Seismic Geyser and Its Bearing on the Origin and Evolution of Geysers and Hot Springs of Yellowstone National Park

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ABSTRACT

The major Hebgen Lake earthquake on August 17, 1959, profoundly affected the hot springs and geysers of Yellowstone National Park. The epicenter of this earthquake was about 48 km northwest of Upper Geyser Basin, and its magnitude was 7.1 on the Richter scale. No earthquake of closely comparable intensity had previously jarred the geyser basins in historic time. By the day after the earthquake, at least 289 springs in the geyser basins of the Firehole River had erupted as geysers; of these, 160 were springs with no previous record of eruption.

New hot ground soon developed in some places or became apparent by the following spring as new fractures in hot spring sinter or as linear zones of dead or dying trees. Some new fractures developed locally into fumaroles, and a few of these evolved into hot springs or geysers.

One fracture was inspected frequently as it evolved into a fumarole and, in about 2½ yr, into a small geyser. During the next few years, it became a very vigorous geyser, now named "Seismic," that erupted to heights of 12 to 15 m and explosively excavated a jagged-walled vent more than 12 m in maximum diameter and more than 6 m deep. Major eruptions ceased in 1971 when a small satellite crater formed and then assumed dominance.

The formation and evolution of Seismic Geyser provide the keys for understanding the origin of the craters and vents of other geysers and probably also the large smooth-walled nongeysering pools and springs of the morning glory type that provide no direct evidence of their origin.

Earthquakes, largely localized just outside the Yellowstone caldera, result in violent shaking of the large high-temperature convection systems of the geyser basins. New fractures form in the self-sealed shallow parts of these systems where high-temperature water is confined at pressures much above hydrostatic. As old fractures and permeable channels become sealed by precipitation of hydrothermal minerals, new channels are provided by the periodic seismic activity.

Our explanations for the origin of geyser and hot spring vents apply specifically to the geyser basins of Yellowstone Park, where near-surface fluid pressure gradients are commonly 10 to 50 percent above the hydrostatic gradient, and temperature gradients and thermal energy available for explosive eruption are correspondingly high. The same general explanations seem likely to account for the origin of geyser tubes and hot spring vents in other less favored areas where pressures and maximum temperatures are limited by hydrostatic pressures, probably with little or no overpressure being involved. *Key words: geohydrology, geysers, hot springs, thermal waters, geothermal energy, volcanology, fumaroles, earthquakes, hydrothermal eruptions.*

INTRODUCTION

The most significant event that has affected the geyser basins of Yellowstone National Park since its discovery was the Hebgen Lake earthquake, which occurred at 11:37 P.M. on August 17, 1959, with a Richter magnitude of 7.1. Its epicenter was just west of the park, about 48 km northwest of the Upper Geyser Basin. No earthquake of closely comparable intensity had previously jarred the geyser basins in historic times. A greater number of hydrothermal changes occurred in response to this crustal disturbance than during the previous 90 yr of the park's history (Marler, 1964, 1973).

During the first few days after the earthquake, a reconnaissance was made of most of the thermal features in the Firehole geyser basins. Early results of the survey revealed that at least 289 springs had erupted as geysers. Of these, 160 were springs with no previous record of eruption. Some previously obscure springs had erupted very powerfully, and large pieces of sinter were strewn about their craters.

The beautifully colored and limpid water of hundreds of springs had become light gray to muddy. An early count revealed that 590 springs had become turbid. During the first few days after the earthquake, most springs began to clear, but several years passed before clearing was generally complete.

During the night of the earthquake, all major geysers erupted that had been recently active, and some that had been dormant for many years were rejuvenated. Several important geysers began to erupt on shorter intervals, and most of these have persisted in having shorter intervals between eruptions. A few geysers soon became dormant, and some of these are still dormant at the present time (1974). After varying periods of quiescence of months to years duration, others that temporarily became dormant were rejuvenated. In 1960, temperature data of all important springs along the Firehole River showed an average increase of about 3°C above their pre-earthquake temperatures. By 1964, the average temperature had declined slightly below the 1960 level.

One of the important changes in the Firehole geyser basins that resulted from the earthquake was the development of new hot ground. In a few places these hot spots were evident as new fractures that developed in the hot-spring sinter which generally mantles the active areas. Most of the less conspicuous hot spots did not become evident until the spring of 1960 when they were revealed as linear distributions of dead or dying lodgepole pines, generally trending northwest toward Hebgen Lake. Twenty-seven such sites were counted, most of which were in the Upper and Lower Geyser Basins. Some fumaroles related to these new fractures later became the sites of hot springs and geysers. The evolution of one of these fractures into a fumarole and then into a large geyser (Seismic) has far-reaching significance in understanding the formation of other geysers, geyser tubes, and hot-spring vents, and is the main subject of this paper.

Among the thousands of thermal springs in Yellowstone Park, Seismic Geyser is one of the few that is totally recent in origin. It is not a quiescent or dormant spring that was reactivated but rather is one that had its genesis as a direct result of the earthquake on August 17, 1959. The following is a résumé of its development and evolution during its first fifteen years of existence.

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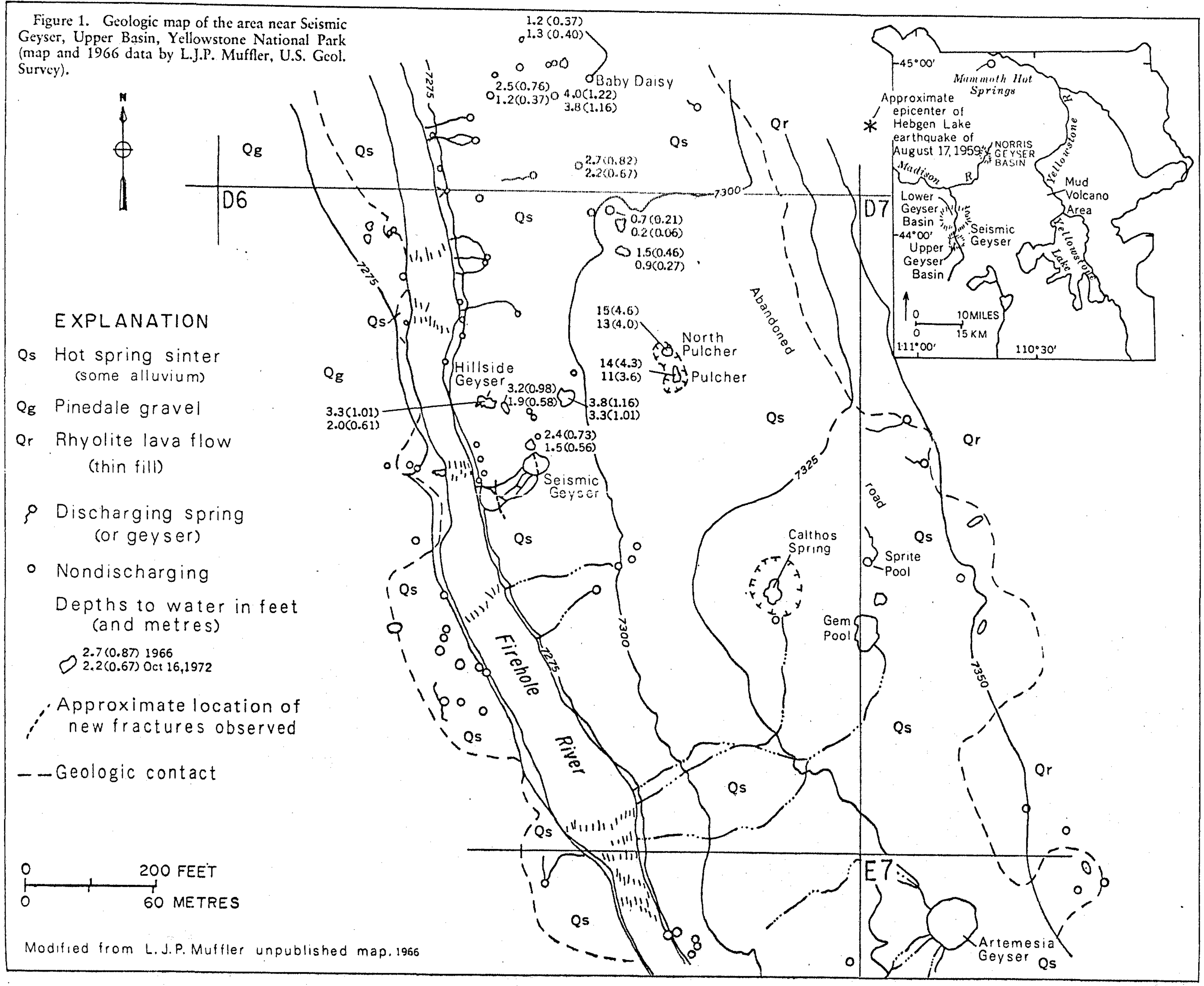
Figure 1. Geologic map of the area near Seismic Geyser, Upper Basin, Yellowstone National Park (map and 1966 data by L.J.P. Muffler, U.S. Geol. Survey).



