar geyser, the eruption consists of a series of detonating steam explosions fed by sporadic overturning of water in the pool with little water being discharged. This overturning is triggered by the density difference that develops between cool heavier water at the top and hot lighter water at the bottom.

Extensive temperature measurements made at Yellowstone National Park; Beowawe, Nevada (Rinehart, 1968, 1969b); and Adel, Oregon by Rinehart, have established both temporal and spatial distributions of the temperatures in a number of geysers. Generally it is found that water enters and fills columnar geysers, such as Old Faithful in Yellowstone and Crump at Adel, shortly after each eruption and begins to heat up slowly. The temperatures of the water both near the top and at depth remain for a long time below the boiling-point pressure curve; but the temperature of the water near the six to seven meter level soon rises above the curve and

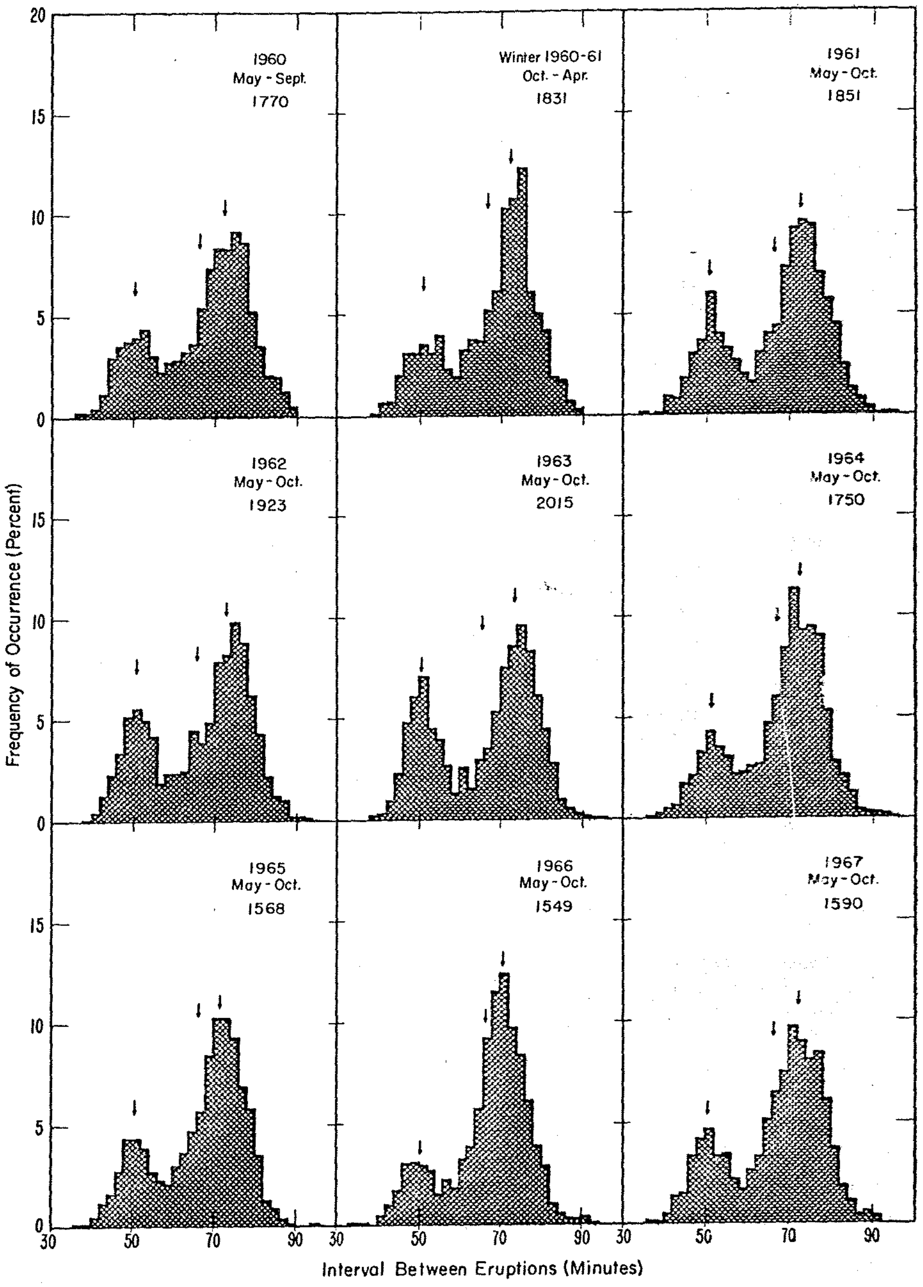

Fig.1. Frequency distribution of intervals between eruptions of Old Faithful Geyser for the summer seasons 1960–1967 and one winter season 1960–1961.

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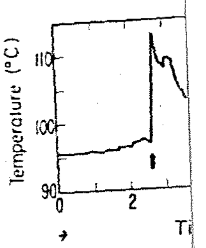

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some boiling takes place. The rising steam bubbles are quickly cooled and condensed by the upper water which is thus further warmed. When the upper water no longer has the heat absorbing capacity to condense the steam rising from below, the head of water that has suppressed boiling is blown off and the geyser begins its vigorous eruption. Geyser action cascades downward partially or totally emptying the tube.

Old Faithful Geyser is at least 200 m deep. The intervals between eruptions of Old Faithful are bimodally distributed (Rinehart, 1969a), the lower mode being 50 min and the upper mode about 70 min, individual intervals ranging from 30 to 90 min (Fig.1). The longer intervals are about twice as prevalent as the shorter ones. The