Physical Results of Research Drilling in Thermal Areas of Yellowstone National Park, Wyoming

By D. E. WHITE, R. O. FOURNIER, L. J. P. MUFFLER,
and A. H. TRUESDELL

GEOLOGICAL SURVEY PROFESSIONAL PAPER 892

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1975

UNITED STATES DEPARTMENT OF THE INTERIOR

ROGERS C. B. MORTON, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

Library of Congress Cataloging in Publication Data

Physical results of research drilling in thermal areas of Yellowstone National Park, Wyoming.
(Geological Survey Professional Paper 892)
Bibliography: p. 69.
Supt. of Docs. No.: I 19.16:892
1. Geothermal resources–Yellowstone National Park. 2. Boring–Yellowstone National Park. I. White, Donald Edward, 1914- II. Series: United States. Geological Survey. Professional Paper 892.
GB1025.W8P49 553 74-28233

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

Stock Number 024-001-02602

CONTENTS

	Page
Abstract	1
Introduction	1
Scientific objectives	2
Scope of this report	3
History of the program	3
Drilling equipment and procedures	3
Scientific data acquisition	7
Definition of terms	9
Acknowledgments	11
Upper Basin and Upper Firehole River	11
Y–1 (Black Sand Basin) drill hole	11
Y–7 (Biscuit Basin I) drill hole	15
Y–8 (Biscuit Basin II) drill hole	17
Horizontal "self-sealing" and circulation pattern between Y–8 and Y–7 drill holes	22
Carnegie I drill hole, Myriad Group	22
Y–6 (Lone Star) drill hole, Upper Firehole River	25
Lower and Midway Basins	28
Y–2 (Firehole Lake) drill hole	28
Lower and Midway Basins—Continued	
Y–3 (Ojo Caliente) drill hole	34
Y–4 (Nez Perce) drill hole	38
Y–13 (Porcupine Hills) drill hole	41
Correlation of data from Y–4 and Y–13 drill holes	45
Y–5 (Rabbit Creek) drill hole	48
Norris Basin	49
Y–9 (Norris I) drill hole	49
Y–12 (Norris II) drill hole	54
Carnegie II (Norris) drill hole	57
Summary of subsurface relations, Norris Basin, and changes induced by the drill holes	61
Mammoth Hot Springs	63
Y–10 (Mammoth Terrace) drill hole	63
Mud Volcano area	65
Y–11 (Sulphur Cauldron) drill hole	65
Conclusions	68
References cited	69

ILLUSTRATIONS

	Page
FIGURE 1. Map of Yellowstone National Park, showing major geothermal areas and sites of research drill holes	3
2. Photographs of truck-mounted diamond-bit coring equipment used in Yellowstone National Park	3
3. Photograph of valve, return water "tee," and stuffing box, Y–2 drill hole, Firehole Lake	4
4. Photographs showing eruptions from drill rods	6
5. Photograph of Y–8 drill hole after completion	7
6. Graph showing recovery of bottom-hole temperature in Y–1 (Black Sand) drill hole when depth was 1 00 ft	8
7. Photographs of apparatus used to measure temperatures at Y–1 drill hole as drilling progressed	9
8. Graph showing temperatures and other data, Y–1 drill hole, Upper Geyser Basin	14
9. Diagram showing preferred explanation for differences in gage pressure recorded in Y–1 drill hole and its redrilled lower segment, Y–1x	15
10. Graph showing temperatures and other data from Y–7 (Biscuit Basin I) drill hole, Upper Basin	17
11. Graph showing temperatures and other data from Y–8 (Biscuit Basin II) drill hole, Upper Geyser Basin	19
12. Graph showing in-hole temperature and pressure, Y–8 drill hole after completion, with other reference curves	20
13. Section through Y–7 and Y–8 drill holes, showing pressures, temperature contours, and deduced self-sealing by deposition of hydrothermal minerals in originally permeable ground	21
14–24. Graphs showing:	
14. Temperatures and other data from Carnegie I drill hole, Myriad Group, Upper Basin	24
15. Temperatures and other data, Y–6 (Lone Star) drill hole, Upper Firehole River	26
16. In-hole temperatures and pressures of Y–6 drill hole after completion	27
17. Temperatures and other data, Y–2 (Firehole Lake) drill hole, Lower Basin	29
18. In-hole pressures of Y–2 drill hole after completion, compared with other data	33
19. Temperatures and other data, Y–3 (Ojo Caliente) drill hole, Lower Basin	36
20. In-hole temperatures and pressures of Y–3 drill hole after completion	37
21. Temperatures and other data, Y–4 (Nez Perce) drill hole, Lower Basin	39
22. In-hole temperatures and pressures of Y–4 drill hole after completion, compared with other d ata	40
23. Temperatures and other data, Y–13 (Porcupine Hills) drill hole, Lower Basin	43
24. In-hole temperatures and pressures of Y–13 drill hole compared with reference curves	44
25. Section through Y–13 and Y–4 drill holes, Lower Basin, showing initial temperature contours, wellhead water pressures, and some hypothesized relationships	47
26–31. Graphs showing:	
26. Temperatures and other data, Y–5 (Rabbit Creek) drill hole, Midway-Lower Basin	50
27. Temperatures and other data, Y–9 (Norris I) drill hole, Norris Basin	52

Page

FIGURES 26–31. Graphs showing—Continued
28. In-hole pressures of Y–9 drill hole compared with other reference curves 53
29. Temperatures and other data, Y–12 (Norris II) drill hole, Norris Basin 56
30. In-hole temperatures and pressures of Y–12 drill hole after completion, compared with other data 58
31. Temperatures and other data, Carnegie II drill hole, Norris Basin 60
32. Vertical section through Norris Basin drill holes Y–9, Carnegie II, and Y–12, showing bedrock, measured bottom-hole temperatures, and inferred temperature contours 62
33. Graph showing temperatures and other data, Y–10 (Mammoth Terrace) drill hole 64
34. Graph showing temperatures and other data, Y–11 (Sulphur Cauldron) drill hole, Mud Volcano area 67