EVOLUTION OF SEISMIC GEYSER

Within several days after the earthquake, two new fractures were observed in an embankment of old sinter that borders the east bank of the Firehole River in Upper Geyser Basin about 550 m south of the Biscuit Basin parking area. The fractures were nearly parallel to the river; their original locations, as nearly as can now be determined, are shown in Figure 1. The breaks had a north-northwest alignment, nearly on the southeastern extension of the Hebgen Lake fault, probably reflecting the regional stress pattern. The break nearest the river was the most conspicuous, being about 20 m long. The eastern fracture was about 15 m east of the edge of the steep declivity to the river and was about 10 m long. Steam was issuing near the central part of each break. The width of the upper (eastern) break near its prominent steam vent was about 1 cm. Recorded temperatures of both the upper and lower fumaroles were about 95°C (but the thermometer had not been standardized). The fact that steam was escaping under pressure indicates a temperature above the boiling temperature at this elevation, about 92.9°C. The upper break traversed an area of densely growing lodgepole pines that were about 50 yr old. One of the first wagon roads into the Upper Basin crossed directly over the site of the upper break.

During the remainder of 1959, the discharge of steam under slight pressure continued unabated from both fumaroles. When this site was first visited by Marler in the early spring of 1960, not only was a heavy discharge of steam still evident (Fig. 2), but also the pines over an area of at least 150 m^2 were either dead or dying. In addition to the heat that was visibly discharging from the fumaroles, these dying trees were evidence that new hot ground had developed, with near-surface temperatures too high to be tolerated by the vegetative cover.

By the fall of 1960, the evolution of steam from both fumaroles had increased in intensity. The shorter break farthest from the river showed the most pronounced change, and at the point of steam egress; its width was then about 2½ cm. By October, its temperature had risen to 96.1°C, and the ground near this fumarole had subsided somewhat, suggesting some change in underground conditions. The possibilities seemed excellent for a new spring or geyser to develop.

During 1961 and 1962, frequent inspections of these steam vents indicated that the vigor of steam discharged from both fumaroles was persisting in a manner comparable to that of 1960. During both years, it seemed likely that water would start to discharge from the upper fumarole.

When the site of the fumaroles was first visited in the early spring of 1963, a major change had taken place. Sometime during the previous winter, explosive activity had occurred at the site of the upper fumarole. Where steam previously had been hissing through a narrow rift, there was now a large crater. Numerous large blocks of sinter from 0.3 to 1 m in diameter were strewn about randomly, bearing evidence that the crater had formed explosively (Fig. 3). The trees that had formerly been over the site of the crater were now scattered and prostrate, especially south and west of the vent. The crater was 1.5 to 2 m deep and was elongated perpendicular to the river, measuring about 2.7 to 4.9 m. Surprisingly, the long axis was perpendicular to the original break, apparently because of the angle at which the explosion(s) occurred, from west to east.

During all of 1963, water jets about 1 m high played into the crater every few seconds; the jets shot at an angle of about 45° from the west end of the crater. The water drained from the bottom of the crater immediately after each jetting. Thus, the former fumarole had evolved into a small geyser.

Further change in the evolution of the new geyser was noted during 1964. The action became more forceful than it was in 1963, but the eruptions were less frequent. Some of the jets angled eastward almost the length of the crater, which was then about 4 m long. Also, water began to remain in the bottom of the crater between eruptions. By the end of summer, the water generally stood between 0.9 and 1.2 m below the rim. The fumarole on the western fracture along the steep embankment below the new geyser had waned in forcefulness and eventually ceased to discharge steam as increased energy was manifested in the new geyser.

The winter of 1964–1965 resulted in new marked changes in the geyser. Sometime prior to April 1965, a new explosion or a series of explosions occurred near the west end of the crater. Sudden release of energy had not only greatly enlarged the earlier orifice but had also torn out obstructions. The water, now discharged in much greater volume, erupted vertically instead of at an angle.

Yellowstone evidently now had a new geyser of no mean proportions. Because of the nature of its origin, Marler (1973, p. 53) suggested that it be named "Seismic." During 1965, little change occurred in the nature of its activity. Massive bursts of water rocketed from the crater every 1 to 3 min. Most of the bursts were from about 2 to 6 m high, but occasionally, water jetted to a height of nearly 15 m.

The eruptions increased in vigor in the late winter or spring of 1966 (Figs. 4 and 5). By this time, the diameter of vigorously washed ground around the geyser was about 21 m, having recently increased to the east by about 3 m. The change was caused by nearly vertical fall of erupted water on ground not previously affected directly. Broken sinter fragments protected by the tree stump shown in Figure 5 and by larger fragments were temporarily preserved, but all fragments lying on firm sinter closer to the vent had been swept away. By the fall of 1966 when the area was mapped in detail (by L.J.P. Muffler of the U.S. Geol. Survey; Fig. 1), Seismic's crater was about 9 by 12 m.

During the years of 1967 through 1969, the pattern of Seismic's eruptive activity underwent progressive changes. The length of the quiet phase between eruptions slowly increased to about 40 to 50 min. Each eruption was complex, with a duration of about 15 to 20 min, during which 30 or more separate bursts occurred, similar to the burst shown in Figure 6. The first burst of each sequence explosively broke the surface of the pool, as indicated in Figure 4. The crater was still slowly being enlarged on its margins.

On several occasions during 1970, Marler spent 2 hr or more at a time at Seismic to determine the nature of its eruptive pattern, which seemed to have changed somewhat from that of the three previous seasons. Each complex eruption consisted of at least three separate periods of activity, of which the second was always the longest, on one occasion lasting for 19 min. The duration of a complex eruption was variable, with extremes from about 19 to 31

Figure 2. Earliest photograph of the fumarole area that later developed into Seismic Geyser (spring, 1960).

Figure 3. Seismic Geyser after initial eruptions in spring of 1963. Note large blocks of sinter near the vent, with fine debris absent in splashed area.

min. An unfailing sign of the termination of each complex eruption was a drop in water level of about 0.35 m in the crater. For comparison, during the quiet periods within a complex eruption, the water stood about 10 cm below the rim. The quiet and eruptive phases were about equal in duration, with each ranging from about 20 to 30 min. The heights of the 1970 eruptions were similar to those observed during the 1967–1969 period. The maximum height was about 12 m or slightly less than the estimated maximum bursts of the 1965–1966 period; many of the highest bursts came near the termination of an eruption.

Sometime between late February and late April of 1971, a vent (now called "Satellite") developed on the east shoulder of the crater. Satellite's vent, like Seismic's, resulted from one or more explosions. Sinter fragments were strewn about the small new crater, which was about 1.8 by 2.4 m when first observed. During the season, some further enlargement occurred. There was a break of about 0.6 m in the side next to Seismic, which resulted in the water of both springs being continuous at the surface.

