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SEASONAL CHANGES IN GROUND WATER IN RELATION TO HOT SPRING ACTIVITY*

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ABSTRACT. The behavior of many of the thermal springs in Yellowstone National Park indicates they are affected, not only by the level of the ground water, but by its temperature as well. This is true of springs that show limited water supply as well as springs that seem to be deep seated or at least connected with a stable source. The latter springs, particularly a number of the better known geysers, are on the floors of the principal basins and show no changes that reflect changes in air temperature; instead their eruptive activity is affected by the temperature of the ground water. As the great bulk of the meteoric supply results from melting snow this annual replenishment cools the whole body of ground water, and many of the springs show changed patterns of behavior. On the other hand during the season when addition of meteoric water is at a minimum, many springs are influenced by a warmer body of ground water. Water from winter snow becomes available to the thermal springs in the Lower Geyser Basins at a different time of the year than it does in the Upper Geyser Basin.

INTRODUCTION

Most of the flowing hot springs in Yellowstone Park show little or no fluctuation in discharge attributable to the season of the year. In the main these springs are situated on the floors of the principal basins. The source of their water permits nearly constant replenishment. On the other hand, numerous springs scattered throughout the Park show rhythmic response to the season of the year. The great majority of these springs discharge little or no water. They are situated on hillsides or perched above the floors of the main basins. With the advance of the season the water table sinks lower and lower, until by late summer many have dried up and become fumaroles. Such springs have their sources in or near rhyolite, whereas the springs in the basins have their sources in glacial gravels, which in places are hundreds of feet thick (Fenner, 1936, p. 232-233).

In areas or basins in the Park where discharge is highest, springs that show seasonal fluctuation in water level are generally few in number and are largely confined to the periphery of the basins. One of the few exceptions is found in the Midway Basin, in the lower part of the Rabbit Creek drainage. Many large springs in this area sink lower and lower with the advance of the season. Whereas all these springs have their sources in gravels, they are on the distal end of glacial outwash, which has been incised by the Firehole River so that ground water shows marked seasonal changes.

UPPER BASIN OBSERVATIONS

According to observations of the geysers and hot springs in the Upper Geyser Basin made by the author during the winter of 1951 and 1952, the discharge of all flowing springs was relatively constant and not less than summer discharge. Further, the geysers showed no decline in temperature or activity attributable to the weather (Marler, 1954, p. 53).

Winter measurements of discharge have never been attempted. The hot-spring activity of winter, however, furnishes some very useful and important

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data. All geysers for which eruption records were kept, with the exception of the Lion, showed an increase in discharge over the previous summer record. This increase, as reflected by their increased activity, was marked for Grand, Giant, Beehive, Splendid, and Riverside (Marler, 1954, p. 41-45). There was no evidence of diminishing flow from any spring. Since spring effluents are lined with algae, even minor waning in discharge is immediately apparent by the state of the algae.