amount of water thrown out determines the time to the next eruption. A short play is followed by a short interval and a long play by a long interval. The quantity of water ejected has never been carefully monitored but is estimated to average 50,000 l per eruption (Allen and Day, 1935). The temperature of the water, which at the beginning of an eruption is about 112°C, as shown in Fig.2, decreases uniformly during the eruption to the ambient boiling point of 93°C at Yellowstone. As the superheated water boils, its heat is used to form steam.

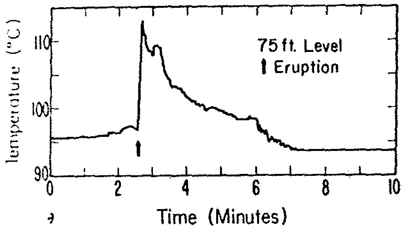


Fig.2. Temperature of water near mouth of Old Faithful Geyser during an eruption.

Narcissus Geyser, near Firehole Lake, Yellowstone National Park, is a pool type geyser having an hourglass shaped vertical cross section. It is about three meters in diameter at the top, narrows to a 0.6 m diameter pipe about 2 m down, and then opens up again toward the bottom, the total depth being 6.5 m. It fills slowly between the eruptions which occur at alternating intervals of two and four hours. The eruption consists of a succession, sometimes more than 300, of detonating explosions, a few throwing water and steam to a height of 10 m. Eruption appears to take place when relatively light superheated water at the bottom of the hourglass, 6.5 m down, becomes unstable and rises to the top where it flashes to steam. Bottom and top temperatures are plotted through several eruption cycles in Fig.3. The water at the bottom reaches a temperature of about 105°C, 12°C above the ambient boiling point, before the eruption takes place. The temperature in the bottom chamber for a height of about 2 m is nearly constant. During the long four hour interval, the water overturns a few times without an eruption taking place. Three such overturnings are discernible, e.g., Fig.3, between the second and third eruption. The top is suddenly heated and the bottom cooled. The eruption erases all temperature and density differences between the top and bottom.

