Whistle, a Nearly Dormant Geyser in Upper Geyser Basin, Yellowstone National Park, Wyoming: The First Geyser to be Studied by Research Drilling

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By DONALD E. WHITE

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METRIC CONVERSION FACTORS

For readers who wish to convert measurements from the inch-pound system of units to the metric system of units, the conversion factors are listed below:

Multiply inch-pound units	By	To obtain metric units
Inches (in.)	2.54	centimeters (cm)
Feet (ft)	.3048	meters (m)
Miles (mi)	1.6093	kilometers (km)
Pounds per square inch (lb/in^2)	6.895	kilopascals (kPa)
Gallons (gal)	3.785	liters (L)

Whistle, a Nearly Dormant Geyser in Upper Geyser Basin, Yellowstone National Park, Wyoming: The First Geyser to be Studied by Research Drilling

By Donald E. White

Abstract

Research hole Y–1 was drilled in 1967 in Upper Geyser Basin of Yellowstone National Park at a distance of 50 ft from the pool of Whistle Geyser. Now nearly dormant, Whistle has erupted only about 12 times in the period 1931–71. Pressure and temperature data were obtained as the hole was drilled. Below a zone of self-sealing at −183 ft, the pressure gradient with depth in the drill hole is greater than hydrostatic. Temperatures cross the reference boiling-temperature curve for pure water (higher than hydrostatic) at about the same depth. Changes in the water level of Whistle Geyser's pool during drilling show that the ground sampled by the drill hole was in pressure communication with Whistle's immediate reservoir from −25 to at least −100 ft. Below about −185 ft, overpressures measured in the drill hole provide the deep feed to Whistle. This is the first geyser that has been proved to depend for its water supply on deep overpressured water from a much more extensive system than can be demonstrated from surface measurements in the geyser tube; this dependence also proves a continuous upward supply of water, though not at a constant rate.

INTRODUCTION

Worldwide experience demonstrates that natural geysers are rare phenomena related to large, deep, hot hydrothermal-convection systems, generally circulating to depths of 1 to 2 mi, where maximum temperatures are near 180°C or higher (as determined by chemical geothermometry). Geysers normally constitute only a fraction of the total number of discharging vents.

A geyser is a rare form of non-steady-state cooling of water that occurs only when its excess energy cannot be lost by steady-state processes (near-surface boiling, cooling from contact with the atmosphere, and conduction of heat through cooler wallrocks). The "roots" or natural channels of all geysers must extend far below the local water table. As hot water rises in a convection system, silica minerals and zeolites are deposited, especially at depths of 80 to 160 ft. A zone of "self-sealing" tends to form as temperatures decrease upward, water boils to steam, and SiO_2 is precipitated. Deep in the system, fluid pressures generally are higher than those along a theoretical boiling-point curve responsive to pressure changes, and so the system is said to be overpressured. Progressing upward, the local pressure becomes dominantly atmospheric plus the pressure of the overlying water. Before an eruption, downward-extending narrowing channels change from normally pressured to over-pressured but are still responsive to the changing reservoir pressures during the eruption. In the upper, permeable part of the geyser, water rapidly boils to steam and forces fluid levels to discharge at the surface, thereby decreasing pressure on the total system and initiating an eruption. Water is discharged more rapidly than it can be replenished through the underlying self-sealed zone of decreased permeability, and so the immediate reservoir, where pressure is controlled by the atmosphere, becomes depleted. Some overpressured water may flow up into the system during an eruption; previous self-sealing limits the volume of fluid involved. An interval of replacement of water and heat (as separate factors) must occur for the geyser to prepare for its next eruption.

Eventually, a geyser becomes less active as its flow rate declines from self-sealing; either it becomes a hot spring with steady-state flow, or its discharge ceases entirely. Coral Spring in Norris Basin (White and others, 1988, figs. 9, 10) is now completely self-sealed, whereas Porkchop Geyser (White and others, 1988, figs. 11–13) became a noisy, partly self-sealed fumarole in 1986, followed by months of continuous eruptive activity that was terminated in September 1989 by a violent hydrothermal explosion. The explosion destroyed the geyser, creating a new pool surrounded by ejected blocks as large as 3 ft in diameter.

Research drilling was undertaken in Yellowstone National Park in 1967 and 1968 (White and others, 1975) to obtain data from shallow parts of the geothermal system. Yellowstone had been selected to test the use of remote-sensing devices in orbital overflights, checking "ground truth" with the results from such devices because of its young volcanic rocks, hot springs, numerous geysers, and high heat flow.

Hole Y–1 was drilled near Whistle Geyser in a subbasin of Upper Geyser Basin to study the pressure

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and temperature distributions in the ground in relation to a nearly dormant geyser. Since 1931, Whistle has had only 1 year with several recorded eruptions (1957), erupting spurts of water 25 to 35 ft high but followed by a noisy steam phase. Only a single eruption occurred in 1968, after hole Y–1 was drilled. The geyser is probably near the end of its eruptive activity.

Acknowledgments.—L.J.P. Muffler has been an invaluable associate in all phases of the Yellowstone National Park studies. R.O. Fournier provided a deep insight into the causes and origin of geysers. A.H. Truesdell, another essential member of our hydrothermal studies team, was not in the park during the drilling of hole Y–1, but both he and Fournier maintained a great interest in all hydrothermal phenomena. An earlier version of this account was originally prepared as a section of our general report on research drilling (White and others, 1975) but was withdrawn for separate publication; the data reviewed here, directly concerning geysers, were clearly a diversion from the main objective of that report. I am also much indebted to George Marler, now deceased, a former park naturalist who had an encyclopedic knowledge of the near-surface characteristics and interrelations of springs and geysers. His intimate knowledge of Whistle's early activity was invaluable. His wife, Larrie, has also had a continuing interest, both before and after George's death. Finally, I am much indebted to P.F. Fix, a former seasonal Yellowstone naturalist and later a full-time member of the U.S. Geological Survey's study team at Steamboat Springs, Nev. He greatly whetted my interest in learning more about geysers, how and why they exist, and their evolution (White, 1967).

RECORDED HISTORY

Whistle Geyser's known history was recorded by Marler (1973, revised in 1976). Its early history before 1931 is unknown, but its rather impressive shield-shaped cone must have required hundreds of years to form.

According to Marler (1973):

> Since I began observing the hot springs [about 1931], there have been but few seasons when Whistle was known to have erupted. The information I gained during the early years I was in the geyser basins was to the effect that it was dormant, with the connotation of it being extinct. The structure of the large mound and the small orifice are highly suggestive that it might be nearing the stage of a sealed-in unit, as is the case with some of the mounds near Old Faithful.
>
> The first eruption of Whistle of which I am aware, occurred during the 1948 season. There was but one known eruption that season. The next known eruptions were during the 1954, 1955, and 1956 seasons. But one eruption occurred each season. During 1957, seven eruptions were recorded. It is believed that this figure represents the total amount of its activity during 1957. This deduction is based on the long duration of an eruption and the protracted period of recovery, making it evident hours afterward, if an eruption has occurred.
>
> An eruption of Whistle lasts from two to three hours. It is only during the first moments of play that any water is discharged. The flow of water barely reaches the base of the cone before the eruption enters a violent steam phase. The momentary water phase jets the water from 30 to 35 feet in height, but the steam mingled with spray shoots up in excess of 100 feet. It is as if a steam valve on a huge boiler were suddenly opened. In the early stages the steam ejection is very impressive. Under great pressure, accompanied by a roar, it is forcefully expelled and with slowly diminishing power continues for the duration of the eruption.
>
> When first observed in May 1958 [no observations were made in winter 1957–58], a change had taken place in the state of the water in the crater. Previous to this observation, the water had always stood 4 to 6 inches below the rim of the crater, with the temperature ranging between 198°F [92°C] and 200°F [93°C]. In May 1958, the water was at the upper rim of the bowl with light seepage. The temperature had dropped to 143°F [62°C].
>
> Except for murky water, the 1959 earthquake had no observable effect. No eruption was induced [by the earthquake], and the water level and temperature were the same as during 1958. With minor fluctuations, it has remained in this state to date (1971) except at the time of an eruption in 1968 [the year after hole Y–1 was drilled].
>
> The 1968 eruption was witnessed by one of the seasonal naturalists. In reporting the eruption, he stated that the water phase was "very brief" and the steam phase lasted for 30 minutes. He also got the impression that the water of the eruption was "cool," which I discount very much. In duration, the steam phase of this eruption was very much shorter than any I had observed.
>
> Whistle is not known to be influenced by any other spring. Probing of Whistle on October 28, 1969 [with D.E. White], provided the following data: maximum accessible depth below lip, 9½ ft; temperature at water level, 56°C; bottom temperature [at –9½ ft], 90.5 to 92.5°C; maximum temperature, 92.5°C at a depth of 9½ ft.