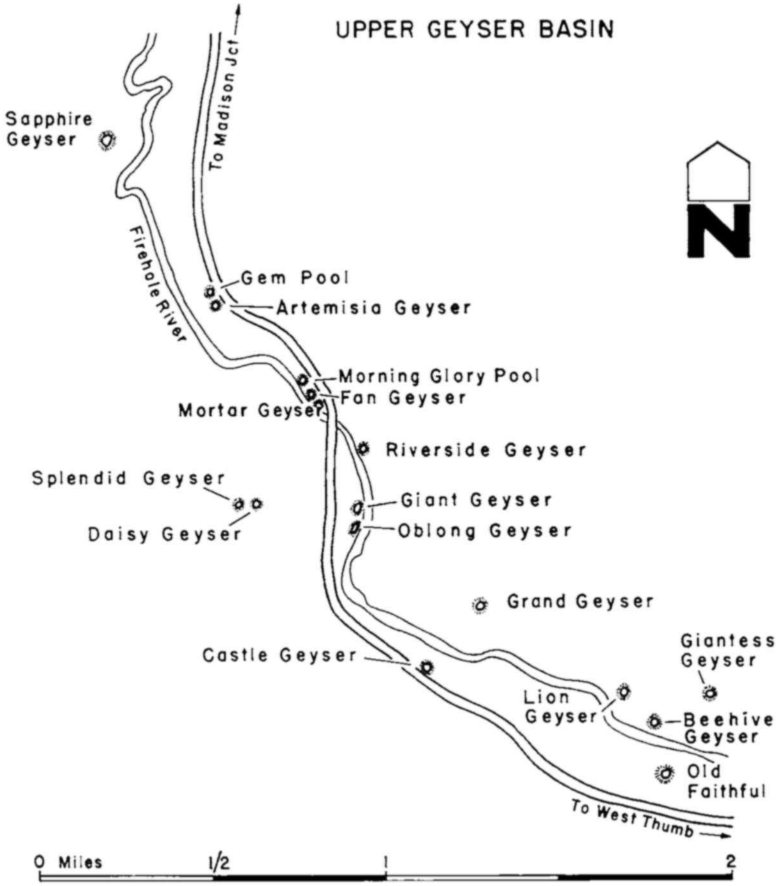


Fig. 1.

Instead of the eruptions of geysers diminishing in frequency in winter, which has been postulated by many observers (Sawyer, 1926, p. 24; Phillips, 1927, p. 144), detailed records showed the opposite. The fact that at least three of the geysers, Beehive, Riverside, and Splendid, shifted back to their previous summer pattern following the melting of the snow proved that the 1951-1952 increase in winter activity was not capricious or coincidental. Further, early spring observations of Splendid Geyser during its active cycle in the 1950's presented certain evidence that it had been more active during at least late winter than it was during the ensuing summers.[1] From these observations it was concluded that if the increase in activity in winter of some Upper Basin geysers was real, perhaps it was due to the fact that the ground water was slightly hotter in winter than in summer due to the heavy snow cover on the surrounding plateau plus the low atmospheric temperature. These conditions would not only slow, but practically stop, the movement of meteoric water into the basins (Allen and Day, 1935, p. 227).

That water from the spring runoff is available at an early period to many Upper Basin springs is suggested by two separate lines of evidence.

(1) In May 1947, the author noted that in a matter of days following the start of melting snow on the slopes leading to the basins, a number of springs lose their pellucid hue and take on a color character very similar to the water of the melting snow. During this short period, lasting about two weeks, the water in the affected springs, including Morning Glory, is rich in humus, a condition indicated by the color of the water and by a pronounced odor of cooked organic matter.

It is quite certain that the water from the spring runoff does not enter the above springs from the Firehole River which courses through their midst, as the springs become limpid two to three weeks before the river water clears. The quite sudden roiling and clearing of these springs suggests that the snow water traverses a crack or small fissure in reaching them. It is highly improbable that slow percolation through the gravels could result in the above observed condiiton and the rapidity of the change.

(2) A second line of evidence suggests that a body of cooler water resulting from melting snows is made available at an early period to Upper Basin springs. A few geysers show increased frequency of activity with the advance of the season; with the probability, as already pointed out, that a few erupt more frequently in winter than in summer, indicating a gradual increase in temperature of ground water following the spring runoff.

On the Park's Main Plateau where the geyser basins are located the bulk of the snow melts in late May and early June. This is the time of the year when the greatest amount of water is absorbed by the ground. That the heavy replenishment of snow water has a general cooling effect on the hot springs in the Upper Basin is indicated by comparative temperature data. Data for the greatest number of springs were obtained in 1952. When the June and September readings are compared for 139 springs, the gain in temperature in September over that of June was 63°C; an average gain of about a half a degree per spring. Due to the delicate balance of some of the geysers, this much change in temperature is sufficient to affect eruptive activity.

The following table shows comparative eruptive data for the major geysers in the Upper Basin. To date the 1951-52 winter is the only one during which systematic observations of the geysers have been made. For location, see map of Upper Geyser Basin.

The problem of determining whether a geyser erupts more frequently in winter than in summer, or vice versa, becomes quite complicated due to the

[1] Periods of increased activity can be determined by the state of the fragmental sinter surrounding the crater and by the state of the algae in the drainage channels.