TABLES

Page

TABLE 1. Casing diameter, bit diameter, and core diameter used in Yellowstone drill holes 4
2. Temperatures, pressures, and other observations from Y–1 (Black Sand) drill hole, Upper Basin, Yellowstone National Park 12
3. Summary of physical data of all research drill holes in Yellowstone National Park 13
4. Temperatures, water levels, and other observations from Y–7 (Biscuit Basin I) drill hole, Upper Basin 16
5. Temperatures, pressures, and other observations from Y–8 (Biscuit Basin II) drill hole, Upper Basin 18
6. Temperatures, pressures, and other observations, Carnegie I drill hole, Myriad Group, Upper Basin (reported by Fenner, 1936 23
7. Temperatures, pressures, and other observations from Y–6 (Lone Star) drill hole of the Upper Firehole River 25
8. Temperatures, pressures, and other observations from Y–2 (Firehole Lake) drill hole, Lower Basin 30
9. Temperatures, pressures, and other observations from Y–3 (Ojo Caliente) drill hole, Lower Basin 35
10. Temperatures, pressures, and other observations from Y–4 (Nez Perce Creek) drill hole, Lower Basin 38
11. Temperatures, pressures, and other observations from Y–13 (Porcupine Hills) drill hole, Lower Basin 42
12. Temperatures, pressures, and other observations from Y–5 (Rabbit Creek) drill hole, Midway-Lower Basin 49
13. Temperatures, pressures, and other observations from Y–9 (Norris I) drill hole, Norris Basin 51
14. Temperatures, pressures, and other observations from Y–12 (Norris II) drill hole, Norris Basin 55
15. Temperatures, pressures, and other data from Carnegie II drill hole, Norris Basin 59
16. Temperatures, pressures, and other observations from Y–10 (Mammoth Terrace) drill hole 63
17. Temperatures, pressures, and other observations from Y–11 (Sulphur Cauldron) drill hole, Mud Volcano Group 66

CONVERSION FACTORS

[English units of measurement are used in this report, except for temperature, because all tables and figures were prepared and all drill cores were marked and cataloged in these units]

Length: 1 inch = 2.54 centimetres
1 foot = 0.3048 metres
1 mile = 1.61 kilometres
Temperature: °C = 5/9 (°F − 32)
°F = 1.8 (°C) + 32
Pressure: 1 lb/in² (psi) = 0.06895 bar
= 0.06805 atm
= 0.07031 kg/cm²

All pressures are absolute, with 11.1 psi (0.78 kg/cm²) added to gage pressures, even though actual ground-level air pressures range from 11.5 psi at the Mammoth (Y–10) hole to 11.0 psi at the Mud Volcano (Y–11) hole.

PHYSICAL RESULTS OF RESEARCH DRILLING IN THERMAL AREAS OF YELLOWSTONE NATIONAL PARK, WYOMING

By D. E. White, R. O. Fournier, L. J. P. Muffler, and A. H. Truesdell

ABSTRACT

The shallow parts of geothermal systems are important for the understanding of total systems, but commercial geothermal drilling has focused almost entirely on target depths of 2,000 ft and more. Previous drilling of the shallow parts of geothermal systems, primarily for research purposes, is known to have been conducted only in Yellowstone in 1929–30 and Steamboat Springs, Nevada in 1950–51. Yellowstone National Park contains a magnificent display of thermal features, unequalled elsewhere in the world, and thus the area is ideal for research drilling of natural hydrothermal systems essentially undisturbed by human activity.

Thirteen research holes were drilled in the principal thermal areas of Yellowstone National Park in 1967–68. Depths of the holes ranged from 215 ft to 1,088 ft, and the total drilled footage was 6,802 ft.

Bottom-hole temperatures were measured as drilling progressed. We conclude that most temperatures measured at the then-existing bottom after 8 hr of drilling and 16 hr for recovery are within 2°C of original ground temperatures prior to drilling. The drilled bottom is least affected by circulation of drill water and its temperature thus recovers the fastest.

Most holes show a near-surface zone of less than 100 ft to more than 250 ft characterized by a large rather linear conductive thermal gradient. Many rocks in this zone were initially highly permeable but lost most of their permeability because of hydrothermal alteration and deposition of silica and silicate minerals. This upper zone is bounded downward by the first aquifer in which significant convective flow occurs.

Other aquifers of convective flow normally occur at greater depths. Temperatures there are generally close to the reference boiling-temperature curve, which is a computed curve that assumes a water-filled column up to the ground surface, with every point just at boiling (thus involving continuous variation in density of water with temperature).

In each hole located in or near centers of upflow, the maximum temperature was measured at maximum depth. Holes drilled on the borders of upflowing systems showed lower gradients and, commonly, temperature reversals. The highest temperature, 237.5°C, was recorded at the bottom of our deepest hole, 1,088 ft, in Norris Basin. Most of our holes were drilled to depths close to 500 ft, with typical maximum temperatures near 200°C.

With increasing depth, every hole showed an increase in static water level, generally rising from the initial water table a few feet below ground to 100 ft or more above ground. The vertical water pressure gradients in all holes except one exceeded 110 percent of hydrostatic and ranged as high as 147 percent of hydrostatic in one hole in the Lower Geyser Basin. These extreme pressure gradients, not generally recognized in other geothermal areas, permit temperatures to exceed the simple boiling-temperature curve at depth, but all temperatures are at or below boiling for water at the existing pressures. In our shallow holes, we could not distinguish between true artesian pressure and thermoartesian pressure resulting from heating of water, with consequent thermal expansion. Thermoartesian pressure clearly is involved, but normal artesian pressure is not excluded.

Two holes in Upper Basin, two in Lower Basin, and three (including one drilled by the Carnegie Institution) in Norris Basin are close enough to each other to justify two-dimensional analysis of temperatures, pressures, and convective flow. In each of the three sets, one hole was in or near a center of upflow, and one was on the border of the same general system.

The very high temperature and pressure gradients account for the rapidly increasing drilling difficulties encountered at increasing depth, and probably also help to explain why major geysers are more abundant in Yellowstone than in other geothermal systems of the world.

In-hole measurement of pressures and temperatures after completion of each hole shows that the aquifer of highest static water level generally becomes dominant over the pressures and temperatures of all other aquifers in the uncased part. If casing is bottomed in permeable rocks, the influence of a deep aquifer can extend up into cased levels of flow of fluids up through the permeable rocks.