According to Marler's description and oral comments, the volume of water available for the eruption is unlikely to have been more than a few hundred gallons, erupting 30 to 35 ft high. The initial eruption of water barely reached the base of the cone. The eruption then changed to a violent, noisy steam phase (a fumarole venting at high pressure, thereby explaining its name). Steam and spray were ejected upward more than 100 ft for 2 to 3 hours.

During an eruption, a "cone of depression" (zone of reduced pressures) forms in the hydrostatically pressured rocks surrounding the geyser tube. Some unpressured water, cooled near the surface by thermal conduction, drains laterally into the erupting column. Water is erupted out much faster than it can be replenished, and so the water level declines. The eruption ends when water can no longer be ejected because of increasing depth to the water table, resistance to flow through narrow channels, and cooling by lateral flow of shallow cooler water. Some recharge continues upward through the zone of partial self-sealing throughout the eruption, but its rate of upflow is much less than the rate at which the immediate reservoir water is normally resupplied from depth. A period of rest must occur to replenish the supply of both water and heat lost in the previous eruption.

The long-lasting period of "whistling" that explains the geyser's name is due to the high velocity of steamflow and, eventually, to declining temperatures and water supply in and near the main channels. The rock mass still contains much high-temperature liquid in semi-isolated pores, and rock temperatures away from major channels are still close to preeruption temperatures. The total mass of rock and pore fluid cools as pore water boils to a mixture of water and new steam, forcing both fluids through narrow channels to the main tube.

LOCATION OF DRILL HOLE Y–1 AND ITS RELATION TO NEARBY THERMAL FEATURES

Our first drill hole, called Y–1, was selected in the Black Sand part of Upper Geyser Basin (figs. 1, 2) for its proximity to a nearby, nearly dormant geyser and for its ease of access at the margins of an active hot-spring system. This subbasin contains many hot springs and a few named geysers, but none was especially notable outside of the park. Drill hole Y–1 is 1¼ mi west-northwest of Old Faithful Geyser (Muffler and others, 1982) and about 1 mi west-northwest of the first geothermal hole specifically drilled in the United States for research purposes (Fenner, 1936).

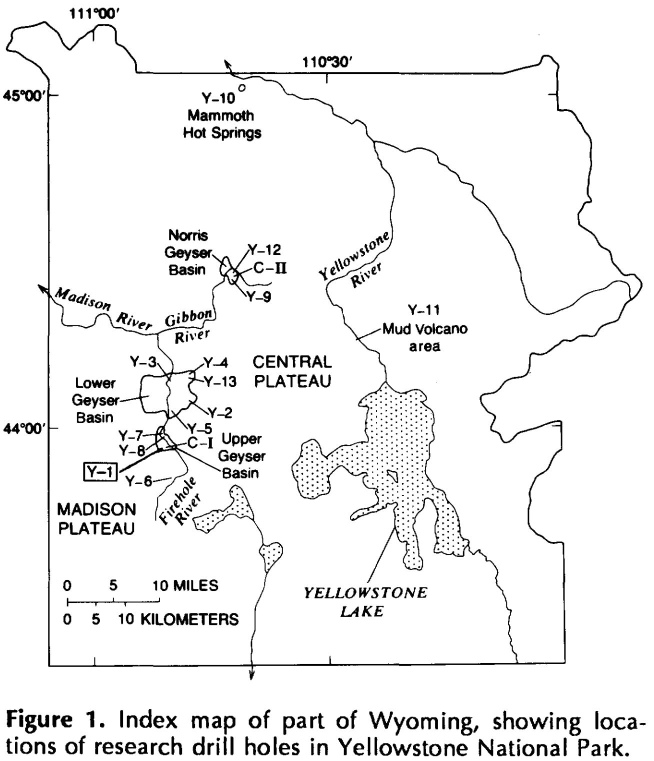

Figure 1. Index map of part of Wyoming, showing locations of research drill holes in Yellowstone National Park.

Drill hole Y–1 is on the southeast slope of Whistle Geyser's cone and 47 ft east-southeast of its summit pool (fig. 2), which is 5.5 ft above the collar of the hole. The geyser's pool is 6½ ft in diameter, and, in recent years, water has just filled the pool to seeping overflow. The visible vent is a shallow bowl that narrows downward to about 1 ft in diameter at a depth of about 1½ ft. The geyser's tube was probed vertically below seepage level to 9.5 ft, where a shelf prevented deeper vertical penetration. Surface temperatures at a depth of about ½ ft commonly ranged from 40 to 60°C, being lowered by evaporation, cold air temperatures, and wind; just below the constriction, temperatures ranged from 90.5 to 92.5°C. Water seeped from five or six places around the pool's perimeter (fig. 3) for a total discharge of about 0.5 gal/min.

In preparation for drilling, these small surface seeps were blocked off except for the largest, which was deepened slightly to install a pipe for measuring total discharge (fig. 4). A water-stage recorder was installed (fig. 5) to provide a continuous record of any changes of water level in the pool while nearby hole Y–1 was drilled. The water-stage record (pl. 1) showed fluctuations even before drilling started. On April 18, 1967, the surface pool level dropped about 0.3 ft in less than an hour; almost without pause, the level then reversed immediately, rising sharply less than an inch. After an hour or so with little change, pool level again resumed a steady rise that decreased to zero only as the level of overflow was approached.

Most other springs and geysers in the Black Sand area are southwest to northwest of Whistle Geyser (Muffler and others, 1982). Spouter Geyser, 425 ft to the northwest, and Cliff Geyser, 410 ft to the west, are Whistle's nearest active neighbors. Other small vents nearby had no active discharge, but large pool-type geysers lie farther to the southwest and west.

THE DRILLING OF HOLE Y–1 AND CONTEMPORANEOUS CHANGES OBSERVED IN WHISTLE GEYSER'S POOL

An account of the drilling was given by White and others (1975, p. 11–15). Drilling started at 9:00 a.m. m.s.t. on April 18, 1967 (table 1). The water level in the drill hole was first identified at a depth of 4.8 ft below local ground level (–4.8 ft) and 10.3 ft below the level of Whistle's seeping discharge, thereby indicating a steep hydrologic gradient of the water table away from the pool. At −21 ft, a 21-ft length of 4-in. casing was set and cemented.