TABLE 1

	1951 May through September	1951-52 November through March	1952 May through September
Geyser	Average interval	Average interval	Average interval
Giant	5 days 15 hrs	3 days 8 hrs	2 days 4 hrs*
Daisy	2 hrs 45 min	1 hr 49 min	2 hrs 48 min
Castle	13 hrs	13 hrs 6 min	13 hrs 18 min
Grand	20 hrs	14 hrs 45 min	14 hrs 30 min
Beehive	3 days 18 hrs	2 days	2 days 23 hrs
Riverside	7 hrs 25 min	7 hrs 3 min	7 hrs 25 min
Giantess	1 eruption	2 eruptions	0 eruption
Splendid	6 days	2 days 16 hrs	5 days 15 hrs
Old Faithful	63.1 min	62.9 min	64.9 min

* In February, 1952 there was a shift of the thermal energy from Grotto Geyser to Giant. This resulted in increased activity of Giant during the remainder of the winter and throughout the 1952 season.

periodic shifting of the thermal energy. There are abundant data supporting the hypothesis that very few of the hot springs are isolated units. In general the numerous springs which make up the groups or clusters are connected underground. The shifting of the focus of thermal energy from one spring to another, which is a common occurrence, takes place independently of the season of the year (Marler, 1951, p. 329-342).

Observations which have been made in the Lower Geyser Basin during the past five years also reveal that the temperature of the ground water has a distinct bearing on the behavior patterns of major geysers. However, the movement of the ground water in the Lower Basin, and the time of the year that the bulk of this water becomes available to the thermal springs is quite different from that of the Upper Basin.

LATE SEASON OBSERVATIONS IN LOWER BASIN

Until November and December 1957, no late-season observations of geysers in the Lower Basin were ever attempted. Systematic winter observations are still lacking. During the November-December period it was discovered that a number of major geysers were not only playing less frequently than in summer, but one, Great Fountain, occasionally showed a pre-eruption behavior pattern quite at variance with its summer performance. Its eccentric behavior will be described in some detail because of its bearing on other variant hot-spring patterns that are seasonal in the Lower Basin.

The first indication I had that Great Fountain might have a different behavior pattern than had ever been noted in summer was on November 19, 1957. On this particular occasion the progress of the overflow, and other pre-eruption symptoms, indicated that an eruption could be expected in about ten minutes. Never having photographed this geyser in winter surroundings (the day was clear) I selected a favorable position and awaited an eruption. After waiting over half an hour and becoming more and more perplexed because of