Other relationships indicate the complex changes that can occur locally in a geothermal system as a result of drilling, with consequent "short-circuiting" of natural aquifers. These include: (1) as gas accumulates in the hole and the water level is depressed, generally to the first uncased aquifer, wellhead shut-in pressures rise; (2) with time, the temperature of any drilled level may increase or decrease, depending on local hydrologic influences; decreases of as much as 22°C (Y–3) and increases of as much as about 150°C (top of Y–9) have been noted; (3) even with the precautions we took at the time, postdrilling analysis of our data indicates that four of our drill holes affected nearby springs, generally converting them temporarily into geysers.

Our conclusions from Yellowstone indicate that physical relations in many commercially explored geothermal reservoirs are not as uniform as routine postdrilling measurements have indicated.

INTRODUCTION

Although there has been considerable drilling for geothermal energy throughout the world (Koenig, 1970, 1973), the data available from shallow parts of thermal systems are sparse and generally unreliable, particularly in the cases of older or wildcat drilling. Modern development practice involves much data acquisition, testing, and evaluation, but few measurements are made in the shallow parts of geothermal systems. The expense of drilling deep, large-diameter holes dictates that the contractor drill round-the-clock in an effort to make as much footage as possible. Downtime for testing or for allowing the well to come to thermal equilibrium is expensive and is normally avoided until the drill penetrates the target reservoir, commonly at −3,000 to −9,000 ft. In addition, the use of drilling muds delays thermal recovery, distorts the thermal regime, and contaminates the natural fluids. Coring in shallow parts of geothermal systems is particularly rare and even at production depths is sporadic, due to the high cost of pulling rods to replace the normal bit with a coring bit.

Aside from measurements in the natural vents of springs and geysers, the shallow parts of geothermal systems have been investigated in detail at only a few places in the world. Many of the relevant data come from the investigations in Yellowstone National Park in 1929–30 by the Carnegie Institution (Fenner, 1936) and from the investigations of the U.S. Geological Survey at Steamboat Springs, Nevada, in 1950–51 (White, 1968).

The shallow parts of geothermal systems are very important in the overall understanding of geothermal systems, because at these depths temperatures change abruptly, fluid compositions change through rock-water interactions and mineral precipitation, steam and other gases separate from water, two-phase fluid flow occurs, and the geothermal fluids interact with the normal hydrologic regime. In addition, many prospecting techniques, including geochemistry and thermal-gradient surveys, depend on knowing the properties of the shallow part of geothermal systems. Accordingly, our drilling program was designed to focus on the shallow parts of geothermal systems, and to compare the various geological and geochemical situations represented by Yellowstone hydrothermal activity.

Yellowstone National Park is particularly suitable for research drilling in the shallow parts of geothermal systems. The Park contains the world's most extensive display of hot springs, geysers, fumaroles, and mud pots. Yet, owing to the area's preservation, the surface thermal features have not been destroyed by man's activities. Furthermore, there have been no efforts to produce fluids for commercial use, so the thermal features have been spared the destruction that followed geothermal exploration and development at Beowawe, Nevada, and at Broadlands and Wairakei, New Zealand. Yellowstone remains nearly undisturbed and is thus uniquely valuable for the study of hydrothermal phenomena in their natural state.

These factors were clearly recognized by Arthur L. Day and E. T. Allen of the Carnegie Institution of Washington, and the first research drill holes in thermal areas were drilled by the Carnegie Institution in 1929 and 1930 under the direction of Clarence N. Fenner. In addition to the published report (Fenner, 1936) we have Fenner's original field notes, and selected core samples from the two Carnegie Institution holes (one in Upper Geyser Basin, one in Norris Geyser Basin) have been transferred to the U.S. Geological Survey. In this report we attempt to reinterpret the data from the Carnegie drill holes in light of our drilling some 37 years later. The fact that our interpretations do not always agree with Fenner's does not detract from the significance of Fenner's accomplishment.

The National Aeronautics and Space Administration's interest in remote-sensing techniques led it to select Yellowstone as a test area for the correlation of remote-sensing data with surface and subsurface phenomena. Under NASA funding and with the close cooperation of the National Park Service, the Geological Survey conducted extensive geologic investigations in the Park. In addition to the drilling, maps were made of thermal features and deposits, hydrothermally altered rock from the drill holes was studied (Honda and Muffler, 1970; Muffler and Bargar, 1974), and hydrothermal fluids, both from hot springs and from drill holes, were sampled and analyzed. Investigations by other Survey personnel included studies of Pleistocene volcanism (Christiansen and Blank, 1972), surficial deposits (U.S. Geol. Survey, 1972b), Eocene volcanism (Smedes and Prostka, 1972), pre-Tertiary stratigraphy (Ruppel, 1973), and geophysics. A summary geologic map of Yellowstone Park (U.S. Geol. Survey, 1972a) is available, and a general review of the geologic history of the Park has been published (Keefer, 1972).

SCIENTIFIC OBJECTIVES

The drilling program in Yellowstone was designed to provide the following:

1. The best possible estimates of original ground temperatures and temperatures within the holes after drilling was completed.
2. Data on wellhead pressures (or water levels) for calculations of down-hole pressures.
3. Continuous cores to determine the stratigraphic sequence, and subsequent mineralogical and chemical analyses leading to a description of rock-water interactions in hot-spring systems.
4. Continuing access to the drill holes to allow intermittent sampling of fluids, measurement of temperatures and in-hole pressures, and testing of geophysical logging devices.

As the drilling program progressed, the limitations of our wellhead pressure data became clear. The data were neither as reliable nor as accurate as we would have liked, and furthermore, no down-hole pressure measurements were made during the drilling program. Equipment for measuring down-hole pressures was constructed after completion of the drilling (Fournier and Truesdell, 1971) and was used to determine the postdrilling pressure profiles discussed in this paper.

SCOPE OF THIS REPORT

This report emphasizes the measurement and interpretation of temperature and pressure data. The petrology of the drill core is published elsewhere (Honda and Muffler, 1970; Bargar and others, 1973). The chemical analyses and interpretations will appear in a separate paper of this series.