The cement plug near the bottom of the casing was drilled out on April 19, resulting in a rise in water level within the casing to −2.0 ft. Whistle Geyser's pool level responded almost immediately (depths noted on casing record, pl. 1) by declining slowly to −0.07 ft. When drilling ceased for the day near −80 ft, the pool level was declining rapidly, indicating strong communication with the drill hole. The pool level continued to decline overnight, showing a dampened response and some tendency to stabilize near −0.55 ft. The pool level again fell rapidly during the afternoon of April 20, several hours after the hole was deepened to −100 ft. Water level in the drill hole changed little during the period of declining pool level. Core near the surface was composed of poorly lithified, porous fragmented sinter to about −12 ft and obsidian-bearing sand and gravel to about −30 ft.

On April 21, 100 ft of 3-in. casing was set and cemented, resulting in a prompt rise in pool level. The drill hole was opened for inspection at about 3:30 p.m. that day by removing the cap from the 4-in. casing, and fluid was found leaking between the two sets of casing. The pool level immediately started to decline after the casing was opened. A sack of quick-setting cement slurry was pumped into the hole between the casings. A cap was installed on the 3-in. casing but not on the larger casing. The pool level immediately resumed its rise to recovery. By this time, 2 days had passed with none of the curious fluctuations that had been observed before April 19.

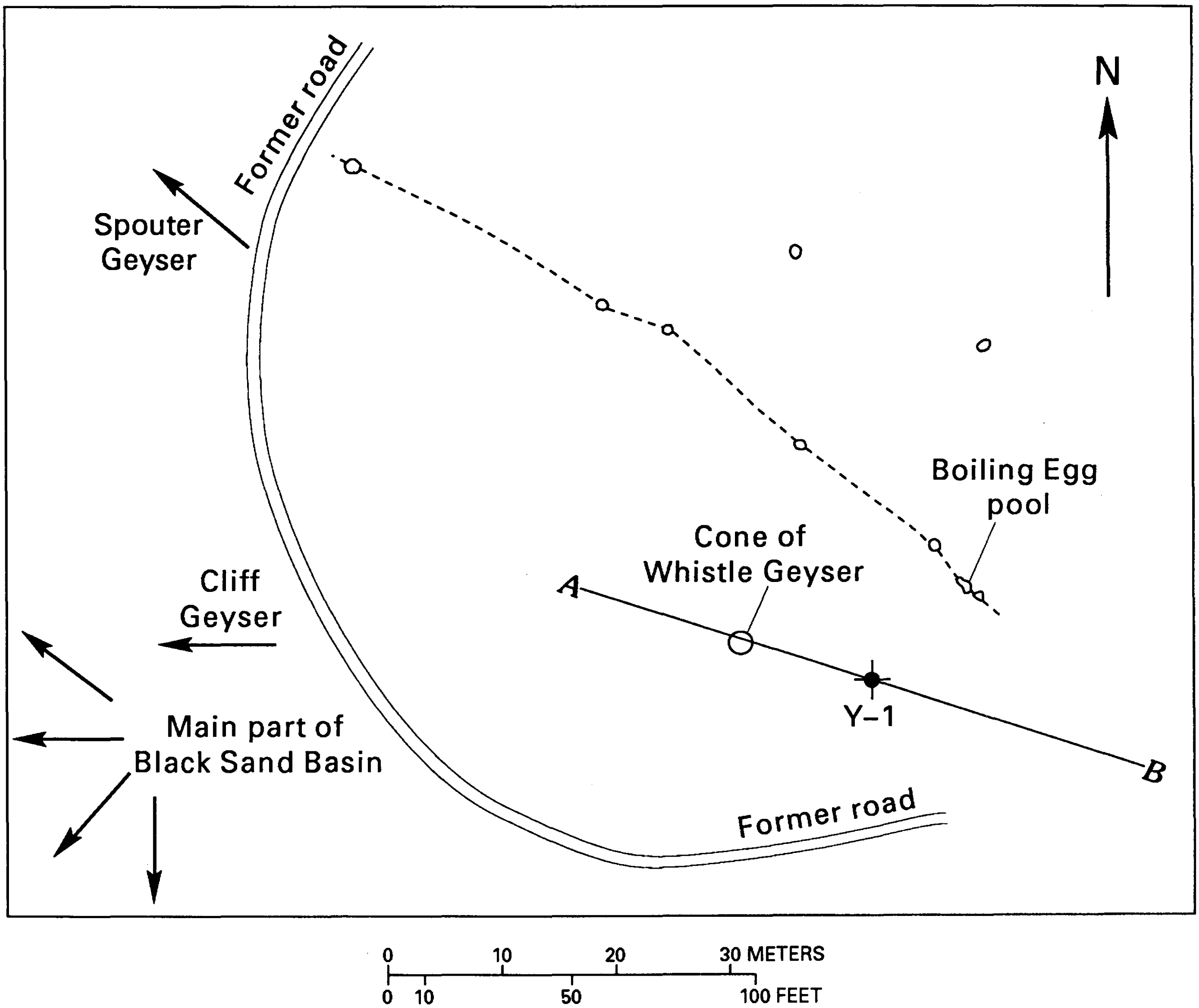

Figure 2. Sketch map of the Black Sand part of Upper Geyser Basin, showing locations of Whistle Geyser, drill hole Y–1, and former access road (modified from Muffler and others, 1982). *A–B*, projected line of section in figure 10. Dashed line indicates fracture-controlled alignment of steam vents.

The intermittent pool-level fluctuations resumed again on April 22 (pl. 1), indicating that some shallow influence had probably caused the approximately 0.3-ft fluctuations in the pool level. A cavity is suspected in the geyser tube at shallow depth and low temperature that permits exsolution of gas below a constriction. Presumably, gas then discharges to cause the changes in pool level.

Drilling continued on April 22 to −185 ft, but the pool failed to regain its former slight discharge. Drill-water return, which had been less than 100 percent, failed completely between −180 to −182 ft but was largely regained between −183 and −185 ft.

Water overpressure of about 6½ lb/in² was measured on the following morning, April 23. After a day of rest, drilling was resumed on April 24 from −185 to −215 ft. Eruption tendencies of drill hole Y–1 became much more troublesome below the zone of lost circulation near −182 ft. When the core barrel was removed at −214.6 ft, cool drill water gushed from the rods in response to high fluid overpressures. The top cool water was followed immediately by hot water and then water and steam as the well surged into violent eruption (fig. 6). This was the drillers' first experience with such high pressures in combination with boiling temperatures (White and others, 1975, p. 14–15). After about an hour of such eruption, with little visible change in total flow, the driller maneuvered the drill chuck over the erupting column and lowered the rods into the drill pipe. Cold water was pumped into the hole, terminating the eruption.

Figure 3. Whistle Geyser's pool, showing seeping discharge. Geyser Hill and Old Faithful Geyser are below tree-covered skyline. View southeastward.

On or about April 24, a "bathtub ring" of dead thermophilic organisms was noted in the lower part of Whistle Geyser's pool (fig. 7). The date of the kill was not recorded. Blue-green organisms of the upper part of the pool, now above water level, were unchanged, but at depths below about 1.3 ft an abrupt change was visible, owing to the killing of organisms that had been exposed directly to temperatures too high for them to tolerate. We had noted qualitatively that near-surface temperatures increased as the water level declined into the bowl, decreasing the pool's diameter, but several days were required to produce these observable effects on organisms. No detailed observations were recorded of this phenomenon.