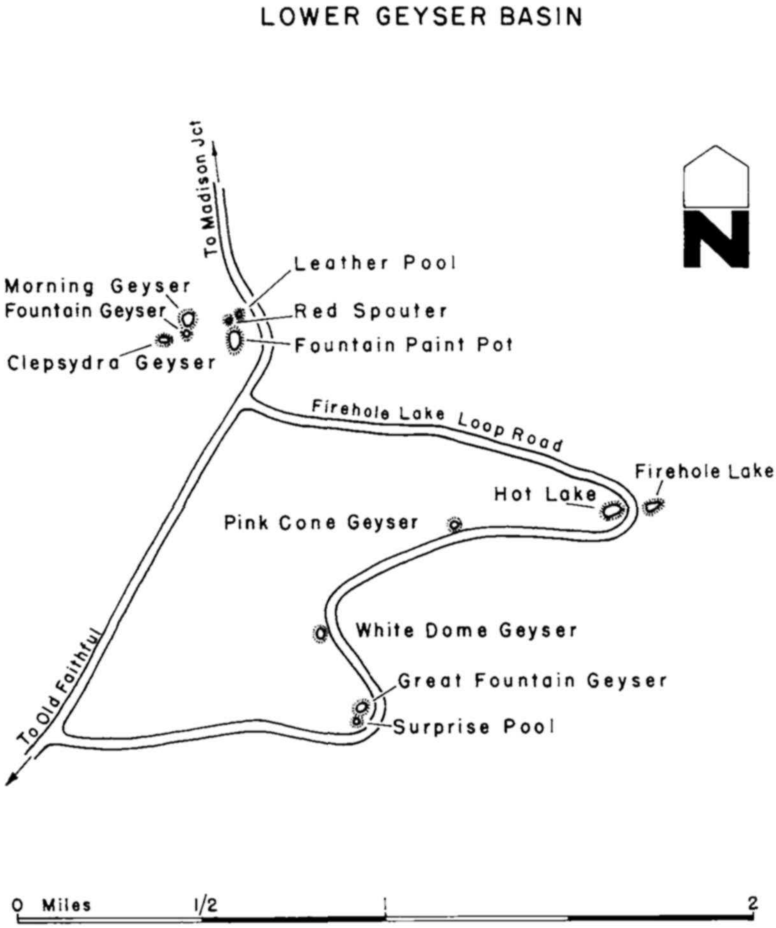


Fig. 2.

no eruptive activity, I approached the crater. To my surprise, no change in the degree of boiling had taken place during the period of waiting. After further vigil there was still no change. Three hours later I returned to find the same state of overflow and that the boiling was no more vigorous than when first observed.

Before leaving the scene I placed markers to determine if an eruption might take place during my absence. When visited on the 20th, both morning and afternoon, no eruption had occurred. It was still in what looked like the late stages of overflow preceding an eruption, which normally took place about every twelve hours. Sometime during the night of the 20th, it erupted. Twice more during November and once in December this same overflow condition was known to have occurred, lasting for periods comparable in length to the first observation. This same condition was observed twice during November 1958. Due to the closing of the road I was unable to observe Great Fountain during December 1958.

The 1959 Hebgen Lake earthquake resulted in Great Fountain undergoing marked changes both in frequency and duration of its eruptions. Eruptive activity from August 17, the time of the earthquake, to the end of the year occurred nearly twice as frequently as during any previous period on record. The period of overflow preceding an eruption also was shortened, and certain pre-eruption symptoms underwent change. Due to a local increase in thermal energy or minor alterations in underground structure (possibly both), no abnormally long periods of overflow occurred during the early winter of 1959 and through 1962. At least none was noted, and frequent checks were made.

On November 8, 1962, when a routine check was being made at Great Fountain, it was noted that the flow of water of an earlier eruption from the large circular terraces surrounding the crater had completely stopped. Many years of observation had shown that when this situation exists sufficient time has elapsed since the previous eruption for this geyser again to be near a state of overflow. The overflow precedes the eruption by about an hour. Not only was there no evidence of immediate overflow, but when the crater was approached it was discovered that the water stood 8 to 9 feet below the rim of the crater, with the water relatively calm except for occasional sizzling where surface tension was broken near the walls. Such a condition as this was without record and unprecedented in 25 years of personal observation. It had been observed that always following an eruption of Great Fountain there was near constant surging and ebullition in the crater as it gradually refilled, with water never being more than 3 or 4 feet below the rim of the crater.

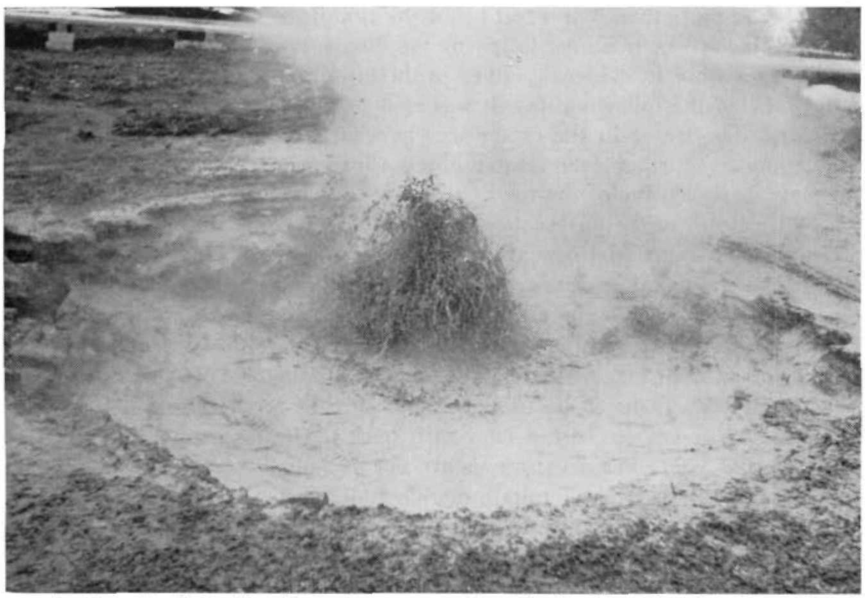
During a 3 hour period following the discovery of low water in the crater, no changes were in evidence, either in the rise in temperature or water level. When visited the following day, it was evident that one or more eruptions had occurred. The water in the crater was in what is considered a normal state. Unfortunately further late season observations were impossible due to abnormally early closing of the road.