Solitary Geyser, located high on the side of the Upper Geyser Basin in

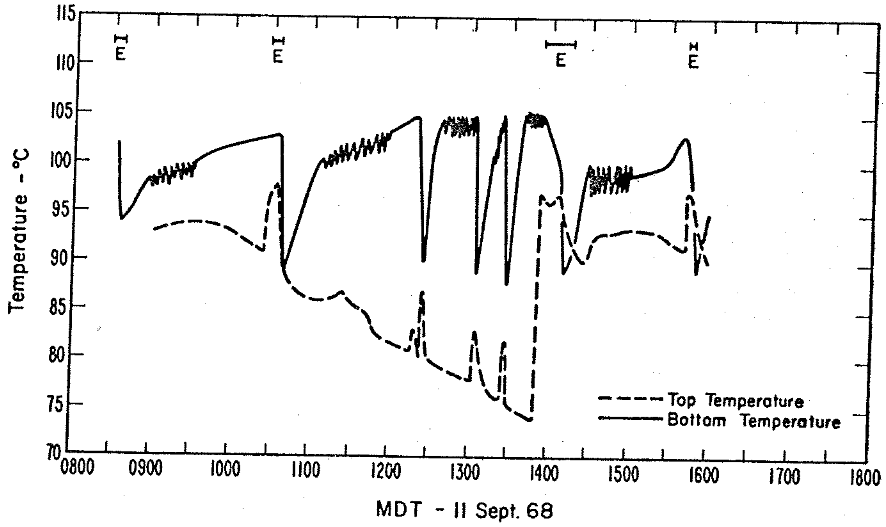


Fig.3. Temperatures near top and near bottom of Narcissus Geyser as a function of time. *E* indicates eruption.

Yellowstone National Park, is another such pool geyser. It is about 20 m in diameter, constantly filled with water. It erupts every six to seven minutes, the eruption consisting of a succession of detonating steam explosions which last a minute or so. Each explosion, as in Narcissus, is the result of a mass of water rising from below and suddenly flashing into steam. Extensive temperature measurements made down to a depth of 270 m definitely establish (see Fig.4) that the water is heated from below by a series of injections of 160°–170°C water occurring at intervals of about one minute. For a few minutes after each eruption, fairly extensive circulation takes place down to about the 140 m level. This is followed by a quiescent period during which the water stagnates and at each level stays at about a constant temperature. Suddenly a blob of light superheated water rises to the top where it turns to steam, and cooler top water drops downward to replace it. After several such excursions (Fig.5), the eruption period stops, the water in the basin

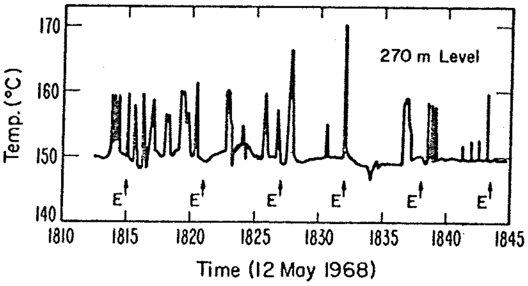
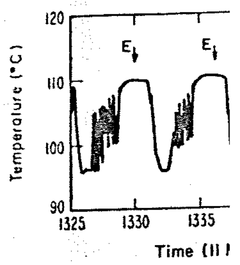


Fig. 4. Temperature as a function of time at a depth of 270 m in Solitary Geyser.



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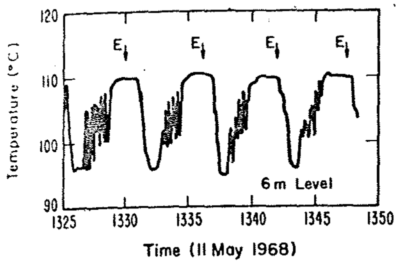

Fig.5. Temperature as a function of time at a depth of 6 m in Solitary Geyser. Note the circulation. *E* indicates eruption.

becomes stable, and a new heating and circulation cycle begins. Fig.5 shows how the temperature fluctuations at the six meter level and the eruptions at the surface are related.

HEAT FLOW CALCULATIONS

The heat flow from Old Faithful can be readily and fairly accurately calculated using the recently acquired temperature data (Rinehart, 1969b). The seasonal average of intervals between eruptions is now about 66.5 min. Most of the water ejected from Old Faithful is meteoric and as such entered the catch basin at the mean ambient air temperature of that area, approximately 5°C. The measured temperature of the water as it begins to emerge (Fig.2) is 112°C. Since the ambient boiling point at the geyser opening, at 2204 m altitude, is 93°C, only about four percent of the total water ejected will flash into steam. The total heat required to raise to 50,000 l of ejected liquid water from 5°C to 112°C is $5.35 \cdot 10^9$ cal. This heating operation is accomplished on the average once every 66.5 min, making the rate of heat output $1.34 \cdot 10^6$ cal./sec.