HISTORY OF THE PROGRAM

Sites for the drill holes were selected in 1966 with the cooperation of John M. Good, Chief Naturalist of Yellowstone National Park. A mixture of scientific and practical considerations was weighed in selecting sites. The drill holes were to be distributed to include the major hot-spring areas and principal types of activity (figure 1). We also wished to locate drill holes near major zones of fluid upflow, yet not where they might damage any well-known thermal feature. We could not drill near active hot springs for stability reasons, so we sought places where relatively cool, stable ground was adjacent to a zone of major upflow or, better yet, between closely spaced areas of prominent activity.

The drilling contract was let in early 1967. Drilling began on April 18, 1967, and continued throughout the summer and fall until November 1. Drilling was resumed on May 15, 1968, and was terminated on July 13. Temperature and pressure measurements have been made in succeeding years in holes not plugged or blocked. Y–1 was plugged and abandoned immediately after drilling. Y–2, Y–3, Y–9, and Y–11 were plugged in 1969.

DRILLING EQUIPMENT AND PROCEDURES

Safety was important at all sites. From experience at Steamboat Springs and elsewhere (White, 1968) we thought that most geothermal wells could be kept under control by maintaining cold water in the well, because a column of cold water is considerably heavier than an equivalent column of hot water (White, 1968, fig. 29). We found that at Yellowstone, however, pressures at depth were high enough for static water levels to rise far above the ground surface. Such high pressures, combined with high subsurface temperatures, establish a high potential for eruption of hot fluids. In order to minimize this possibility we sought sites elevated above local hot springs. Such locations gave us a greater head of cold water to counterbalance the high water pressures at depth, and usually provided good unaltered ground in which we could cement our near-surface casing.

Drilling was done with a truck-mounted diamond-bit drilling rig (fig. 2) equipped with wire line for withdrawing cores through the rods without pulling out the whole drill string. This capability allowed nearly continuous coring, greatly increased the efficiency of drilling operations, and facilitated down-hole temperature measurements.

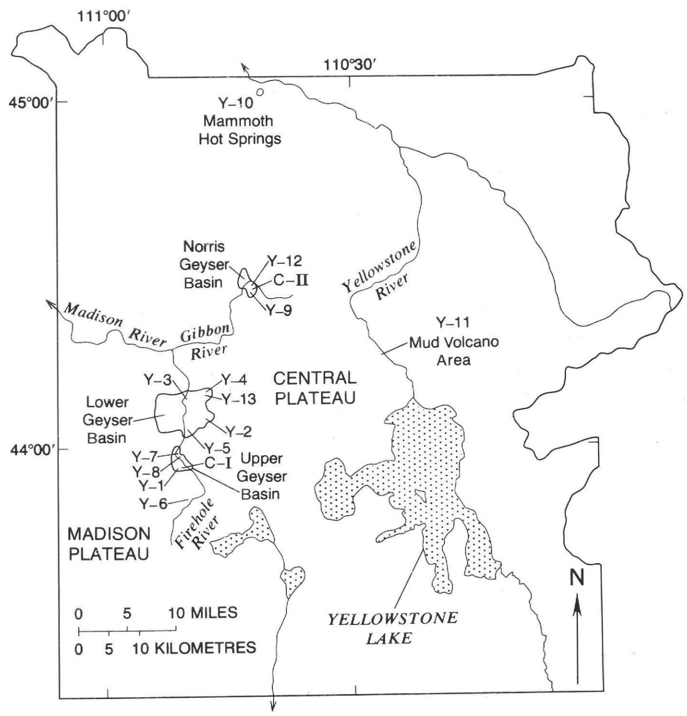

FIGURE 1.—Map of Yellowstone National Park showing major geothermal areas and sites of research drill holes. U.S. Geological Survey holes are numbered Y–1 to Y–13 in order of drilling; holes drilled by the Carnegie Institution of Washington in 1929–30 are designated as C–I and C–II.

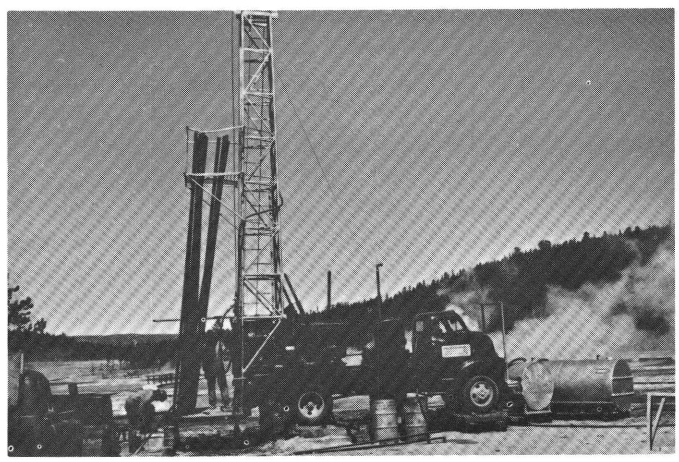

FIGURE 2.—Truck-mounted diamond-bit coring equipment used in Yellowstone National Park. Y–2, Firehole Lake, Lower Geyser Basin.

Water, generally pumped from nearby streams, was used as the circulating fluid. Storage tanks of 1,000-gal capacity at each drill site provided a reserve water supply in the event the pump failed. Drilling mud was not used, in order to avoid contamination of the core, to avoid sealing off pores and fractures, and to allow collection of clean fluid samples. In addition, mud would have significantly delayed thermal recovery after stopping circulation, hampering efforts to obtain temperature data. Furthermore, use of mud would have delayed the drilling operation and increased the expense, both for the mud itself and for a cooling system for the hot (30°C–90°C) return fluid.[1]

The main difference between holes drilled at Yellowstone and those drilled at Steamboat Springs was that at Yellowstone subsurface water pressure in most holes was high enough for static water levels as much as about 220 ft above ground surface. Immediately after circulation stops, water level may drop below ground level, and may rise to ground level as the water expands upon heating. Such a column of water, if everywhere just at boiling for existing pressures, is metastable. If undisturbed the water level remains constant, but if disturbed by boiling or injection of gas, the water level rises, the hole starts to overflow, and a steam-water eruption begins.