As a result of the observations made at Great Fountain in November and December 1957 my first conclusion was that, in spite of all previous observation to the effect that geysers are not affected by atmospheric temperature, here was one that showed response to the cold of winter. Long observation, however, had firmly established the fact that most geysers are quite eccentric. After long periods of more or less set patterns of eruption, the nature of their activity can vary considerably, due to an underground shift of the thermal energy to another spring or geyser, with a later shift back to the former pattern (Marler, 1951, p. 329-342). These variations are not dependent upon the season of the year. In the case of Great Fountain there certainly was the possibility that these long periods of overflow merely represented a shift to some previously unobserved condition, wholly unrelated to atmospheric temperature.

Observations made during this period in the Fountain group of hot springs (see map of Lower Geyser Basin) suggested an explanation for the cause of these long periods of overflow of Great Fountain which is quite apart from possible effects of external temperature or a shift of the thermal energy; an explanation that might be more fully in accord with the facts. It also offers an

PLATE 1

A.



B.

A. Fountain Paint Pot. This picture was taken October 8, 1962, following a 15-inch rise in general level of the liquid part of the crater. The small active cones in the background have formed since the 1959 earthquake. The steam beyond the rail is from new mud springs which developed following the quake.

B. Red Spouter—November 5, 1961. Winter liquid phase. Some of the mud blobs go up about 10 feet.

C.

C. Red Spouter—July 8, 1961. From about June 1 until about October 1, Red Spouter is a powerful fumarole.

explanation for the unusual state of Great Fountain observed on November 8, 1962.

OBSERVATIONS IN FOUNTAIN GROUP IN LOWER BASIN

During the 35-day period in November-December 1957 that the geysers in the Fountain Group were under observation the activity of the major geysers was well below that of the previous summer. In June as well as in July, Fountain, Morning, and Clepsydra were each known to have had six eruptions. During August they were known to have erupted 19 times. In September, between the first and the twentieth, 19 more eruptions occurred.[2] Due to absence from the Park, no more observations were made until November. During November and December but six eruptions of Fountain and six of Morning were determined. Clepsydra did not erupt, yet they had been active from two to three times weekly during the summer. As a result of the 1959 earthquake, Fountain

[2] That the same number of eruptions is reported for these geysers might seem somewhat anomalous. They are connected underground and in their eruptive behavior there is a chain action. The function of Morning Geyser stimulates the others.

and Morning became dormant. Nearby Clepsydra was stimulated into constant eruptive activity, which has not ceased since the time of the quake.

Marginal observations made during the 1950's (late fall and early spring) presented certain evidence that none of the major geysers in the Fountain Group is as active in winter as in summer. When observed in the spring, it was always noted that the sinter surrounding the craters of Morning, Fountain, and Clepsydra showed no evidence of recent activity. Further, the growth of the algae in the margins of the craters of Morning and Fountain (Clepsydra is a cone-type geyser) indicated a period of dormancy.

The decline of activity in this group in winter posed a rather complex problem. That this decline might result from surface cooling is highly improbable. This assumption is based on the observations that geysers with large open craters, such as Morning and Fountain, are not affected in eruptive activity by low atmospheric temperatures. The geysers to which reference is made are located in the Upper Basin and include Grand, Oblong, Giantess, Artemesia, Sapphire, etc. (Marler, 1954, p. 41-45). It would seem that in winter an opposite condition between the Upper and Lower Basin exists in regard to the functioning of the bigger and better known geysers.