When first observed in 1971, the water was boiling vigorously in Satellite's crater, welling up from 0.6 to 1 m. Steady boiling was generally characteristic of its pattern throughout the remainder of the season; but periodically, Satellite erupted, with massive bursts to a height of about 3 to 3.7 m and occasionally to 6 m. Its eruptions were synchronized with those of Seismic, with both vents erupting simultaneously. The new geyser's activity decreased the vigor of Seismic's eruptions. However, at times, Seismic erupted to heights as much as 7½ to 9 m.

By the spring of 1972, further changes were evident. During the previous winter of 1971–1972, Satellite's vent had enlarged to about 3.7 by 3.7 m, compared with the 1.8 by 2.4 m vent of 1971, and had become heart shaped. No further change took place in Seismic's crater during the 1971–1972 winter, probably because it had ceased eruptive activity; its crater was then 12.5 m north-northwest by 13.4 m east-northeast, excluding Satellite's vent as a protuberance on the southeast side. Geyser activity was confined wholly to Satellite's vent, while Seismic had become an intermittently overflowing spring.

Intervals between eruptions of the new vent during 1972 ranged from 15 to 37 min; each eruption lasted 21 to 31 min and consisted of either two or three separate periods of spouting. Each eruption was initiated by a rise in water level of about 20 cm in both craters. During each period of activity, Seismic discharge without boiling at an estimated rate of about 1,000 lpm (liters per minute). At times, Seismic overflowed for a few minutes with no consequent eruption of Satellite. Boiling in Satellite was continuous from eruption to eruption, with surges of 0.6 to 1 m between eruptions. As each eruption progressed, massive surges rose from 2 to 3 m high (Fig. 7), with an occasional burst to 6 m. Some eruptions were more powerful than others. From 30 to 45 m east and southeast of Seismic, new hot ground had developed, killing additional lodgepole pines.

In June 1974, all eruptive activity was confined to Satellite, most commonly surging to heights of about 1 m but with some spurts to 3 m or a little higher. During an eruption, discharge at rates estimated to range from 750 to 4,000 lpm flowed over the sill from Satellite into Seismic's crater, but the net discharge from both vents (almost entirely from Seismic) was only 200 to 400 lpm. These relationships indicate that previously erupted water, probably near 90°C, was flowing beneath the surface in convective circulation from Seismic to Satellite and mixing with a small part of new hot upflowing water.

The duration of observed eruptions of Satellite ranged from 31 to 47 min, and the eruption intervals ranged from 49 to 66 min (data from Roderick Hutchinson, Natl. Park Service). At times, between eruptions, both pools were quiet (Fig. 8), in striking contrast to earlier almost constant activity. Layers of nearly horizontal sinter were clearly visible in both vents to depths of about 1½ m; massive jagged-edged rocks without conspicuous bedding were visible at greater depths. Within the sinter, individual beds had been disrupted, with the radius of disruption increasing upward to form a jagged-walled, funnel-shaped vent.

Seismic's vent was probed extensively in 1974, but the maximum accessible depth was 6.6 m, where temperatures ranged from 89.6° to 95.6°C. Temperatures at the bottom were, in general, slightly below those at −3.7 m, where the observed range was 88.9° to 99.0°C. Satellite's vent was probed to a maximum depth of −3.7 m, where the temperature range was from 94.3° to 97.8°C (temperature data from M. Nathenson, U.S. Geol. Survey).

INTERCONNECTED THERMAL SPRINGS

Seismic and its satellite vent are evidently connected subterraneously with many other nearby springs as well as the 1959 fumarole on the river embankment. Hillside Geyser (Fig. 1; Marler, 1973, p. 49) had been very active from 1948 to 1961, with some eruptions as high as 9 m. Eruptions then decreased in intensity and ceased in 1964 as Seismic became more vigorous. As the 1965 season progressed, Hillside's water level slowly declined and was 1.0 m below discharge level when observed in 1966 by L.J.P. Muffler (Fig. 1). Its minimum observed level was −1.2 m in 1970 and, with declining activity in Seismic and creation of its satellite vent, Hillside's water level then rose to −0.6 m in October of 1972. Observed temperatures in Hillside's vent were 95°C in 1963 and 75°C in 1970. After the beginning of Seismic's major geyser activity, the water levels in Pulcher and North Pulcher (Fig. 1) dropped quite rapidly at first and were 4.3 to 4.6 m below discharge level in 1966. By 1972, their levels had risen slightly.

Seismic's indicated underground connection with Hillside Geyser is not at all surprising, because the initial break in the sinter extended in the general direction of Hillside (Fig. 1). The fact that Seismic evidently has underground connections with other hot springs, several of which were geysers, does not augur well for future consistency of performance. Geysers in other groups known to be connected subterraneously commonly become dormant when the thermal energy shifts to one of the related springs (Marler, 1951, 1973).

HISTORIC FORMATION OR ENLARGEMENT OF OTHER VENTS

Other less dramatic events recorded by Marler (1973) were either directly or indirectly related to the Hebgen Lake earthquake, and evolutionary changes were not as diverse or were not documented at as many stages as for Seismic Geyser.

On the south side of White Creek about 170 m directly south of Great Fountain Geyser in Lower Basin, one or more violent eruptions scattered great quantities of sinter around two existing craters, probably at the time of or very soon after the 1959 earthquake. At some time early in 1960, a new crater formed in Lower Basin on the eastern shoulder of Honeycomb Geyser in the Kaleidoscope Group. When first observed, the vent was about 1 by 2.4 m, but it was enlarged to 1.8 by 3.7 m by 1972, and large blocks were strewn around the crater. As closely as could be determined by Marler, this vent immediately became an active geyser that erupted to heights of 1.5 to 2.4 m; by 1972, the eruptions rose to heights of 4½ to 7½ m.

In 1963, about 18 m northwest of Kaleidoscope Geyser, a violent eruption that may have been a single event scattered scores of blocks of sinter about a newly created crater about 3 m in diameter. The explosion was directed to the southwest, with a debris ring still recognizable in 1966 and mapped by White (unpub. data) as much as 24 m southwest of the vent. In 1972, water nearly filled the new crater but did not discharge. Also in 1963, two small geysers in Biscuit Basin evolved from earthquake-created fumaroles, with explosions forming the present craters.

At the southern base of a sinter mound on which the cone of Sponge Geyser is located (Geyser Hill Group of Upper Basin), a violent eruption in 1969 scattered fragmental sinter about a newly created crater. Since the initial explosion, occasional geyser eruptions from 3 to 4½ m high have further enlarged the crater. In this same group of springs, two new fumaroles developed soon after the earthquake, and these were enlarged by explosions. One, named "Bench Geyser," is very active and erupts several times daily (1972) to a height of 1½ to 2 m.

Since the earthquake, other explosions have formed craters, mostly small and in the vicinity of active geysers. One occurred in 1969 on the east shoulder of Spasm Geyser in the Fountain Group, forming a crater about 1.2 by 1.5 m.

A large explosion that may have occurred in the early 1900s was responsible for a crater about 15 m in diameter called "Black Opal Spring" in Biscuit Basin. In 1931 when Marler first observed Black Opal, large blocks of cemented sandstone were strewn about the crater. During the winter of 1932–1933, Frank Childs, a Park Ranger, reported a powerful eruption from Black Opal that tore out new sandstone blocks. This eruption was evidently much smaller than the earlier one(s). The sandstone contains granules of rhyolite and obsidian and is similar to the cemented and partly altered drill core from shallow depths in a research drill hole of the U.S. Geological Survey (White and others, 1975; Y-8, 140 m east-southeast of Black Opal).

The explosion that created Black Opal's crater was of considerable magnitude. Since Marler's first observations in 1931 of the great array of sandstone blocks north of the crater, weathering has disintegrated most of the smaller blocks, but erupted debris was recognized in 1966 (D. E. White, unpub. map) as much as 240 m north, 180 m west, and 30 m south of Black Opal, thus indicating explosions directed to the north and west. Some of the blocks near the crater were as much as 0.6 m thick and 0.9 m in diameter.