It is somewhat more difficult to establish the heat flow from Narcissus Geyser, since the water runoff from it is negligible and the underground reservoir dimensions cannot be measured directly. Flashing of superheated water into steam is the principal mode of transfer of heat from this geyser to the atmosphere. Temperatures at the top and at the bottom as a function of time are plotted in Fig.3. It is possible from these to estimate the total volume of water in the bottom portion of the hourglass shaped reservoir. Three cases of mixing of the bottom hot water with the top cooler water are evident (see, for example, 1329, 11 Sept. 1968, Fig.3). From the relative temperature increase and decrease, it appears that the top reservoir is about three times as large as the bottom reservoir since during mixing the decrease in temperature of the bottom water is nearly three times the increase in temperature of the top water. The top accessible reservoir can be measured as having a volume of $9.0 \cdot 10^6$ cm^3, making the volume of the lower reservoir $3.0 \cdot 10^6$cm^3. At the time the eruption begins, the bottom water is at a temperature of 105°C. When this hot water rises to the top, the explosions and mixing cool it to the ambient boiling point of 93°C. The total heat liberated per eruption is this temperature difference, 12°C, times the volume of water, $3.0 \cdot 10^6 cm^3$, or $36.0 \cdot 10^6$ cal. Part of this heat is used to heat the water in the upper reservoir and eventually is taken up by the atmosphere as the top cools down between eruptions. Taking the average of the two and four hour intervals between eruptions as three hours, the rate of heat flow is $3.3 \cdot 10^3$ cal./sec.

An eruption lasts from 5 to 15 min, averaging 10 min, during which an average 200 explosive bursts occur, the number of bursts being almost directly proportional to the interval between eruptions. Each explosive bubble carries away about $1.8 \cdot 10^5$ cal. of heat.

Heat flow from Solitary is even more difficult to estimate. While the temperature profiles are known (Fig.4, 5), the volume of water cannot be established. The size and number of steam bubbles provide perhaps the best basis for estimation. The average interval between eruptions is about seven minutes (Fig.5), each eruption lasting for about one minute during which something like ten steam explosions occur. From the calculations on Narcissus, each blob of its superheated water that flashes into steam contains about $1.8 \cdot 10^5$ cal. of excess heat which it can deliver to the atmosphere. The water in Solitary is 7°C hotter than that in Narcissus (Fig.5) so that perhaps each explosion in Solitary represents $2.7 \cdot 10^5$ cal. of energy. With these somewhat arbitrary assumptions, the heat flow from Solitary is of the order of $6.4 \cdot 10^3$ cal./sec, about 50% more than Narcissus.

REMARKS

The magnitudes of these heat flows are many times larger than the world average of $1.5\ \mu$ cal./$cm^2 \cdot$sec, and much greater than the high values of heat flow of $40\ \mu$ cal./$cm^2 \cdot$sec given for geothermal areas (Elder, 1966). Taking the latter value, the heat flowing from Old Faithful must have been extracted from an area of 3.4 km^2; for Narcissus, the area would be $8.3 \cdot 10^{-3}$ km^2; and for Solitary $16.0 \cdot 10^{-3}$ km^2. These values are compatible with visual observations. Old Faithful lies at the head of a large catch basin whose dimensions could easily encompass an area about 1 km in diameter. Narcissus and Solitary are both isolated geysers whose performances might be expected to be affected by only very local conditions.

The above values of heat flow are entirely consistent with White's views (1967) of the extensiveness of the heat and water reservoirs involved in geothermal activity. These three geysers, of course, constitute only a small part of the total geothermal activity of Yellowstone for which the U.S. Geological Survey (Marler, 1969) estimates heat flow at the rate of $840 \cdot 10^6$ cal./sec.

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