In the Yellowstone drilling, wellhead water pressures ranged up to about 90 psig (pounds per square inch gage), far more than needed to cause a drill hole to overflow and burst into eruption. Accordingly, on every hole we attached a 4-inch valve as soon as the surface pipe (5 ½″ O.D.) was set. The valve, with suitable reducers, was transferred to narrower casings as these were emplaced. Mounted on top of the valve (fig. 3) was a "tee" for return water and then a stuffing box, which consisted of two opposed hard-rubber cylinders. The inner end of each cylinder was shaped to fit around the drill rods. The rubber cylinders could be forced against the rods by manually operated cranks, thus controlling leakage around the drill rods.

Rotation of the drill rods abraded the valve seats, causing the valves to leak. Accordingly, an old 4-inch valve was used during drilling and was replaced with a new 3-inch valve after completion of each hole. Replacement was accomplished by inserting a packer through the 4-inch valve and expanding the packer against the casing just below ground surface. The 4-inch valve could then be removed and slipped up over the packer rod, and the 3-inch valve emplaced. In Y–13 the packer, designed for NX casing (table 1), could not be forced through the erupting column into the hole, either because the BX casing was too close to the ground surface or because the pressure was too high for the rubber

[1]Drilling mud was used once at Y–2 in an attempt to prevent eruption from the rods as the upper part of the drill string was pulled from the well after shearing the drill string at depth. The mud (a mixture of bentonite and Baroid) was not heavy enough to prevent a violent eruption that spread the mud over a large area around the drill site. Drillers were scalded by the sticky, hot mud. In this respect, mud is more dangerous than water; one can be splashed with hot or even boiling water with little effect, because of rapid evaporative cooling and water's low viscosity. Mud, however, retains heat and adheres to flesh, causing painful burns.

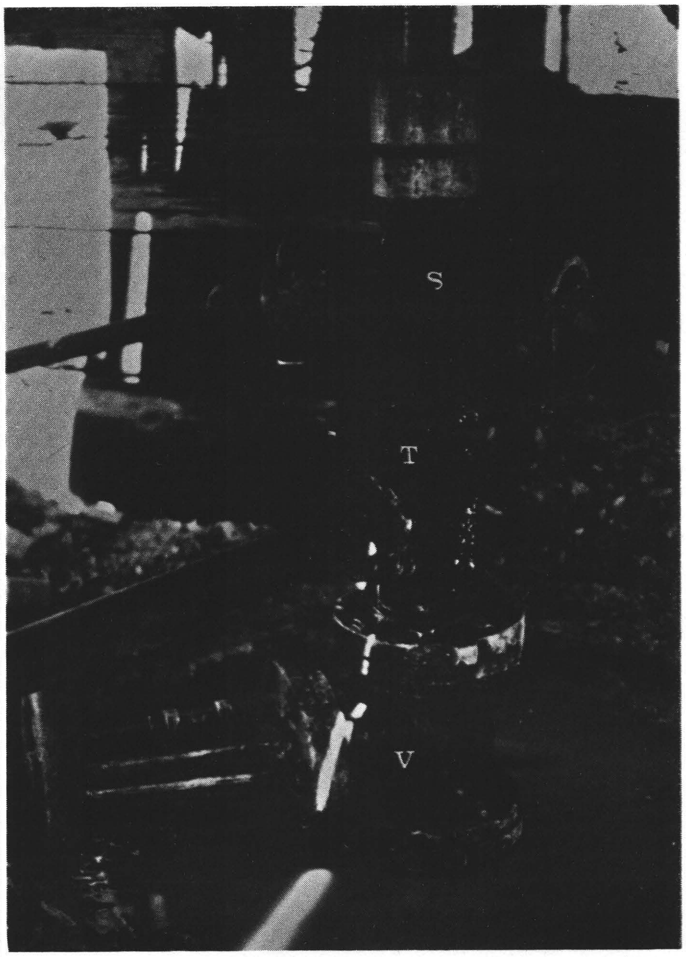

FIGURE 3.—Photograph of valve (V), return water "tee" (T), and stuffing box (S), Y–2, Firehole Lake.

TABLE 1.—*Casing diameter, bit diameter, and core diameter, in inches, used in Yellowstone drillholes*

Size designation	Casing O.D.	Casing I.D.	Bit Set, O.D.	Core diameter Std.	Core diameter Wire line
4×5½	-------	-------	5.495	4	-------
NC	4.500	4.026	3.875	2 3/4	2 11/32
NX	3.500	3.000	2.980	2 1/8	1 7/8
BX	2.875	2.375	2.360	1 5/8	1 7/16
AX	2.250	1.906	1.890	1 3/16	1 1/16

Example—NX bit passes through NX casing and drills a hole that accepts BX casing.

expanding unit. Cement was forced into the top part of the hole, and, after it set, the 4-inch valve was replaced with a 3-inch valve; the cement was then drilled out.

Our drilling would have been seriously affected by an uncontained eruption *out*side of any casing in the hole.[2] An eruption inside the rods or casing can be controlled, although not without excitement and some danger. But

[2]This is essentially what happened at the Norris drill hole (C–II) of the Carnegie Institution in 1930 (Fenner, 1936, p. 286). The situation there was remedied by pumping 5 tons of cement down the casing and out into the formation!

leakage of hot fluids at high pressure outside the casing would have been very difficult to control. To preclude such an accident, we started each hole with a 4″ × 5½″ bit and set and cemented NC casing (table 1), generally to a depth of 20 ft. We then drilled with an NC bit to a nominal depth of 100 ft, where we set and cemented NX casing. Except for the initial string in the open hole, cement was forced at pressures up to 400 psig down the casing and up the annulus. Cement also was pumped through the return valve and down the annulus. Ordinary portland cement was used; it sets very quickly at the temperatures of the geothermal systems. Additional casing (BX) and cementing were required at −415 feet in Y–2, −530 feet in Y–12, and −227 feet in Y–13. AX casing was required at −451 feet in Y–2.