Black Opal Pool is immediately east of Wall Pool, and the two pools are separated by a narrow septum of cemented gravel. Wall Pool is a spring about 9 to 18 m wide and 58 m long, elongated northwest. This vent probably also formed by explosions that may have occurred concurrently with those of Black Opal. The southern edge of Wall Pool's crater is vertical and consists of abruptly terminated horizontal laminated sinter. The evidence for historic explosions from both vents is indirect. Hague's detailed map of Upper Basin (Hague, 1904, sheet XXIV) does not show either of these two prominent pools in spite of the fact that the wagon road to the Biscuit Basin group was only 15 m to the south, and a discharge stream from Sapphire Geyser was mapped across the middle of Wall's present location. Could Hague have missed these prominent features, was there a major cartographic error, or did the craters form within the next 30 yr but were not recorded? The almost total absence of reliable records from 1904 to 1931 (Marler, 1973) preclude resolution of these questions, but we favor the latter explanation.

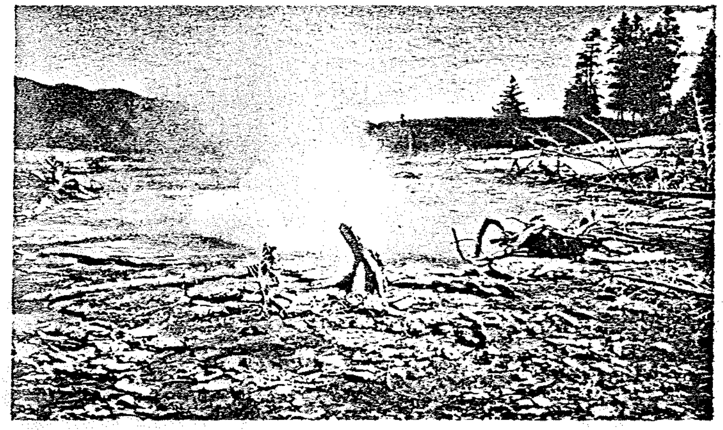


Figure 4. Explosive burst just breaking surface pool of Seismic Geyser with water level below level of discharge (May 30, 1966).

Similar evidence suggests that the vent of West Flood Geyser in the Midway Geyser Basin formed by explosive activity sometime after 1904 and was enlarged before 1940 (Marler, 1973, p. 389). Hague's detailed map of Midway (1904, sheet XXIII) shows no vent in West Flood's present location. The crater is about 9 by 10½ m in diameter and was formed in cemented gravels overlain by sinter. Large blocks or slabs of cemented gravel in the crater indicate enlargement over the years due to undermining of the crater's walls by explosive eruptive activity.

SEISMIC ACTIVITY IN AND NEAR YELLOWSTONE PARK

Historic Record

Since the discovery of Yellowstone Park, earthquakes of sufficient intensity to be recognized have occurred rather frequently with occasional reports of rattling dishes, swinging lamps, and creaking buildings. The earliest report of an earthquake in the Yellowstone country was by the first scientific expedition to the area (Hayden, 1872, p. 82):

> While we were encamped on the northwest side of (Yellowstone) lake, near Steamboat Point, on the night of the 20th of July (1871), we experienced several severe shocks of an earthquake, and these were felt by two other parties, fifteen or twenty-five miles distant, on different sides of the lake. We were informed by mountain men that these earthquake shocks are not uncommon, and at some seasons of the year severe, and this fact is given by the Indians as the reason why they seldom or never visit that portion of the country. I have no doubt that if this part of the country should ever be settled and careful observations made, it will be found that earthquake shocks are of very common occurrence.

One of the parties to which Hayden refers as being camped 24 to 40 km distant (Barlow, 1872, p. 38–39) reported: "We experienced last night the singular sensation of an earthquake. There were two shocks, the first one being quite severe accompanied by a rumbling and rushing sound."

After the 1959 earthquake, the National Park Service, in cooperation with the U.S. Geological Survey, installed three seismo-

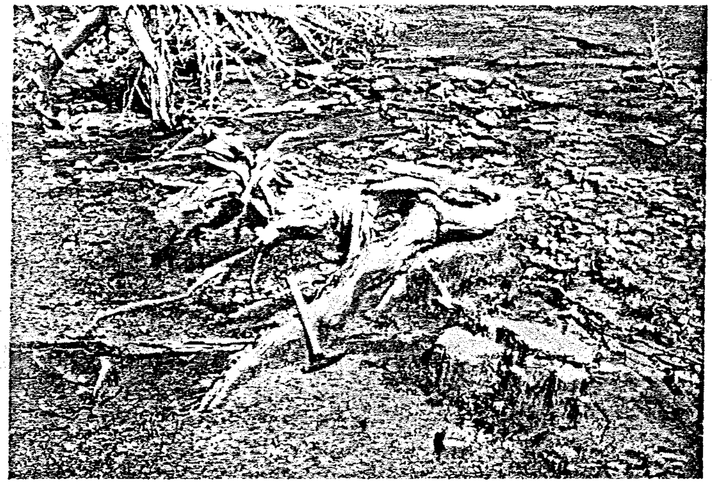


Figure 5. Border of splashed area very recently enlarged to 7.6 m east of vent. Loose debris under tree stump and large sinter fragments protected from nearly vertical fall of water (May 30, 1966).

graphs in the park. One was also set up at Hebgen Lake. According to Keefer (1972, p. 87) seismographs record an average of about five shocks daily in and around the park; on rare occasions, they may record 100 or more in a single day. Most events are so slight that they cannot be felt by man; but occasionally strong earthquakes occur, such as that of August 17, 1959.

Seismic records indicate that on an average of about once in ten years, a strong earthquake occurs in the states adjoining Yellowstone, particularly in Montana. The last strong earthquake prior to August 17, 1959, was on November 23, 1947. Although neither the 1947 earthquake nor any earlier historical one was sufficiently intense to produce major hydrothermal changes, some of the evident changes in hot-spring functioning that have occurred over the centuries are probably associated with strong seismic activity. The Hebgen Lake earthquake, far from being the only incident to markedly affect the geyser basins, was no doubt preceded by many earthquakes of equal or greater intensity during the past millenia.

Microearthquake monitoring of the park in recent years by the U.S. Geological Survey and by the University of Utah has revealed a pattern of frequent small events that tend to be localized immediately outside of the Yellowstone caldera but rarely occur inside the caldera (A. M. Pitt, D. P. Hill, H. M. Iyer, R. B. Smith, 1973, 1974, personal communs.). The active belt extends eastward from Hebgen Lake to Norris Basin and thence eastward adjacent to the caldera rim as mapped by Christiansen and Blank (1975; Keefer, 1972, Fig. 35). Thus, of the major geyser basins, only Norris is near the most active seismic belt; Shoshone, the major Firehole geyser basins, and West Thumb are all within the relatively inactive caldera.

Prehistoric Geologic Record

Recent geologic mapping in Yellowstone Park (U.S. Geol. Survey, 1972b; Christiansen and Blank, 1975) indicated extensive faulting associated with the eruption of ash-flow tuffs and collapse of the double-centered Yellowstone caldera about 600,000 yr ago. The caldera ring faults approximately underlie the Firehole geyser basins and seem likely to provide the deep controls over circulation of thermal fluids. Extensive faulting was also associated with the resurgent Mallard Lake and Sour Creek domes near the two centers of the double caldera about 150,000 yr ago. Nearly all recognizable fault scarps inside the caldera are localized within or between these two resurgent domes (R. L. Christiansen, 1974, oral commun.). A very few faults near the margins of Yellowstone Lake cut glacial and alluvial deposits that are less than 150,000 yr old, but other young fault scarps are scarce throughout most of the caldera and, specifically, in or near the major Firehole geyser basins. The steep margins of the geyser basins are the fronts of very viscous thick rhyolite lava flows that range from about 90 to 160 thousand years old and are not fault scarps. Thus, the present-day relatively low level of seismicity within the caldera also seems to have characterized this area for the past 150,000 yr.