WHAT THE FOUNTAIN PAINT POT SPRINGS REVEAL

The Fountain Paint Pot is a part of the Fountain Group (pl. 1-A). Observations made here in late 1957 seemed to offer a satisfactory explanation, not only for the unusual behavior of Great Fountain but for declining activity in winter of many geysers in the Lower Basin. Whereas the Paint Pot is very different in character from nearby springs in the Fountain Group, its close proximity makes it highly probable that it and all springs in this group are connected, in varying degrees, to the same source. Further, if connections exist, any variations in supply and temperature of ground water might be reflected in all springs in the group.

When the Fountain Paint Pot was observed in mid-November 1957, I was greatly surprised to note that the mortar-like mixture was more fluid than it had been in September; also that the general level of this large mud cauldron had risen over a foot. The nature of the activity made it highly suggestive that the temperature had declined from its September reading, 95°C. Readings taken on December 3 and 13 showed the temperature to be 90°. The temperature had also dropped in both Fountain and Morning. In September the temperature of Fountain was 72°, Morning 90°. By December these temperatures had dropped to 67.5° and 87.5° respectively. At this elevation water boils at 93°C.

Heavy storms will noticeably increase the fluidity of mud springs due to their inherent and necessarily scanty water supply. In trying to interpret the cause of the conditions existing in the paint pots, this factor was given due consideration. However, there had been no recent storms of any consequence in the area. Further, it was a period of drought in the Park. The possibility that the increased water supply and lower temperature might be seasonal presented itself. Comparative data for these speculations were completely lacking. However, during the succeeding five years the state of the Fountain Paint Pot has been closely observed. These observations clearly indicate that the late autumn change described for these mud springs is indeed seasonal in its recurrence.

The most plausible explanation for this condition is that meteoric water available to these springs is augmented in early autumn, rather than immediately following the melting of winter snow. Certain effects of the 1959 earthquake support this hypothesis. The quake not only greatly stimulated and increased the areal range of activity of the Paint Pot and caused a rise in water level, but new mud springs began developing outside the main crater to the north. By mid-September 1959, one of the new springs, under considerable steam pressure, was ejecting reddish colored muddy water. It was given the name Red Spouter (pl. 1-B).

During all of the 1959-60 winter the Red Spouter, without any known cessation, ejected its tinted liquid. By the end of May 1960, when the melting of snow on the surrounding plateau was at a maximum, the liquid part of the eruption ceased, resulting in the Spouter becoming a hissing steam vent (pl. 1-C). At this same time, the Paint Pot began its seasonal drop in level.[3] In late September, Red Spouter again changed its state to that of a steady geyser, and synchronously with this transition, the mud began rising and thinning in the Paint Pot. During all succeeding seasons, the above-described changes have taken place and about the same time of the year. The water level of nearby Leather Pool also shows a sympathetic response to changes in level of the mud springs. These conditions would seem to present incontrovertible evidence that ground water is higher in this area in winter than in summer.

The rise of ground water in the Paint Pot springs in autumn, rather than at the time of melting snows, offers a reasonable explanation, wholly unrelated to atmospheric temperature, as to why some geysers in the Lower Basin erupt less frequently in winter than in summer. It also affords an explanation for Great Fountain's occasional digression from its summer eruptive pattern. The late season changes in some of the Lower Basin springs apparently result from the temperature and rate of movement of the ground water. Topographic and geomorphic conditions in the Lower Basin would appear to be such that the bulk of the great addition of ground water during the early part of the year does not become available to many groups of springs in this basin until several months after its seepage into the ground. It is not coincidental that eruptive activity of Morning, Fountain, and Clepsydra becomes much less frequent at the time new water addition shows in the Paint Pot springs; also that Great Fountain's pre- and post-eruption behavior shows occasional alterations at this same time. They are subject to a cooler body of ground water.

CAUSE OF THE LOW EBB IN GREAT FOUNTAIN

The low ebb and other unusual conditions which were observed in Great Fountain on November 8, 1962, like the long periods of overflow, are the result of a cooler body of ground water. In the case of the slow response of Great

[3] Observations made during the 1950's reveal that it was at about this time of the year that Morning and Fountain would rejuvenate from winter dormancy. It was not known before 1957 that there was a fall and spring change in level and temperature of the Paint Pot.