During drilling, cold water was pumped down inside the drill rods and returned, usually heated to as much as 80–85°C, up the annulus between the rods and casing and out a 2½-inch pipe mounted between the valve and the stuffing box (fig. 3). Unless there was a major influx of hot water at depth, the return fluid did not boil and drilling was straightforward.

Pulling core or adding a length of drill rod, however, posed more significant problems. In the absence of high fluid pressures, core was pulled by raising the rods about 10 ft off the bottom, unscrewing the quill from the uppermost drill rod, backing the kelly off of the drill string, and lowering the "picker" down the water-filled drill rods until it latched to the inner core barrel. The picker and inner core barrel were then pulled up through the rods, and an empty core barrel was dropped down the drill string. With high wellhead pressures (or even with just an unstable column of water that boiled near the surface if the core barrel was withdrawn rapidly), water gushed from the open drill string, changing quickly to a steam-water eruption that could forcibly drive out the inner core barrel, picker, and wire line. This was prevented by inserting the wire line through a cap before attaching the picker. The cap is threaded for attachment to the drill pipe and also fixed with a swiveled water inlet so that cold water can be pumped down the rods as the picker and core are pulled up. A 2-foot-long rubber sleeve around the wire line between the picker and the cap prevents the picker from being jarred against the cap and dropping the core. When the picker reaches the top of the drill string, the cap is unscrewed, the picker and core barrel quickly withdrawn, and a new core barrel dropped down the hole.[3] During this time cold water may gush from the pipe. As soon as the second core barrel disappears down the drill string, a new rod is maneuvered over the drill string and screwed into place. Since the new rod is suspended by a blank plug, the whole string can then be lowered into the hole. The blank plug is then unscrewed and, as water discharges from the rods, the kelly is repositioned over the rods, and the quill joined to the rods. Water is then forced into the rods at considerable pressure to insure that the inner core barrel locks in place.[4]

Alternatively, one can add the length of drill rod before pulling the core, and then lower the whole drill string so that the bit rests on the bottom of the hole. In this position, flow of hot water into the bit is restricted, thus reducing the chance of eruption during the critical few seconds when the picker and core are being extracted and the new inner core barrel dropped down the rods.

In several of the hotter holes, the water in the drill rods was heated so rapidly after circulation ceased that an eruption occurred almost immediately after removal of the quill. In the first seven drill holes we merely tried to keep eruptions from occurring, but during the drilling of Y–8 we installed a check valve in the upper part of the inner core barrel. This allowed cooling water to go down but blocked flow of hot water back up the rods, restricting the eruption to the water in the rods. Such eruptions, although initially spectacular, ended quickly when the water in the drill string was exhausted (fig. 4). The picker could then be lowered and the core withdrawn.

Under extreme pressures, our method of withdrawing cores consisted of lowering the picker into an extra 20-ft length of drill rod, attaching the swivel cap and water hose to the upper end of this drill rod, and hoisting the rod to the top of the mast. The quill was then moved off the drill string, the rods allowed to erupt dry, and an open valve attached to the drill string. The 20-foot length of drill rod was then attached to the valve, and the picker was lowered as cold water was pumped down the rods. After capture of the core barrel, the picker was withdrawn into the 20-foot length of drill rod, the valve closed, the rod removed, and the core barrel extracted. The new core barrel could be inserted by resting it on the closed gate valve, attaching a 10-foot length of drill rod to the valve and over the core barrel, attaching the swivel cap to the top of the drill rod, and simultaneously pumping water and opening the gate valve to let the barrel drop. At times, the barrel had to be forced down the hole by water pressure from the pump. Once the barrel was locked, the rods were again allowed to erupt dry, the valve was removed, and the quill attached.

All these techniques became increasingly arduous

[3] The rods should contain water when the new core barrel is dropped. On Y–11 we made the mistake of dropping the core barrel into a drill string full of steam. The core barrel belled out and damaged the bit when it hit, forcing us to pull the whole string.

[4] If the barrel is not securely locked, an eruption of the fluid in the drill string may expel the inner core barrel. At Y–11 for example, the inner barrel (with 5 ft of core) was not locked when the rods erupted; the core barrel shot out of the rods, careened off the mast, and landed in the woods 50 feet away.

FIGURE 4.—Eruptions from drill rods. *A*, Initial discharge from Y–4 drill hole on July 22, 1967, when static water level was about 190 ft above ground level. When the fittings were disconnected, cool drill water was first discharged. *B*, Initial explosive eruption of water-steam mixture from open drill pipe in Y–5 (Rabbit Creek) drill hole, August 20, 1967. The "bursting" effect results from flashing of superheated water erupted to atmospheric pressure at and just above the top of the drill pipe. The eruption phase typically follows a brief interval of quiet overflow such as shown in *A* and passes rapidly into the near-vertical ejection of steam and water, such as shown in *C*. *C*, Eruption of water and steam above the top of the drill tower, Y–9 drill hole, Norris Basin.

and dangerous at wellhead pressures over 50 psig and particularly in highly permeable rocks such as at Y–13. In several holes (Y–9, Y–11, Y–13) we approached a point where any failure of equipment, human error, or even delay in action would have resulted in an eruption controllable only with great difficulty. In each case we terminated drilling while we were still in control.

Upon completing each hole, a 3-inch valve was mounted on the casing, and an inconspicuous concrete box was built around the valve by the National Park Service (fig. 5). The valve was locked in a closed position by a chain and padlock, and a steel lid on the concrete box was also locked. This arrangement allowed periodic access to the holes for temperature and pressure measurements and for fluid sampling, but prevented tampering or vandalism.

Several holes (Y–2, Y–3, Y–9 and Y–11) displayed increasing wellhead corrosion and leakage with time and were plugged with cement in 1969. Y–10 also developed a bad leak from a defective nipple below the valve. In June 1968 we successfully replaced the nipple and valve by the use of a packer.