However, this evidence indicates only that fault displacements and hypocenters of earthquakes seldom occur within the caldera. The geyser basins have without doubt been subjected frequently to seismic shaking from activity outside the caldera, just as in the 1959 Hebgen Lake earthquake. Many springs and geysers in the geyser basins are aligned on the northeast-, northwest-, and north-striking trends that agree with regional tectonic patterns. Local alignments, probably controlled by fractures, have been recognized for many years by Marler (1964, 1973), and many are shown on detailed maps of the geyser basins (L.J.P. Muffler, R. O. Fournier, A. H. Truesdell, and D. E. White, unpub. data). Some of these may be locally controlled, but most are consistent with regional stress patterns.

Specific fracture-controlled vents that can be cited as examples include Old Faithful Geyser, Fan and Spiteful Geysers, the Chain Lake group of vents southeast of Morning Glory Pool, and the Three Sisters in the Myriad Group, all of Upper Basin. Two lines of vents and visible fractures west and northwest of Clepsydra Geyser of the Fountain Group and four distinct lines of vents between Gentian Pool and Deep Blue Geyser of the Kaleidoscope Group of Lower Basin are also examples.

GENERAL CHARACTERISTICS OF HIGH-TEMPERATURE GEYSER-BEARING CONVECTION SYSTEMS

Many advances have been made in the past 25 yr in understanding the large high-temperature convection systems of the world that are associated with natural geysers. Much of this new understanding has resulted from deep drilling for geothermal energy, but a significant part is from general scientific study and research drilling.

Wells drilled in a few geothermal areas produce dry or superheated steam with little or no associated liquid water (Larderello, Italy; The Geysers, California, with no true geysers; and the Mud Volcano area of Yellowstone). Such areas have been called "vapor-dominated" (White and others, 1971).

With only a few exceptions such as the above, most geothermal areas are dominated by liquid water, including *all* drilled areas that have natural geysers. In such areas, temperatures generally increase rapidly with depth in drill holes and are close to the temperatures of boiling at existing water pressures. At some depth and temperature characteristic of each particular system (if drilled deep enough), temperatures level off and show little further increase within explored depths (the base temperature of Bodvarsson, 1964). White (1967) listed the maximum temperatures found in 19 drilled areas then thought to have natural geysers. All except five had temperatures above 180°C; of these five, three are now known to have intermittently erupting hot-water wells but no natural geysers. Deeper drilling in a fourth (Bradys, Nevada) yielded temperatures as high as 215°C (White, 1970).

Subsurface temperatures, either indicated by the silica geothermometer (Fournier and Rowe, 1966; Fournier and Truesdell, 1970) or measured in wells in areas of natural geysers (White, 1970, Table 4) have added Rotorua, New Zealand (~230°C), Uzon-Geyzerny, Kamchatka, USSR (~200°C) and El Tatio, Chile (>200°C) to White's earlier list of geyser areas with temperatures above 180°C. Siliceous sinter is also characteristic of geyser areas, and its presence indicates subsurface temperatures in excess of 180°C, either now or in the past (White, 1970).

The highest temperatures tend to occur within the central core of ich system, surrounded by zones of lower temperature (Elder, 1965). The distribution patterns of temperature demand active convection with hot water rising in the core of each system because of thermal expansion, and with descending cold water in other parts of the total system. Few details are actually known about the descending cold parts of these systems, but light stable isotopes have proved an overwhelming dominance of water of surface origin in the thermal waters. In general, at least 95 percent of the water is of such origin, with no positively identified water of magmatic or other deep origin (Craig, 1963; White, 1970).

The geyser-bearing convection systems are large and deep — much deeper than had been assumed prior to geothermal exploration. Most known geyser areas have now been drilled to depths from 610 m to more than 2,400 m with no evidence that the base of meteoric convective circulation was attained in any of them (White, 1970).

These high-temperature convection systems tend to fill their outlet channels and pore spaces in adjacent rocks by depositing silica minerals, zeolites, calcite, and other minerals (White and others, 1975) as temperatures decrease upward and as mineral solubilities decrease (calcite because of increasing pH with loss of CO_2 as boiling occurs). The resultant decrease in permeability is called "self-sealing."

SUMMARY OF SUBSURFACE CHARACTERISTICS OF YELLOWSTONE'S GEYSER BASINS

The temperature and pressure gradients in the upper few hundred feet of Yellowstone's geyser basins provide the basis for understanding how and why new vents form; these data also help to explain why Yellowstone Park has the greatest display of geysers and other hydrothermal phenomena in the world.

Two research holes were drilled in Yellowstone Park by the Carnegie Institution of Washington in 1929 and 1930 (Fenner, 1936), and thirteen holes were drilled by the U.S. Geological Survey in 1967 and 1968 (White and others, 1975). Depths of the holes range from 65.5 m to 331.6 m, and maximum measured temperatures in the 13 holes (excluding one in the travertine terrace of Mammoth) range from 143° to 237.5°C. Nine of the thirteen holes attained 180°C or higher, and the four of lowest temperature were either shallow or were drilled on the margins of upflowing systems. Most holes were drilled in rocks of initial high permeability, but permeabilities have decreased greatly from deposition of hydrothermal minerals in fractures and pore spaces.

The depth to the water table ranged from 0.3 m to 8.8 m below ground, depending on local relationships of drill holes to nearby springs and topography. As drilling progressed, the standing level of water in each hole rose to the ground surface and then attained positive pressures (in capped holes) that ranged up to an equivalent level of 65.5 m above ground! The excess pressure gradients above simple hydrostatic exceeded 10 percent for all holes except one, and the gradient in one hole exceeded hydrostatic by 47 percent!

The very high near-surface fluid pressure gradients in rocks of initial high permeability imply that self-sealing has been extensive (but not complete). Water leaks through any available permeable channels, generally into near-surface rocks or sediments of somewhat higher permeability. In the geyser basins of Yellowstone Park, the greatest tendency for self-sealing occurs in the temperature range from about 125° to 180°C. Sinter, sands, and gravels near the basin floors where temperatures are below 100°C are generally porous and only partly cemented and hydrothermally altered. Thus, the high-pressure fluids probably flow upward in a few principal channels through the nearly self-sealed zone to the near-surface, where increasing permeability in channel walls then permits the escape of some water into adjacent ground with lower fluid pressures.

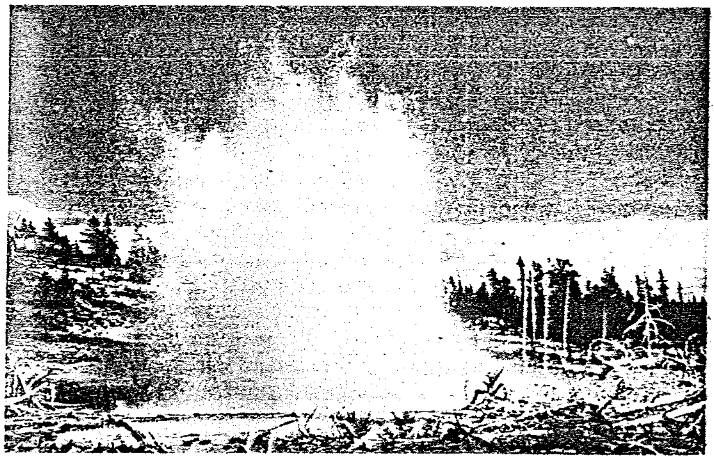


Figure 6. Bursting eruption of Seismic Geyser (August 1968).

The relationships just described help to explain the otherwise puzzling occurrence of adjacent springs discharging at different altitudes; of discharging springs located adjacent to nondischarging vents of lower altitude; and the fact that the water table, as first identified in drill holes, is generally lower in altitude than nearby discharging springs.

The drill cores also show that much of the floor of Upper Basin is underlain by stream-deposited silt, sand, and gravel ranging in thickness from more than 61 m in the southern part of the basin to about 53 m in the northern part (Biscuit Basin). These sediments were deposited rapidly as kames adjacent to the margins of glaciers of Pinedale stage (U.S. Geol. Survey, 1972a). Bedrock is shallow, however, along much of the northeastern side of Upper Basin and crops out in places (Christiansen and Blank, 1975; L.J.P. Muffler and others, unpub. data). The depth of stream sediments under Seismic Geyser is not known but is probably less than the 52 to 55 m found in the two Biscuit Basin drill holes about 550 m to the north.