A maximum wellhead water pressure of 31 lb/in² was measured on April 25, equivalent to about 74 ft of cool water standing above ground surface. (For convenience, we use 1 lb/in² = 2.4 ft of water, but the conversion actually depends on the water temperatures.) On April 26, the wellhead pressures were slightly lower (29½–30½ lb/in²) than on April 25. The water level in Whistle Geyser's pool failed to regain that of the previous day after a fluctuation, and then started to decline. This combination of changes was probably caused by overpressure in the drill hole, forcing fluid into the surrounding ground between −100 and −183 ft. The flow up the drill hole lowered the pressure in the deep feed zone to the geyser (reflected in lower pressure in the drill hole) and caused the pool level to decline. The delay between when the drill hole first reached the zone of

Figure 4. Whistle Geyser's pool, modified by diverting all seeps through a pipe for measurement of discharge.

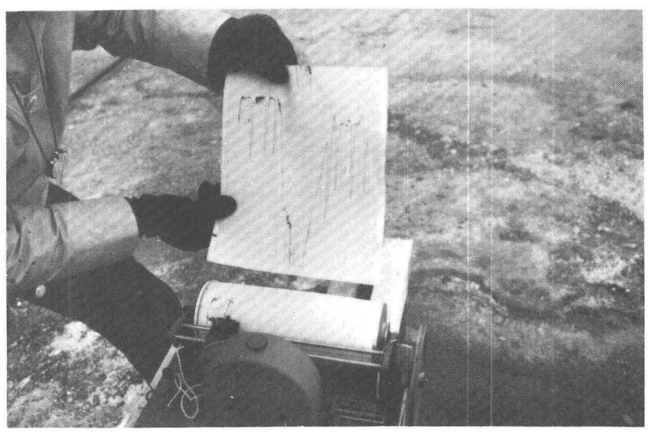

Figure 5. First week's record of water stage from April 17, 1967, has been removed, and a second chart installed.

Table 1. Temperature, pressure, and other data from drill hole Y–1, Upper Geyser Basin, Yellowstone National Park, Wyoming

[Data from White and others (1975, table 2). Drill hole Y–1x is drill hole Y–1 redrilled below 3-in. casing at –100 ft. Parenthetical values, least reliable or estimated]

Date (1967)	Time (m.s.t.)	Observation depth (ft)	Temperature (°C)	Static water level (ft)	Wellhead-gage water pressure (lb/in^2)	Comments
				Drill hole Y–1		
04/18	10:15	6.2	(17)	–4.8	---	1-hour shutdown for measuring water level, then drilled to –21 ft, with loose fragments in hole; set and cemented casing to –21 ft.
04/19	07:30	12.8	48.6	---	---	17 hours after hole cemented.
	11:30	30.5	---	–1.8	---	10 min after shutdown; good water level(?). Water level had risen by nearly 3 ft.
	16:45	79.7	(103)	(–2.7)	---	Drilled to –80 ft in open hole; measurements taken 1 hour after drilling.
04/20	07:35	79.6	125.9	–1.4	---	In open hole, water level 3.4 ft above initial level; then drilled to –100 ft at 11:25 m.s.t.
	19:30	99.3	129.1	–1.7	---	8 hours after circulation stopped.
04/21	07:20	99.3	134.1	–.7	---	100 ft of 3-in. casing set and cemented at 10:30 m.s.t.; water leaking between casings from –21 to –100 ft.
04/22	08:00	(43.5)	97.0	---	---	In cemented hole; drilled out cement, then drilled on to –185 ft at 15:40 m.s.t.
04/23	09:21	183.4	158.1	(+15.6)	~6½	Circulation lost at about –178 to –182 ft, regained at –183 to –185 ft.
04/24	07:26	182.9	159.2	(+17)	~7¼	Drilled to –215 ft.
	17:00	---	---	---	~26	High increase in overpressure; no further drilling.
04/25	07:27	214.6	169.6	(+74)	~31	14½ hours after circulation; large pressure increase. No further drilling.
04/26	07:38	214.6	170.7	(+71)	~29½ to ~30½	38 hours after circulation; slight decrease in measured pressure from previous day.
	11:30	---	---	---	~24	After pumping cold water for 40 minutes. Hole filled with cement to –100 ft.
				Drill hole Y–1x		
04/27	---	---	---	---	---	Drilled cement below –100 ft, then hole started to diverge; entirely in new hole below –120 ft.
04/28	07:25	128.4	146.8	---	~8	Wellhead pressure above that of 04/23; drilled to –180 ft, cemented up to –152.8 ft.
04/29	07:25	152.8	155.0	---	---	On cemented bottom; drilled to –194 ft.
04/30	09:45	190.7	163.7	(+30)	~12.5	Measured depth, –190.7 ft.
05/01	07:34	190.7	163.4	(+33.6)	~14	Slight temperature decrease, but pressure inreased slightly 40 hours after circulation. Drilled to –211 ft.
	11:30	---	---	---	---	No measurements obtainable; erupted trying to get into hole, more gas than on April 26. Hole abandoned, filled with cement to top.

overpressure and when the decline in pool level started could be caused either by the flow needing time to reduce the pressure in the deep feed zone to the geyser or by a new hydraulic fracture higher up in the drill hole that then permitted flow to start.

On April 26, cold water was pumped into the hole for 40 minutes, succeeding only in decreasing wellhead pressure to 24 lb/in^2. An attempt was then made to decrease formation permeability by pumping 10 sacks of cement slurry into the hole, using a maximum pumping pressure of 550 lb/in^2. The pool level attained its sill level on April 27 for the first time since April 19, indicating that this cementing probably sealed a connection between the drill hole and Whistle Geyser.

REDRILLING THE HOLE BELOW THE 100-FT CASING

The cement below −100 ft set up so rapidly that it was harder to drill than the zeolitized sand and gravel of the altered wallrocks. With renewed drilling on April 27, the hole (called Y–1x) started to deflect almost immediately below the casing, and the core showed that it was in totally new ground below −120 ft. Water began discharging from the drill hole at this depth, in contrast to the previous drilling, during which no discharge had occurred. The hole was cemented again on April 28 in a further attempt to decrease permeability, but without notable success. Drilling continued on April 29 to −194 ft. On April 30, Whistle Geyser's pool level started to decline once again.

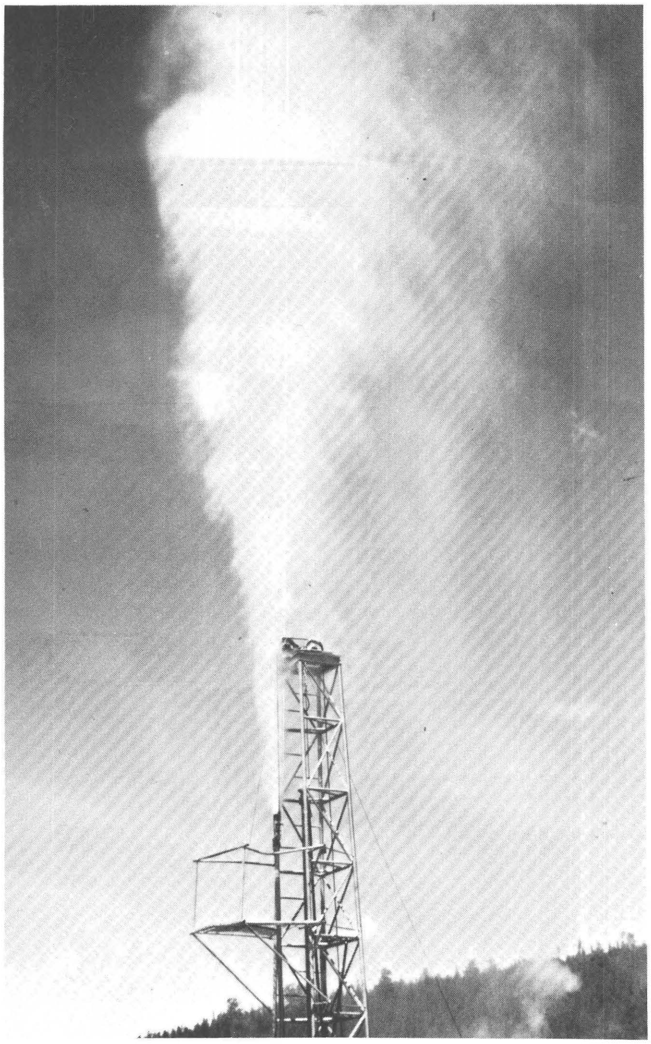

Figure 6. Drill hole erupting temporarily out of control. Drilling was into overpressures with sufficient permeability to sustain continuous flow. Note "bursting" discharge of water and steam immediately above drill rods.