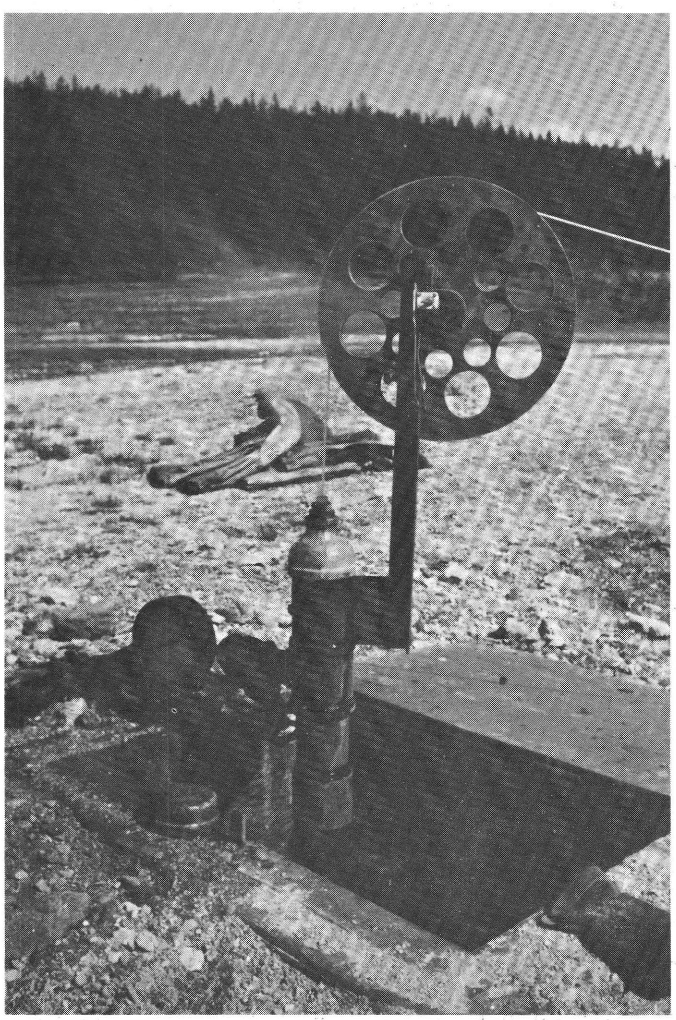

FIGURE 5.—Typical arrangement at wellhead after completion, showing valve mounted at top of casing, concrete box (with steel lid) around the wellhead, and the gear used to introduce temperature-measuring equipment into the completed well. Y–8 drill hole, Upper Basin.

SCIENTIFIC DATA ACQUISITION

The primary data needed for interpreting the dynamics of a geothermal system in its undisturbed state are the original predrilling distributions of temperature and pressure. Knowledge of these parameters in three dimensions would be ideal, but is clearly financially and logistically impossible. In most areas of Yellowstone we had to be satisfied with a single hole in each hot-spring area, and thus with a one-dimensional analysis. In three areas, however, holes were close enough together to allow two-dimensional analysis (Y–7 and Y–8 in Upper Basin; Y–4 and Y–13 in Lower Basin, and Y–9, C–I and Y–12 in Norris Basin).

The mere act of drilling the hole distorts the temperature and pressure regimes to an uncertain extent. Circulation of drilling water cools the rock adjacent to the hole. The uncased length of hole serves as an easy flow path (a "short circuit") between aquifers of differing wellhead pressures, causing distortions of temperature and pressure. The hole may also develop small convection cells, and any separate gas phase accumulates in the upper cased portion of the hole. All of these effects result in a temperature profile unlike that in the original ground.

Although drilling does disturb the previous regime, the initial distortion is minimal at the bottom of the hole. Drill fluid has generally not been in contact with rock at the bottom for more than a few minutes, and thus has lowered the temperature only slightly, and only immediately adjacent to the hole. In regaining temperatures at the bottom, heat is conducted both vertically upward and radially inward, rather than just radially. Accordingly, rock temperatures at the hole bottom are lowered the least and rebound the fastest to a state not much different from the original ground temperature. To obtain a depth profile consisting of a series of bottom-hole temperatures, we drilled no more than 8 hours per day, let the drill hole stand overnight, and measured the bottom-hole temperature immediately before drilling started the next day. The hole was nearly always free of cuttings and slough to the depth reported by the drillers, as shown by the agreement between drilled and probed depths. In zones of rapid penetration, we limited the footage drilled per day to obtain a sufficiently close spacing of data points.

An example of the recovery of bottom-hole temperature is shown in figure 6. Temperatures recover rapidly during the first 6 to 8 hr after circulation ceases. After

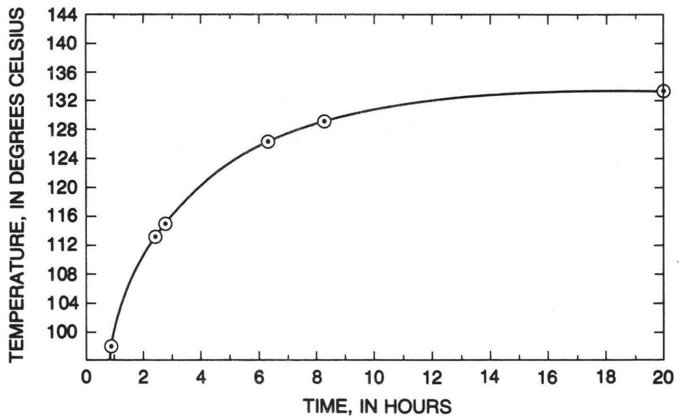

FIGURE 6.—Recovery of bottom-hole temperature after circulation of drilling fluid was stopped in Y–1 (Black Sand) drill hole when depth was −100 ft.

16 hr the temperature has nearly recovered to that of the original ground. Normally we did not attempt to determine a recovery curve such as figure 6, but at nearly every shutdown of a day or more, measurements were made at longer intervals for comparison with our normal overnight shutdown of approximately 16 hr. These comparisons indicated that recovery over 16 hr was generally within 1° or 2°C of the maximum eventually observed. With more time, temperatures either remained constant or fluctuated a degree or so, due probably to convective disturbances in the drill hole.

Bottom-hole temperatures were measured using maximum-recording mercury thermometers rather than thermistors, thermocouples, or other devices. This choice was determined primarily by considerations of reliability. Our experience with electrical temperature-measuring devices was that they worked for only a few trips in and out of a high-temperature hole before failure either of insulation or of potting compound. Furthermore, with the large local temperature contrasts, we did not require great precision, and we needed only a single reliable bottom-hole temperature at each depth, rather than a continuous profile. The maximum-recording thermometers proved to be an effective compromise between accuracy and reliability.