HYPOTHESIZED EVOLUTION OF HYDROTHERMAL ACTIVITY IN UPPER BASIN

No evidence has been found for pre-Pinedale hydrothermal activity in Upper Basin, although such activity seems likely in view of evidence for its existence in Lower Basin and Norris Basin (L.J.P. Muffler and others, unpub. data). Relatively well-sorted sands and gravels of early or middle Pinedale stages (U.S. Geol. Survey, 1972a) were deposited in Upper Basin by streams adjacent to melting ice. The core from four research drill holes in the basin shows no break in the hydrothermal record from the underlying lava flows up through the entire sequence of stream sediments. Hot-spring deposits generally overlie the sediments but are absent within or below the sediments; soil zones and organic matter also seem to be absent in the drill core. Thus, regardless of the possibility of early unrecognized hydrothermal activity in Upper Basin, the sedimentary fill within the basin seems to have evolved as if in response to a single period of thermal perturbation that is still continuing. The following model of evolution of activity is based on this assumption.

When thermal waters first flowed upward into the newly deposited permeable basin sediments, vigorous convection and mixing with cold ground waters from the surrounding area must have occurred. Fluid pressures in these sediments must have been hydrostatically controlled, and temperatures, because of mixing and convection, were probably much below the reference boiling-temperature curve except perhaps locally in upflow currents near the water table. With time, however, permeability decreased drastically as a result of deposition of hydrothermal minerals and conversion of abundant obsidian granules into zeolites, partly devitrifying in place but also dissolving and redepositing (with silica minerals) in pore spaces (Honda and Muffler, 1970; unpub. data on other drill holes). In some sediments, porosity did not decrease as much as permeability; in others, both porosity and permeability decreased greatly.

In consequence of these changes, the ease of upflow of thermal fluids decreased with time as impedances were imposed. Convective circulation within the sediment pile must have become more and more constricted, and fluid overpressures only then could start to develop. With time, thermal water started to discharge over various parts of the sediment-filled basin with decreasing regard for differences in surface altitude, in contrast to former outlets that presumably were localized at low altitudes adjacent to streams. Temperatures could then generally increase within the sediments, at first approximately up to the reference boiling-temperature curve (which assumes a water table at ground level) and then locally exceeding the curve as water overpressures started to develop. Direct inflow of cold water from the valley floor and surrounding terrain gradually decreased as fluid overpressures developed to exclude such water. Important consequences of these changes were that, with time, boiling temperatures at points of discharge became more characteristic, and the SiO_2 contents of discharged waters increased because of rapid cooling from higher temperatures and also because of decreased dilution by cold water. Broad shields of nearly horizontal sinter were deposited around centers of discharge. Geysers, or at least large geysers, were not yet characteristic because the underlying stream sediments were not yet thoroughly cemented and average permeabilities were still too high. The broad sinter shields were probably not strictly contemporaneous with each other but probably developed at different rates and at different times. It is significant that parts of Upper Basin, as in the western part of the area shown in Figure 1, are still floored by these stream sediments, considered to be of the same general age but not yet having undergone any of the described changes. The northern Biscuit Basin drill hole (Y-7) is in the less-cemented outer border of such an area; its vertical water-pressure gradient is only about 1 percent above hydrostatic, in contrast to a pressure gradient nearly 30 percent above hydrostatic in the second Biscuit Basin drill hole (Y-8) only 150 m to the south and 550 m north of Seismic Geyser (White and others, 1975).

The response to the formation of a new fracture in an overpressured environment is best illustrated by the data provided here for Seismic Geyser and other comparable features. In contrast, a new fracture in bedrock lavas overlain by permeable gravel outside of an overpressured area probably would not be recognized, and it could not evolve immediately into either a fumarole or a new geyser.

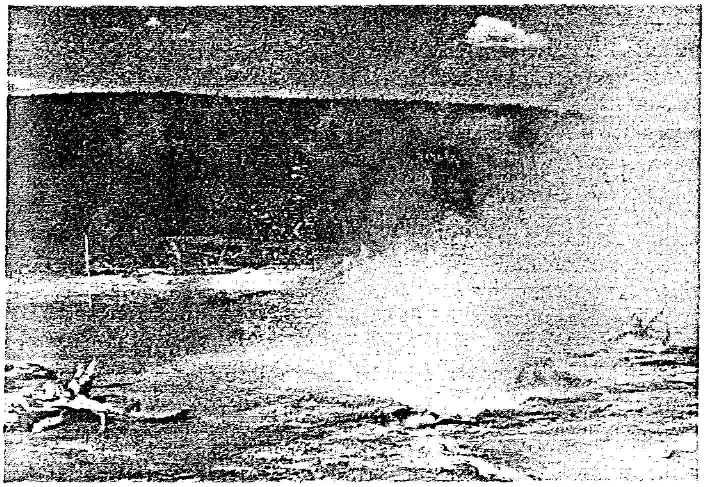


Figure 7. Satellite vent erupting, with Seismic Geyser's pool in background (August 1972).

The evolution of activity in the parts of Upper Basin where bedrock either crops out or is at shallow depth, as from Old Faithful northwestward to Artemesia Geyser (300 m southeast of Seismic; Fig. 1) is less predictable. Similar stages of self-sealing, development of high near-surface overpressures, and exclusion of abundant cold meteoric water were probably necessary before sinter shields and then major geysers could form, but these stages in evolution may already have occurred in the bedrock lava flows before the stream sediments were deposited in Upper Basin. At least in favorable places the rate of evolution to major geysers was probably much faster than in areas underlain by deep permeable stream sediments. In fact, the localization of major geysers along the northeast side of Upper Basin may be related to shallower depths to competent bedrock.

EVOLUTION OF VENTS FORMED BY SEISMIC DISTURBANCE OF AN OVERPRESSURED HYDROTHERMAL SYSTEM

A high-temperature hydrothermal system characterized by near-surface pressure gradients 10 to 50 percent above the simple hydrostatic gradient has subsurface temperatures that may be much above the reference boiling-temperature curve (Honda and Muffler, 1970; White and others, 1975). The seismic response of such a system evidently differs greatly from place to place. Some responses are nearly instantaneous, but others evolve slowly over a period of years. Most previously existing spring vents, sufficiently disturbed in 1959 to permit increased discharge from the overpressured system, erupted immediately as geysers. A few vents, such as that of Clepsydra in the Fountain Group of Lower Basin, evidently tapped one or more deep aquifers that were sufficiently high in permeability to maintain continuous discharge, much like a continuously erupting geothermal well.

The new fractures formed by the 1959 earthquake provided new channels for escape of thermal fluids from the overpressured systems. Some new fractures were immediately conspicuous, such as the one that evolved into Seismic. Others did not become prominent until enough thermal fluid had escaped to produce near-surface ground temperatures that were too high for pine trees to tolerate. How are these delayed reactions best explained?

A new fracture first permits the upflow of some fluid and heat at a locus where near-surface temperatures were formerly controlled by conductive gradients, as in the shallow parts of most of the research drill holes in Yellowstone (White and others, 1975). As a consequence of the new upflow, temperatures rise, and if liquid accompanies steam, the added supply of water raises the local water table, eventually to the surface if surrounding ground is not very permeable. The vent then changes from a fumarole to a spring, a perpetual spouter, or a geyser.[1]

The historic record of development of vents suggests that some may form as results of single explosions but that others evolve gradually from a continuing series of eruptions of increasing vigor. The single explosions (or a closely spaced flurry of explosions) are similar to (but much smaller in scale than) the major hydrothermal explosions that occurred in 1951 in northeastern California (White, 1955) and that formed Pocket Basin in Lower Basin

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[1] A perpetual spouter (also called a "steady geyser" in Yellowstone) forms where high-temperature water flows up a channel of restricted dimensions and where a local reservoir is absent; the rate of total mass discharge of water and steam (but with proportion of steam increasing upward) is nearly constant, equaling the rate of supply from depth. Wherever a vent is large enough and a local reservoir can form (by processes to be described), discharge tends to become intermittent with rates during eruption exceeding the rate of supply from depth. An interval of repose, with both fluids and heat being supplied from depth, are essential before the geyser can erupt again (White, 1967).