After drilling to −211 ft on May 1, water was erupted from the drill pipe again. Water pressures seemed a little easier to control than on April 26, but the hole surged immediately into eruption upon removal of the core barrel. Our earlier explanation (White and others, 1975) for the strong eruptive tendency at −211 ft had assumed that an open fissure was intersected at about −200 ft, permitting water and vapor to flow into the hole (White and others, 1975, fig. 9, p. 15). A better explanation for these deep phenomena is that earlier cementing of drill hole Y–1 on April 26 had not sealed off the bottom of the hole. The very high upflow pressures had diverted all cement into the "lost circulation" zone near −180 ft, while none had reached the bottom of the hole. Overpressured water from depth had boiled as it rose to lower pressures, thereby accounting for the differences in the behavior of drill hole Y–1x relative to Y–1. The hole was filled with cement on May 1, and the pool again reached sill level on May 2.

Major fluid overpressures occurred in the hole below a drilled depth of about −182 ft, increasing rapidly to its drilled bottom at −215 ft, where a maximum of 74 ft of H_2O was measured at the well head on April 25. The vertical pressure gradient was more than double that of simple hydrostatic gradient of hot water and was locally near the lithostatic gradient.

INTERPRETATIONS

White and others (1975, p. 14–15) saw no obvious reason for separating the physical data of drill hole Y–1 from those of Y–1x. With more time for thought, however, differences were found that indicated imperfect cementation near the bottom of hole Y–1 as first drilled.

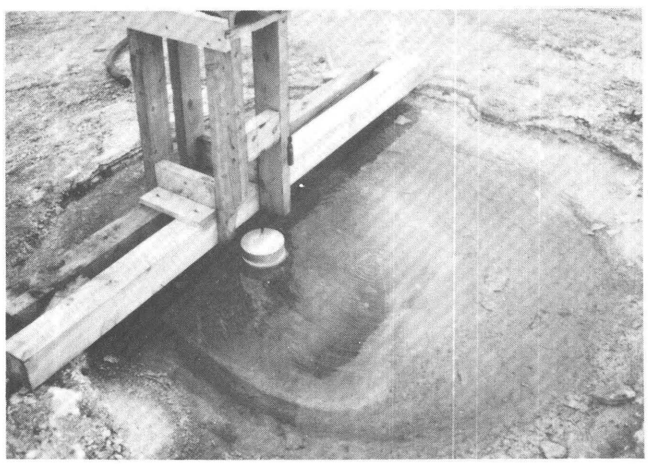

Figure 7. Whistle Geyser's pool on or about April 24, 1967. Note "bathtub" ring and gas disturbing pool's surface when water level was low and temperatures were high enough to kill thermophilic organisms.

Deep overpressured fluids could have continued to flow upward from zones previously thought to have been cemented. Overpressures and temperatures both increased significantly between the times of the two drillings. As plotted in figure 8, both data sets now give nearly parallel straight lines, but the data from drill hole Y–1x are clearly 4 to 6°C higher, and overpressures (points above the reference curve) are correspondingly higher. These adjustments best account for the added problems of drilling hole Y–1x (White and others, 1975), and not intersection of a gassy fracture, as originally interpreted. Data referring to drill hole Y–1x are also consistent with an interpretation of increasing overpressures with depth.

Core recovery had been low near the top of the hole, where sealing of sinter fragments was only partial, but recovery was nearly complete between about −20 and −160 ft except for somewhat lower recoveries near −70 ft and between −110 and −125 ft. Recovery then decreased significantly, averaging only about 50 percent from −160 to −182 ft. Drill-water return through this 22-ft interval was low and declined to 0 (lost circulation) between −178 and −182 ft. Most circulation was regained between −182 and −185 ft.

The alteration and replacement mineral assemblages plotted in figure 9 are useful in correlating changes in flow from the ground to Whistle Geyser's tube. Some flow may have occurred near −70 ft, where the assemblage quartz-analcime±celadonite±montmorillonite was identified, and probably from about −110 to about −125 ft, where celadonite coexists with quartz, analcime, and montmorillonite. Recrystallization to hydrothermal quartz and analcime is especially favorable for increasing permeability, in contrast to clinoptilolite, montmorillonite, and celadonite, which tend to plug up narrow openings. At neither depth was a decrease in the rate of water circulation noted, but the possible significance of this observation was not yet recognized. Slight decreases, as high as 50 percent of full circulation, would not have been noticed without careful attention, and some changes in drill-water discharge resulted from changes in the pump-gear ratio. For these reasons, slight enlargements in horizontal channels are shown in figure 10 near −67 ft, from −110 to −123 ft, and