Fountain in overcoming the effects of the eruption that produced the November 8 condition, an additional factor other than cooler water was involved, namely, an unusually heavy influx of ground water at the end of the eruption. That the replacing of discharged water during and following an eruption is not always steady is amply demonstrated by the behavior patterns of many geysers. It is the inflow of water, cooler than that of an eruption, that terminates a geyser's activity (Allen and Day, 1935, p. 215). Many geysers, Old Faithful in particular, show that this inflow will at times come suddenly, abruptly stopping the eruption (Marler, 1953, p. 13). It was the heavy influx of cooler water that resulted in the abnormally low ebb and slow response of Great Fountain in overcoming the effects of the eruption.

EFFECTS OF WARMER GROUND WATER ON GEYSER BEHAVIOR

The eccentric behavior patterns of some geysers are caused by more than one factor. Observations seem to present certain evidence that one of these factors is seasonal changes in temperature of ground water. That warmer ground water might result in changed behavior, as cooler water evidently does, is indicated not only by the behavior patterns of some of the geysers in the Upper Basin already alluded to, and by the more frequent activity in summer of Fountain, Morning, and Clepsydra in the Lower Basin, but by the nature of some of Great Fountain's eruptions. During most of Great Fountain's active phases, the maximum height attained by any of the separate bursts is seldom in excess of 100 feet. The maximum burst is generally less than 100 feet. While this condition is the situation as to height for the greater portion of the year, at times there will be an explosive type eruption when one or more jets will vary in height between 125 and not less than 200 feet. During the 1950's these huge bursts of water were of frequent occurrence in August and September, at the season of the year when observations, confirmed by other springs in the Lower Basin, indicate that the body of ground water is warmest. Park Ranger Naturalist William J. Lewis has spent considerable time in summer observing the hot springs in the Lower Basin. In his 1962 report in reference to Great Fountain, Dr. Lewis states: "The strength of the eruptions increased as the summer progressed. It has been my observations over the years that the eruptions are higher in August than in June. On September 1, I witnessed the highest eruption I have seen since the 1959 earthquake—near 200 feet" (Lewis, 1962, p. 1).

Great Fountain's plumbing would seem to be of such a nature as to make it unusually sensitive to what must be very minor changes in temperature of ground water. This is indicated by the fact that during the different stages of its eruption cycles, regardless of the season of the year, its surface temperature is relatively constant. Be that as it may, its occasional seasonal digressions form what is considered its normal behavior pattern make it a useful barometer in determining what must be small changes in temperature of ground water.

CONCLUSION

Through long observation, it has become a well established fact that most geysers are very sensitive to even minor changes in temperature. Due to the tortuous nature of all geyser wells, no temperature determinations have ever been made in that section of the plumbing where an eruption is initiated. That temperature changes here are small and yet are in sufficient degree to result in either a dormant or an active cycle is inferred from the minor changes in temperature that take place at the surface of some geysers when they are in an active or dormant cycle. In the case of cone-type geysers like Castle, Beehive, and Giant, the change amounts to scarcely a degree centigrade. The fact that some of the cyclic geysers like Union and Beehive can be in a dormant state, never having erupted for months, and then be stimulated into eruptive activity by the addition of a small amount of soap, is indicative of their delicate balance and the small changes in temperature involved in determining dormancy or periodic activity. Next to "exchange of function" (Marler, 1951, p. 329-342), the periodic shifting of the thermal energy to or from a hot spring with eruption potential, the temperature of the ground water would seem to be the most important factor in determining whether a geyser is dormant or in an active cycle; also the frequency with which it erupts.

When all the evidence is evaluated the observation that the temperature of the ground water in the geyser basins is variable, and that these variations are seasonal in nature, assumes a high degree of probability. Further, there is the interesting observation that the great addition of meteoric water in the basins, resulting from melting snows, becomes available to the geysers in the Lower Basin at a very different time of the year than it does to the geysers in the Upper Basin.

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