Muffler and others, 1971). All of these explosions, as well as geyser eruptions, derive their energy from hot water at initial temperatures much above surface boiling, permissible where pressures are higher than atmospheric. Single explosions are especially likely to occur where near-surface fluid pressure gradients are much above hydrostatic and locally exceed the lithostatic gradient.

The explosions are not simple steam explosions resulting from rapid expansion of steam decompressing from an initial high pressure to a lower pressure. Instead, they are caused by the thermal energy contained in liquid water at temperatures above the new boiling temperature at the new decompression pressure; this extra thermal energy is utilized to convert part of the water to steam. White (1955, p. 1124) calculated that one volume of water decompressing from a temperature of 200°C and 225 psia (pounds per square inch, absolute or 15.82 kg/cm^2), to 100°C (sea-level atmospheric pressure assumed) increases its initial volume by 278 times as 19.2 percent of the original water is converted into low-density steam.

If this expansion were contained in a vent of constant diameter, such as a well casing, a mass unit of liquid water flowing upward and flashing to a mixture of water and steam must increase in velocity by 278 times, assuming equilibrium at ground level and atmospheric pressure. Instead, in natural vents, the rising column approaching the free face (ground surface) tends to expand horizontally by enlarging its channel as well as to increase in velocity upward.

The water immediately involved in forming new geyser vents is likely to be supplied relatively near the surface where deep temperatures of 200°C or more have already decreased to the general range of 150° to 125°C. Corresponding volume increases of water when flashed from 150° or 125°C to mixtures of water and steam at atmospheric pressure (calculated to 100°C or sea-level boiling rather than 92.9°C for surface boiling in Upper Basin) are approximately 145 and 75 times the initial volumes, respectively. This large increase in volume of a given mass of fluids as the ground surface is approached, along with decreasing cementation of sinter and sediments upward, explains the general tendency for the upward flaring of vents.

Other relationships help to explain the enlargement of deep channels and the increasing volume of the immediate reservoir of an evolving geyser. When an eruption occurs and water is discharged faster than its rate of supply through narrow fractures from the overpressured environment at depth, the local reservoir becomes depleted, with consequent decreases in fluid pressures. Liquid in pores in adjacent sinter and cemented sediments is then exposed to lower fluid pressures and consequently lower temperatures of boiling than immediately prior to eruption. The pore water thus tends to flash into steam, with additional heat being supplied by the rocks. If permeabilities are low enough, the high fluid pressures within the pores cannot be relieved rapidly, and pressure gradients[2] may be sufficiently high to break and disrupt the rocks.

For the most part, channels are widened and cavities are created and enlarged in the less competent layers of rock where initial porosity or degree of fracturing is greatest. Especially subject to disruption are the less thoroughly cemented beds of sediments. As a consequence of such enlargements, the magnitude and vigor of eruption of a geyser can increase as its local reservoir increases with time.

Each explosion that ejects fragments tends to clear and enlarge the channel near the surface as well as at depth, thus increasing the rate of discharge and also the average heat content of the escaping fluids as a smaller proportion is lost by conduction. Eventually, however, a vent attains some maximum surface diameter and deep-channel dimensions. This attainment of stability probably occurs when dimensions become so large and remaining constrictions are so limited that convection *within* the reservoir becomes completely dominant. The excess energy contained in the very hot recharging water from depth can then be lost by steady-state processes, including surface evaporation from hot pools, the rise of individual steam bubbles, near-surface boiling, and conductive loss of heat from the channels to cooler adjacent rocks. Dominance of these mechanisms is probably also fostered by deposition of silica and other minerals in the deep channels, now no longer subjected to the extreme pressure gradients resulting from eruption and reservoir depletion.

New fractures that develop in bedrock lava flows, competent sinter, and thoroughly cemented gravels with large heavy interlocking blocks may commonly evolve into cone geysers with near-surface vents and tubes of relatively small diameter. In contrast, where an evolving geyser of increasing vigor can fragment and eject near-surface incompetent rocks, an upward-flaring vent and a geyser with fountain-type activity are the normal consequences.

EXPLOSIVE ORIGIN FOR ALL GEYSER VENTS

The known craters that resulted from the disruption and ejection of near-surface sinter and cemented sediments suggest a similar explanation for all of Yellowstone's spring and geyser vents. Like Seismic's crater and other similar craters of recent origin, jagged ledges of sinter and sediments in the crater walls bear mute evidence that powerful eruptions were responsible for the origin of such vents. The vents of the following well-known springs are typical examples: in the Upper Basin, Oblong Geyser, Rainbow Pool, Emerald Pool, Green Spring, Artemesia Geyser, Cauliflower Geyser, and Sapphire Pool; in the Lower Basin; Celestine Pool, Silex Spring, Fountain Geyser, Gentian Pool, and Diamond Spring.

Our hypothesis of explosive origin of geyser vents is especially attractive for Yellowstone's geyser basins where fluid-pressure gradients are commonly 10 to nearly 50 percent above the hydrostatic gradient and very high temperatures are correspondingly closer to

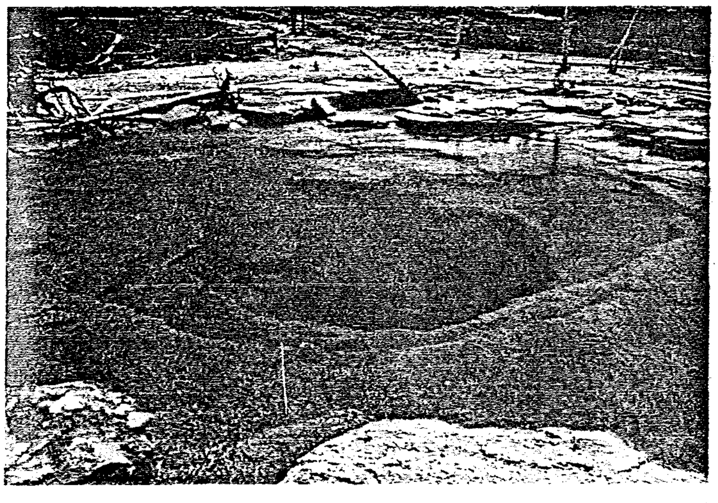

Figure 8. View southeastward across vent of Seismic Geyser toward Satellite's vent during a quiet interval between eruptions. Individual beds of sinter are visible; each bed was originally continuous but was fragmented as the geyser increased in vigor. The vent flares upward, probably as a consequence of increasing volume of an erupting two-phase mixture as pressure decreases upward (June 16, 1974).

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[2] Pressure gradients locally may greatly exceed the lithostatic gradient in channels that feed directly from a highly overpressured environment into the local reservoir of a geyser; the water in this local reservoir is in direct contact with the atmosphere, and pressures are therefore controlled by a hydrostatic gradient down to the feeding channels. In and near these channels where pressure gradients may be extremely high, the tendency for enlargement during and immediately after an eruption is great and can be resisted only by hard competent rocks that are not intimately fractured.

the surface. A similar explosive origin of vents is also indicated in other less favored geyser areas where pressure and temperature gradients are probably not so high.

If geyser craters are generally formed by hydrothermal explosions, why then are rock fragments not found around most of them? This question was considered by Allen and Day (1935, p. 135). Three examples of known explosions that ejected great quantities of disrupted rock illustrate how rapidly the surface evidence is obliterated.