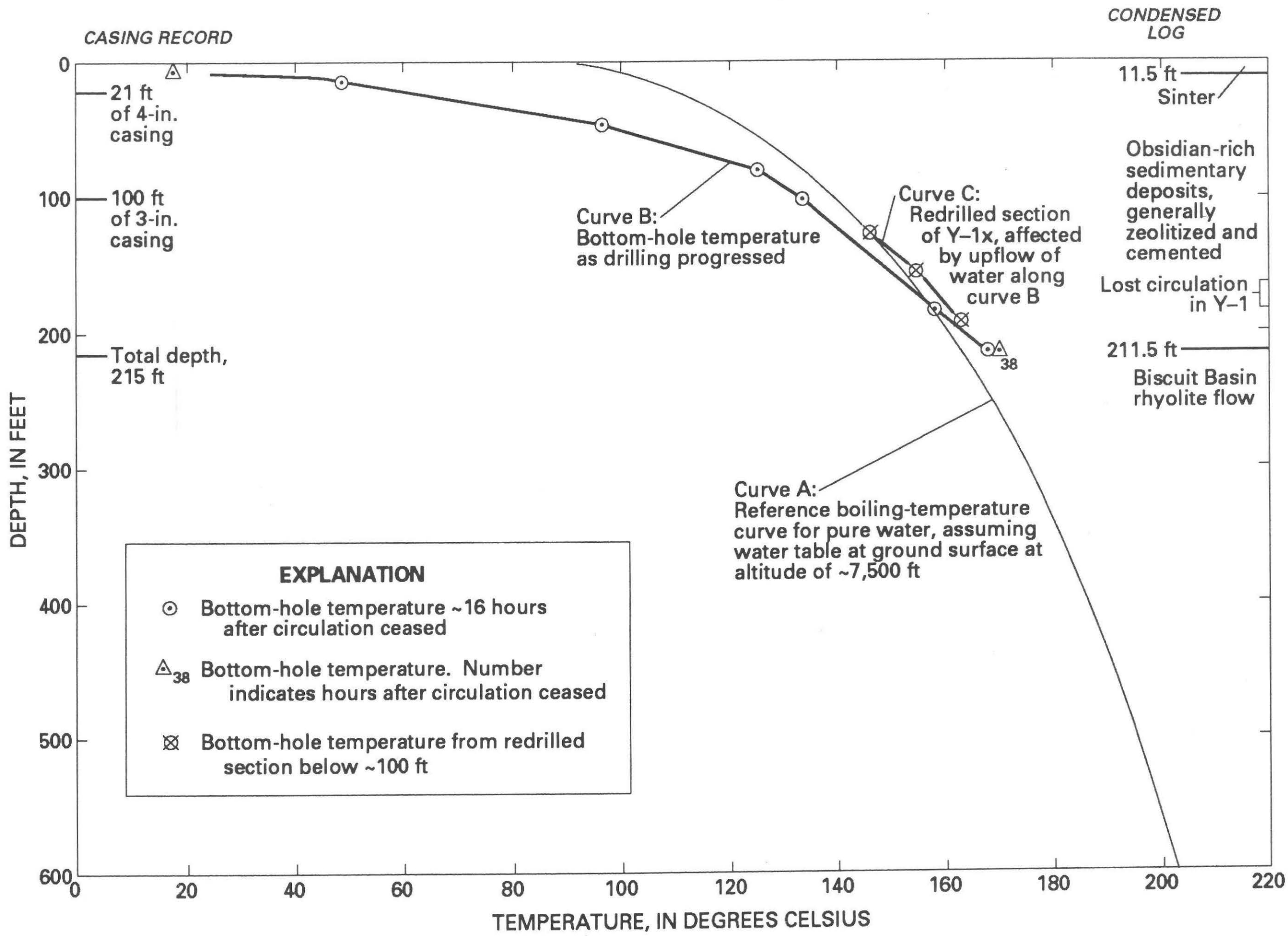

Figure 8. Temperature versus drilled and cased depths in drill hole Y–1 (modified from White and others, 1975, fig. 7) and drill hole Y–1x (below casing at −100 ft).

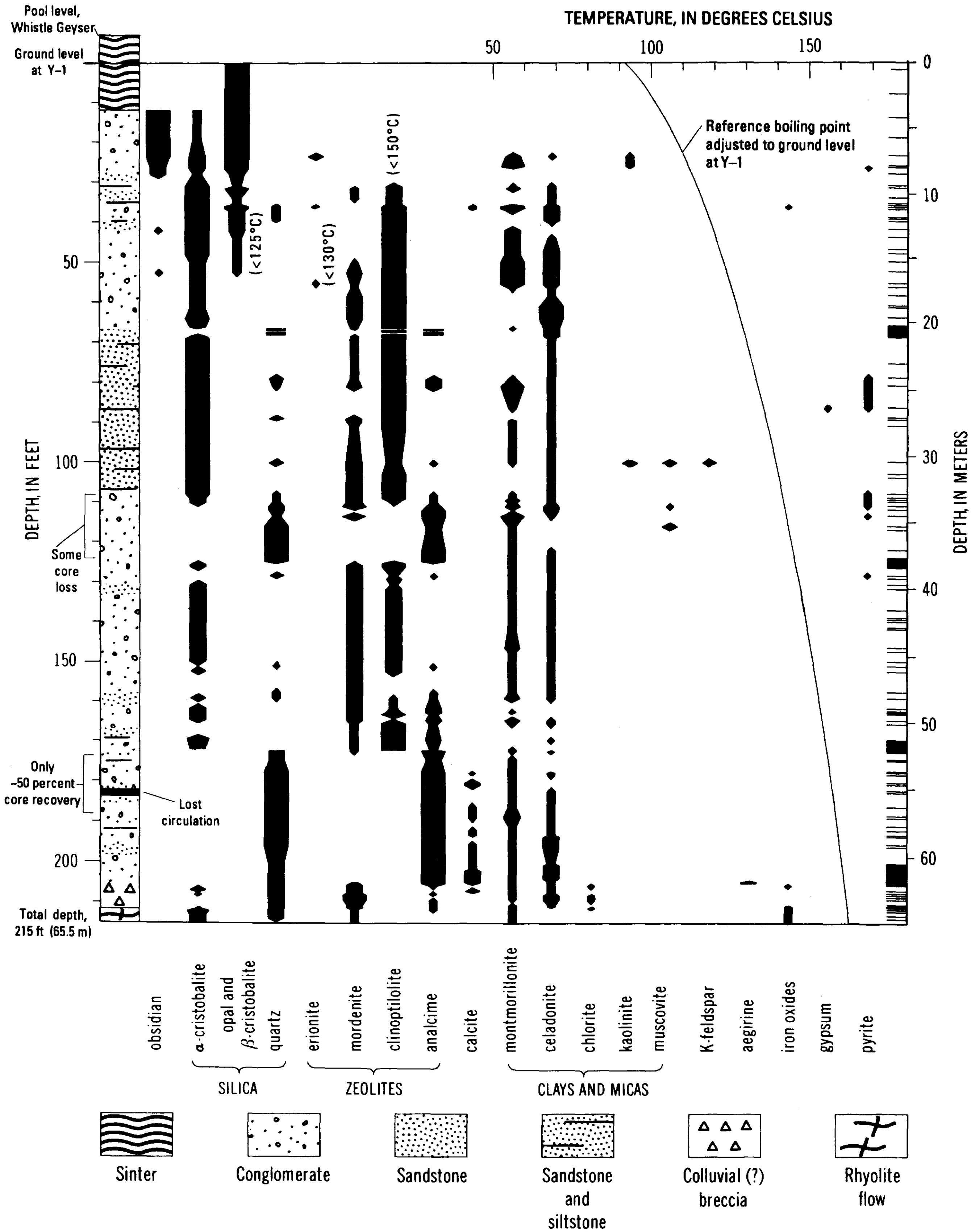

Figure 9. Stratigraphy and alteration mineralogy in drill hole Y–1 (modified from Honda and Muffler, 1970). See figure 8 for corrected temperature data.

especially from −172 to −182 ft. The two lower zones have temperatures nearly on the boiling curve, and so any decrease in pressure causes boiling and an increase in pH, thereby accounting for the local deposition of some calcite and K-feldspar (Browne and Ellis, 1970); calcite is especially abundant below about −180 ft. Hydrothermal K-feldspar is scarce; it was detected only near −100 ft.

Whistle Geyser's immediate reservoir is defined as the part with permeable interconnections that are open and responsive to air pressure to about −100 ft. Evidence for this responsiveness is that the water level in Whistle's pool (pl. 1) started to decrease when drill hole Y–1 was at about −25 ft on April 19, dropped farther when it reached −80 ft, and dropped still further when drilled to −100 ft on April 20. The pool level rose strikingly after cementing the 100-ft casing and sealing the leak found between the casings on April 21. It is unclear whether this second cementing completely sealed off the connection because drilling resumed on April 22, before the pool level reached a steady state. The connection between the drill hole and Whistle's plumbing system must have been somewhat permeable because the water level in the drill hole was below local ground level and more than 5.5 ft below Whistle's sill level.

The relation between the water level in Whistle Geyser's pool and the water level and pressure in the drill hole is difficult to interpret deeper in the hole because of uncertainties in the effect of cementing above −100 ft. Between −100 and −185 ft, the pool level remained fairly constant except for fluctuations about once a day. This pattern indicates little communication between the geyser and the drill hole because the drill hole went from underpressured to an overpressure of 7¼ lb/in^2 during this period, with no obvious response in the pool level. After the drill hole had been at −215 ft for 1½ days, the pool level failed to recover completely after the fluctuation of April 25 and then started to decline on April 26. This decline is probably a response to flow up

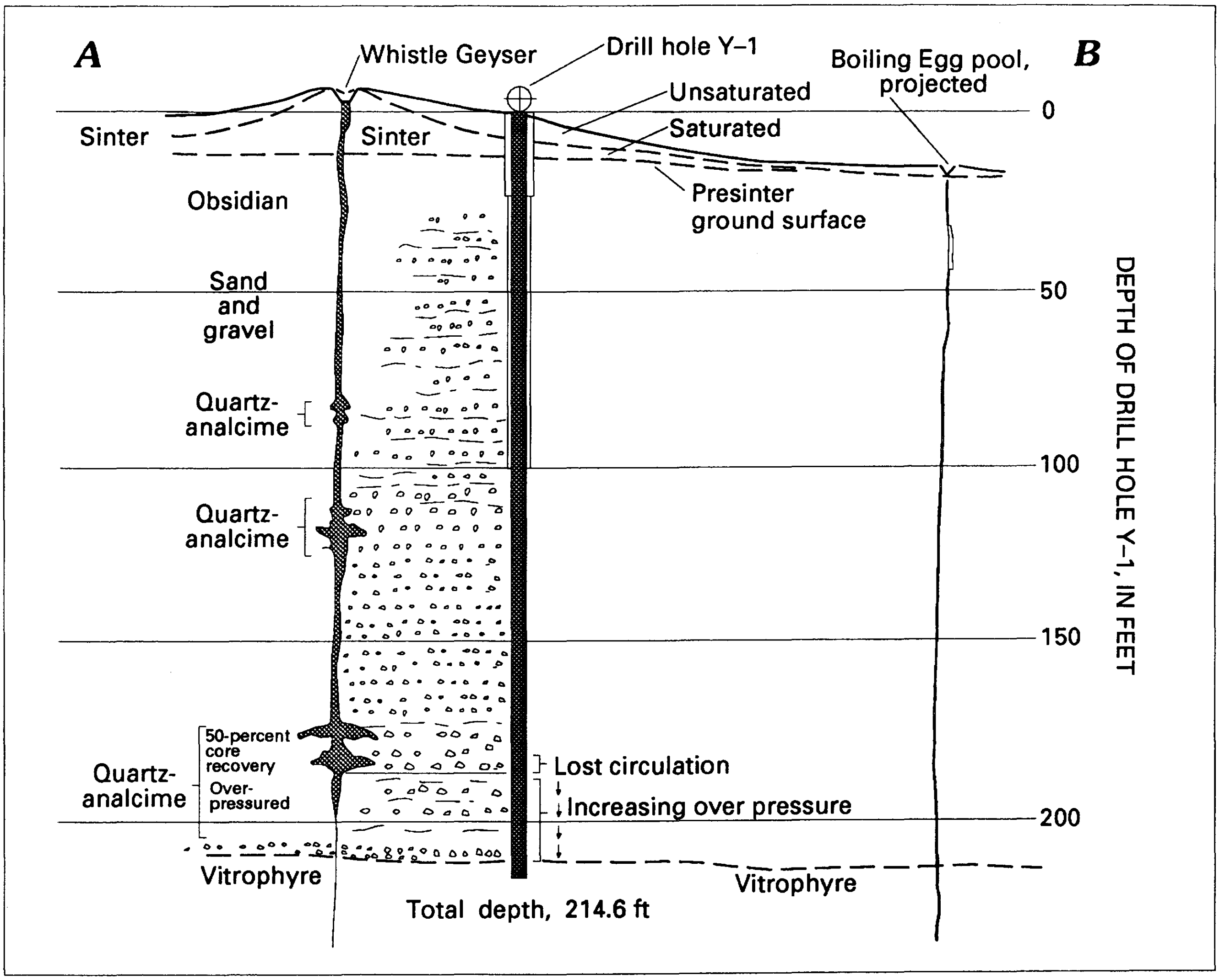

Figure 10. Strata penetrated by drill hole Y–1, showing original rock types. See figure 9 for hydrothermal minerals.

the drill hole, lowering pressure in the deep feed zone to Whistle. After the drill hole was filled with cement on April 26, pool level regained the sill level on April 27 after about a day and retained this level until early on April 30. The shorter time interval for recovery of the pool level relative to the time needed to start lowering the pool level after the drill hole first reached substantial overpressure at −215 ft may indicate that some restriction had to be forced open, possibly by hydraulic fracturing high up in the drill hole. During the redrilling of April 27 to 30, the pool level appeared insensitive to the drill hole until the drill hole sat for nearly a day at −194 ft, at which point it started to drop at a rate similar to, but slower than, the April 26 decline. After the drill hole was filled with cement on May 1, the pool level regained its sill level on May 2 after about a day.

The ground at drill hole Y–1 clearly communicates with Whistle Geyser's immediate reservoir between −25 and −100 ft, but there is little obvious communication between −100 and −183 ft. The high overpressures detected below −183 ft are responsible for feeding water continuously up to Whistle's immediate reservoir, but they communicate through a region of limited permeability. At greater depths, overpressure forces water continuously up the natural channels but at rates dependent on resistance to flow. For the geyser's normal discharge to be nearly zero at the pool's present level in spite of the high vertical pressure gradients at depth, the channels must have walls of limited permeability (far smaller than the 2- to 3-in. diameter drill hole and casing). Slight overpressures are necessary to overcome frictional resistance, which varies linearly with the rate of water flow but increases greatly with the percentage of exsolved steam. Because the pool level declined periodically by about 0.3 ft (pl. 1), some water was leaking upward and outward into surrounding porous ground. Near-tube permeability gradients toward the drill hole are ineffective in accounting for the observed changes in pool level, suggesting that the cause of the 0.3-ft fluctuations is high up, observable only when the pool level was high and surface temperatures were low.

APPLICATION TO OTHER GEYSERS

The drilling of hole Y–1 demonstrates clearly that the water sustaining an eruption comes from more than the water stored in the geyser tube. The tube is the largest part of the system, with nearly infinite permeability for a limited depth. It can normally be probed only vertically below the surface vent, where dimensions are large enough to permit entry and recovery of a probe. Convection is most likely to occur where the tube has such characteristics, probably distorting greatly the shape of temperature curves in other places (for example, Allen and Day, 1935, p. 191–198). Convection probably is particularly important in initiating some eruptions, but not necessarily everywhere. Temperature reversals and near-surface temperatures below the boiling reference curve are both exceedingly common in most of the examples cited by Allen and Day, but most geyser models do not require such reversals. Boiling occurs most frequently near a constriction high up in the tube, but it also occurs elsewhere in the immediate reservoir in areas not easily observed.

Major variations in the discharge altitudes of pools, springs, and geysers are extremely common. Some levels are much higher than expected, whereas others are lower. If all potential channels from a system are equal in permeability, length, and resistance to flow, most water would normally discharge from the vent of lowest altitude. If the water supply is too great to discharge from a single vent, successively higher vents assume parts of the discharge. But, in fact, the altitudes of active vents seldom are closely related. Other factors, such as extent of boiling, steam lift by the bubble fraction, and self-sealing, are also essential. Such relations explain why Whistle Geyser's pool is generally discharging, although the water level in drill hole Y–1 was about 4.8 ft below local ground level and about 10 ft lower in altitude than the pool. "Boiling Egg" pool farther to the northeast had the lowest altitude of all but lacked surface discharge.

Much greater extremes in altitude occur in other outlets elsewhere in Upper Geyser Basin. For example, Solitary Geyser in the eastern part of the basin has a surface altitude about 85 ft above the cone of Old Faithful (Muffler and others, 1982). A major difference between vents in the same area is their degree of openness, or absence of restrictions to flow. Some features may have large near-surface dimensions, but their channels down to a common reservoir cannot be observed directly. Although waters from Solitary and Old Faithful Geysers are nearly identical in chemical type, Solitary is near the eastern high-altitude limit of the Upper Basin system, and so higher temperatures, more gas, or a stronger vapor lift cannot be invoked to account for Solitary's differences. A tentative conclusion is that the large abundant vents and geysers near the floor of Upper Basin have, over time, partially self-sealed their channels, whereas Solitary's system is relatively open (Marler and White, 1975).