The sundered rock is most commonly hot-spring sinter or partly cemented stream sediments that are porous and disintegrate rapidly when exposed to weathering and especially to frost action. Less commonly, the ejected fragments are either dense sinter or thoroughly cemented sediments that do not disintegrate easily. During the 1957 and 1958 seasons, unusually powerful eruptions of Link Geyser in the Chain Lake Group of Upper Basin tore a score or more of large blocks of sinter from its crater walls. Some of these blocks were fully 1 m in diameter and were deposited 4½ to 6 m away from the vent (Marler, 1973, p. 88–92). Ten years later, all of these blocks had disappeared and no direct evidence exists today.

Four days after the 1959 earthquake, Sapphire Pool of Biscuit Basin became one of the park's most powerful geysers (Marler, 1973, p. 26–34) with eruptions up to 45 m high and jetting to widths of as much as 75 m. With diminishing frequency, the mammoth eruptions continued through 1960 and 1961, and the geyser then declined in force and power. Due to the explosive nature of the major eruptions, the crater nearly doubled in surface diameter. Layers of sinter 0.2 to 1 m thick, including most of the ornate fringing "biscuits," were torn from the shallow borders of the original vent, thus increasing the upward-flaring of its margins, as discussed for Seismic's vent. The great deluge of water from each major eruption, estimated to weigh about 50 tons, washed the broken sinter fragments 18 to 30 m away from the crater and formed an encircling wall about 1 m high. Two large deltas of sinter fragments formed in the Firehole River to the south and east. The clastic rim was still sharp and easily recognized when mapped in detail by White in 1966 (unpub. data) but by 1974 was evident only when specifically sought.

Excelsior Geyser of Midway Basin was one of the most powerful geysers in the park and is now the most copiously flowing thermal spring (Marler, 1973, p. 367–368). Its huge crater is 45 to 75 m wide and 107 m long and elongated to the northeast; it clearly was formed by explosions. The crater walls rise almost vertically as much as 4 m above the water level of the spring. These walls, which encircle Excelsior on all sides except on the northeast near the Firehole River, consist of thinly laminated sinter that was probably deposited by Grand Prismatic Spring over a period of many centuries. These sinter deposits rise unchanged in character through the 4-m-thick section visible in Excelsior's southwest crater wall. Excelsior's crater abruptly terminates these beds and thus is of comparatively recent origin. Further, observational data indicate enlargement of the crater to its present dimensions in the early years after the park was established. Colonel F. P. Norris (1881, p. 60), then superintendent of Yellowstone Park, described an eruption of Excelsior in 1878:

> Crossing the river above the geyser and hitching my horse, with bewildering astonishment I beheld the outlet at least tripled in size, and a furious torrent of hot water escaping from the pool, which was shrouded in steam, greatly hiding its spasmodic foamings. The pool was considerably enlarged, its immediate borders swept entirely clear of all movable rock, enough of which had been hurled or forced back to form a ridge from knee to breast high at a distance of from 20 to 50 feet from the ragged edge of the yawning chasm.

Excelsior was not known to erupt again until 1881 when much eruptive activity was observed. In reference to the power of the eruptions and the discharge of rocks, Norris (1881, p. 61) stated, "During much of the summer the eruptions were simply incredible, elevating to heights of 100 to 300 feet sufficient water to render the rapid Firehole River nearly 100 yards wide, a foaming torrent of steaming hot water, and hurling rocks from 1 to 100 pounds weight, like those of an exploded mine, over surrounding acres."

Today, 90 yr after the great discharge of sinter "knee to breast high," not a shred of direct evidence remains that solid matter ever was disgorged from Excelsior's crater.

SPECULATIONS ON THE ORIGIN OF HOT-SPRING VENTS NOT KNOWN TO HAVE ERUPTED AS GEYSERS

The geyser basins contain hundreds of vents that lack direct evidence of their origin. The smooth upward-flaring margins of Morning Glory's classic vent in Upper Basin are characteristic of many of these, ranging from a few feet in diameter up to the magnificent symmetrical funnel of Grand Prismatic Spring in Midway Basin, which is about 180 m in diameter. The internal structures of the vents are largely concealed by deposits of sinter, algae, and silica gel, at least partly in layers parallel to the borders of the funnels. Fracture-bounded blocks and irregular surfaces, such as are visible in the vents of Seismic (Fig. 8), Excelsior, West Flood, and Artemesia, are generally absent. Can small pools and vents evolve into large-diameter pools by some nonviolent process such as an upward-flaring deposition of scores or hundreds of feet of sinter? Or have these vents formed explosively by Seismic's general mechanism, followed by evolution from rough-walled geyser vents to quietly discharging smooth-walled pools and eventually to inactive vents as maximum dimensions are first attained and then as self-sealing of channels becomes significant. In our opinion, the evidence is indirectly but strongly in favor of the second mechanism.

The broad terraces of sinter in general extend only to depths on the order of 1½ to 5 m but most of the large morning glory vents extend down into underlying rocks. Six of Yellowstone's research drill holes were collared in hot-spring sinter, and these, with only one exception, penetrated only 1.5 to 3.5 m of sinter. The single exception, near Hot Lake in Lower Basin, penetrated alternating sinter and hot-spring travertine to 10.0 m, with travertine being dominant (but rare elsewhere in the geyser basins). The depth of vertical penetration of large funnels such as that of Grand Prismatic is not known, but the intense blue color of this pool suggests a depth of scores of feet. Smaller flaring funnels have been probed to depths as much as 11 m, and others no doubt penetrate deeply into cemented stream sediments and perhaps into underlying volcanic rocks. The nearly vertical throats of these funnels could not have been maintained in these stream sediments prior to their lithification.

A jagged-edged, explosively formed geyser vent probably evolves into a smooth-walled hot spring funnel as silica is deposited on the margins; the rate and temperature of discharge from the vent decrease with time as a consequence of self-sealing. The jagged near-surface borders, initially showing a clear sequence of sinter overlying cemented stream sediments or a lava flow, are eventually concealed by deposits of new sinter, algae, and silica gel.

Most hot spring vents, especially those that flare upward in geyser areas, probably involve the disruption and violent ejection of previously existing competent rocks. This mechanism of explosive ejection also helps to explain the nearly vertical tubes that characterize the throats of most geysers. Such openings must have formed mechanically and were not inherited from previously existing rocks.

CONCLUSIONS

The evidence suggests that the great majority and perhaps all vents in geyser areas were formed by mechanical enlargement of initial narrow channels. In the geyser basins of the Firehole River, the evidence is convincing that many hot springs started as fractures in older sinter. These rifts or breaks resulted largely and perhaps entirely from seismic shaking and fracturing of hydrothermal systems characterized by fluid pressures much above hydrostatic but below the lithostatic gradient. The epicenters of the earthquakes were largely outside the Yellowstone caldera, and appreciable fault displacements in the geyser basins were rarely if ever involved. In general, geyser craters evolved from fractures by repeated explosive decompression of hot water at local temperatures as high as 150°C and pressures at least as high as 4.85 kg/cm². Pressure gradients locally exceeded the lithostatic gradient, thus favoring the disruption, fragmentation, and ejection of rocks, thereby enlarging flow channels and increasing the volumes of individual local geyser reservoirs.

We suggest that cone-type geysers tend to form where near-surface rocks are competent and not easily fragmented and that fountain-type geysers with upward-flaring funnels tend to form where the near-surface rocks are easily broken and can be ejected.

Some effects of the 1959 earthquake include new breaks, many but not all of which show the same northwest-trending alignment as do many of the earlier breaks. These breaks provide evidence that earthquakes have played an important role in creating new channels for discharge of thermal fluids as old channels become clogged with hydrothermal minerals and cease discharging.

GENERAL CONSIDERATIONS AND ACKNOWLEDGMENTS

Marler was a naturalist and geyser specialist for many years in Yellowstone with the National Park Service; he was privileged to observe the profound changes that have occurred, especially during and soon after the Hebgen Lake earthquake in 1959. White desires this opportunity to express his deep appreciation for many years of association and access to Marler's detailed knowledge and observations in the geyser basins. Both authors are especially indebted to L.J.P. Muffler, R. O. Fournier, A. H. Truesdell, and Manuel Nathenson for products of their geologic mapping, observations, and critical reviews that are incorporated in the present report.

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