FACTORS THAT HELP EXPLAIN THE ABUNDANCE AND MAGNITUDE OF GEYSERS IN YELLOWSTONE NATIONAL PARK

Enough has now been learned about Yellowstone's geysers (Marler, 1973, Marler and White, 1975) to justify some speculations on geysers in general. Many factors help explain why Yellowstone National Park contains such a large proportion (possibly 50 percent or more) of the world's known geysers:

1. Magnitude of its deep reservoirs—their high heat content and proximity to the ground surface are all exceptionally favorable. Convective heat flow above "normal" is estimated at 10^9 cal/s for the 80 to 95 percent of all the convected heat flow of Yellowstone caldera northeast of the Continental Divide; average heat flux within the caldera is about 50 heat-flow units, or about 35 times "normal" (Fournier and others, 1976). Little is yet known about depths or temperatures of reservoirs within and near the caldera. Most geyser basins have temperatures of 180 to 200°C at depths greater than 1,300 ft, but reasons exist for estimating higher temperatures, possibly 300°C or more at great depths (Fournier and Pitt, 1985). Of the geyser basins outside the caldera, only Norris Basin has been drilled. Drill hole Y–12 attained a temperature of 237.5°C at a depth of 1,088 ft, with no indication that temperatures were leveling off. A maximum temperature of at least 275°C is reasonable.

2. An abundant water supply—depth to water is shallow in most basins. Highly permeable, young volcanic rocks absorb much precipitation in an ideal environment for deep circulation of water.

3. Kinds of bedrock—permeable or impermeable—requiring much or little self-sealing to decrease permeability significantly. Thick young silicic rhyolite flows and ash-flow tuffs that cover much of the caldera are ideal for localizing geysers on and near the basin floors. Even a powerful geyser does not eject rhyolite blocks much greater than 3 ft in diameter; such large blocks may be bypassed, eventually choking a potential vent.

4. Basin sedimentary deposits between lobes of large lava flows—these places are favorable, especially if not much time has elapsed since eruption of the lavas to produce extensive alteration and self-sealing of associated sedimentary deposits. Silica solubility is highly important because the SiO_2 content of the water depends so much on the temperature of the reservoir. Extensive precipitation of SiO_2 occurs from most thermal waters as they cool below about 180°C. Zeolites are also important, tending to deposit in cavities and especially in narrow channels.

5. Near-surface interconnections—these are important in determining whether a geyser becomes major or whether many small geysers and hot springs, in total, can discharge enough fluid and heat to approach a steady state without eruption.

6. Stage of evolution of a specific geyser—a major influence, implied in discussing Whistle Geyser, is the presence of two or more different reservoir levels connected to the same channel. The upper reservoir (probably near –65 or –120 ft, as shown in fig. 10) evidently participates in all eruptions, and the reservoir indicated near –180 ft may also be generally involved.

7. Pool versus cone geysers—geysers are commonly classed into two types, pool and cone (also called "columnar"), although a few geysers are difficult to classify by a two-type system. Pool geysers are likely to start from earthquake fractures that cut horizontal, incompletely sealed sinter or sedimentary deposits. Seismic shaking results in new fractures that cut imperfectly cemented sinter or sedimentary deposits insufficiently self-sealed to withstand violently explosive eruptions.

In contrast, cone geysers are likely to start in hard bedrock or well-cemented sinter. Cone geysers normally start on a sloping surface where most discharge drains away; the site is not "flooded" by cooled water returned from the eruption. Some cone geysers start in hard, well-cemented rocks that are not readily disrupted. Erupted water largely drains away or evaporates, thereby building up the geyser's cone.

8. Changes in a geyser's water supply—the supply may be derived from two main sources. (a) Largely subsurface drainage from adjacent lower pressured areas—simple hydrostatic pressure forces water to flow toward the tube through an enlarging cone of depression. Rate of inflow and its average temperature may change over time with the hydraulic gradient. Heat is lost upward mainly by conduction and convection. (b) Deep over-pressured water—it flows upward, decreasing in temperature, energy content, and, possibly, rate as levels in the immediate reservoir decline and the proportion of steam to water changes. The acid geysers of Norris Basin may be related mainly to the first type, with heat and water being supplied by local basin convection (White and others, 1988, p. 27–28).

9. Stage in the evolution of a geyser—Marler and White (1975) suggested that upward-flaring pools in the park are the end result of a gradual evolution of pool geysers. The inactive northern vent of Double Bulger in Norris Basin is an especially convincing example (White and others, 1988, fig. 57). Successive layers of infilling of pool and vent channels by amorphous silica demonstrate this process. Some former pool geysers were once huge: Grand Prismatic Spring (Prismatic Lake) of Midway Basin (Allen and Day, 1935, p. 271) may be the largest; it is nearly circular, about 370 ft in diameter, with a temperature of 63°C in one discharge stream (Allen and Day, 1935, p. 271) and an estimated discharge rate of about 580 gal/min. Dead cones of former cone geysers are sparse; they probably include the mounds near Old Faithful and the still-seeping cones of Monument Basin.

CONCLUSIONS

A geyser cannot be understood from surface measurements alone, confined to the large accessible parts of its tube, where free convection is common. Whistle Geyser was probed to only 9½ ft, but research drilling has demonstrated a far more extensive system that is responsive to atmospheric pressure to a depth of at least 100 ft below its lip, or about 10 times deeper than measured. With still deeper drilling to depths of more than 184 ft, high water overpressures developed, increasing rapidly downward. This rapid change is generally caused by self-sealing (hydrothermal deposition of silica minerals and zeolites in fractures and other channels). Temperatures of upflow near the top of this overpressured zone are about 160°C at about −184 ft—adequate to account for even a major eruption if all the heat, water, and steam lost during the previous eruption are replaced before the geyser again erupts.

The maximum size and depth of an immediate geyser reservoir differ greatly from geyser to geyser and, possibly, also with time and depth during a given eruption. Depth is probably greatest in large geysers of huge discharge with near-vertical tubes that were probably enlarged downward as a result of the decompression of overpressured water as it expanded explosively to water and steam. During initial growth of these tubes, rock fragments are torn from the walls and ejected. The required mechanical energy results from expansion of overpressured steam until the process eventually stops by attaining a steady state.

Downward extension of a reservoir is probably also limited by the size of interconnections with other springs and geysers. Water bleeds off near and just above zones of thorough self-sealing, focusing the mechanical energy at sites of greatly increased rates of boiling.

A geyser essentially attains a state where temperature and the expansive force of available water and steam can no longer enlarge its reservoir, either downward or laterally. It first attains a maximum average rate of discharge, after which self-sealing causes the rate of upflow to decline (unless new fracturing occurs). Without new fracturing, the discharge must eventually decline to a steady-state spring, and the former geyser dies (see White, 1988, figs. 9, 10, 57). Whistle Geyser is evidently close to such a state.

Pool-type geysers normally erupt some water outside their immediate vicinity, but much water drains back to the pool after losing heat by boiling and evaporation (see Marler and White, 1975). Such geysers commonly first recover their water supply by vertical and lateral recharge, and then undergo preliminary overflow of nonboiling water as the system gradually regains its essential heat supply. Deep overpressured water has a higher than average temperature, much higher than that of lateral discharge. Such preliminary discharge is preparing the geyser for subsequent eruption by discharging partly cooled water that is replaced by hotter upflow.

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