Individual thermometers selected for use must have a tight restriction between bulb and temperature scale; a loose restriction increases the probability of mercury being jarred down during withdrawal of the thermometer. At most depths two measurements were made, with different thermometers. In the tables for individual holes, the thermometer number is shown, permitting comparison of differences between thermometers, and also reproducibility using the same thermometer at different times. In the field, the thermometer was cooled to about 20°C before reading; the thermometers must not be read while still hot.

Thermometers were standardized in the laboratory, and those with large positive or negative corrections were rejected. Pressure corrections were also obtained experimentally but were found to be small for the type most commonly used. Significant pressure corrections were applied, however, to the thermometers used at temperatures much above 200°C, as discussed for Y–12 drill hole.

Obviously, a simple maximum thermometer provides accurate bottom-hole temperatures only where the temperature at the bottom is hotter than at all other points in the hole. This was the case in most of our Yellowstone holes. But in some (for example, Y–5, Y–8, and Y–10), temperatures appeared to level off with depth. To determine accurate bottom-hole temperatures in these holes, the thermometer was placed in a capped metal pipe filled with dry asbestos. The thermometer was lowered to the bottom as quickly as possible (usually less than a minute), left at the bottom for at least 30 minutes, and then raised quickly. Measurements made with various times over 15 minutes gave consistent results. The thermal lag in the iron case plus the insulating properties of the asbestos allowed the thermometer to measure the bottom-hole temperature, rather than the temperature at some higher level.

The means by which the maximum thermometer was lowered into the well is illustrated in figure 7. Normally the pressure chamber (a short length of pipe) was mounted on the drill rods, but with suitable fittings it could equally well be mounted on the main valve or the stuffing box (if the rods were out of the hole for any reason). Advantages of taking the measurements through the drill rods were fewer round trips for the drill string and eliminating the chance of jarring the thermometer on a rock lip in the hole wall or on the bottom of the casing.[5] Upon finishing a day's drilling, the drillers would suspend the rods 10 or 20 ft off the hole bottom, tighten the stuffing box to prevent much leakage, and attach a valve to the top length of rod.

Temperature profiles measured after a hole was completed were usually obtained with thermistors, which were generally satisfactory at low temperatures, but they commonly failed after short intervals near or above 200°C. We are now (1973) hopeful that thermistor cable and insulation problems have been solved for temperatures somewhat above 200°C. Silicone grease forced into the thermistor cage with a grease gun has proved to be much more reliable than the solid potting compound formerly used.

When the thermistor gear was inoperative, temperature profiles were made with successive runs with a maximum thermometer—a tedious exercise.

[5]Although the thermometer could be jarred when being raised through the bit, normally we knew about how far the bit was above the bottom of the hole, and thus could raise the thermometer very slowly through the bit.

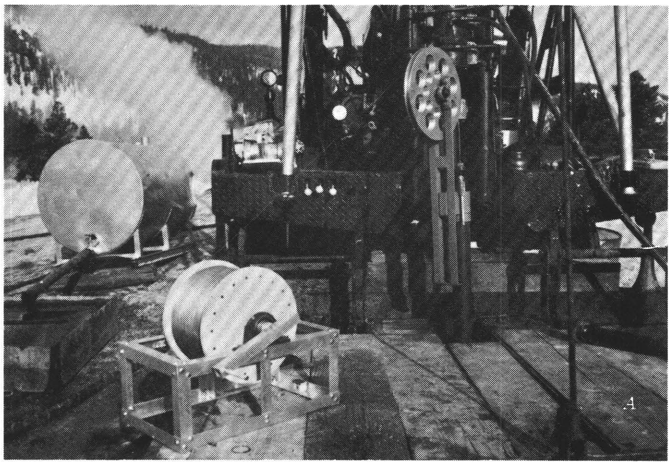
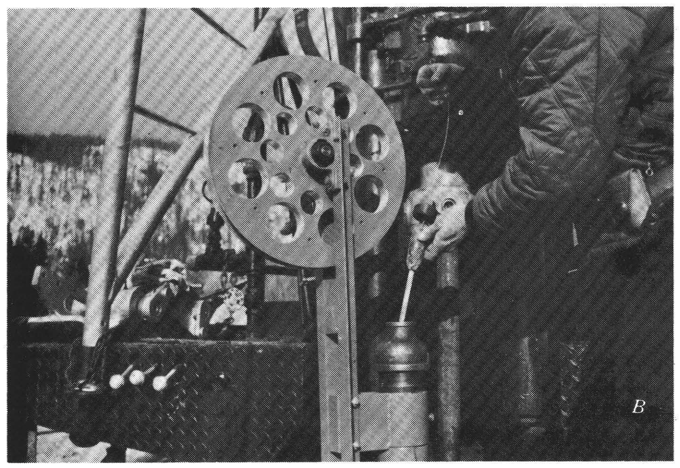

FIGURE 7.—Apparatus used to measure temperatures at Y–1 drill hole as drilling progressed. *A*, Stainless steel wire on a reel (lower left, on drilling platform); wire extends over an aluminum sheave, through a threaded plug, and is attached to lead weight. A maximum-reading mercury thermometer screws into the bottom of the lead weight, thus permitting emplacement of thermometer as close as possible to drilled bottom. The four-inch pipe upon which the sheave is mounted constitutes a pressure chamber, which extends below the drilling platform. The pipe is fastened either to the main valve (fig. 3) or to a valve on the uppermost of the drill rods in the hole. *B*, Detail of the sheave, lead weight, and thermometer. The sheave rotates a counter (opposite side, not shown). The threaded cap through which the stainless steel wire runs is pierced here by a simple hole. In later versions, as in fig. 5, the cap was modified by the addition of a Teflon insert around the wire. The insert could be screwed further into the cap, compressing packing material against the wire, thus minimizing or eliminating leakage when the valve below the pressure chamber was opened for in-hole measurements.

Fluid pressures of the natural environment are more difficult to measure than temperatures, and in retrospect, we are aware that our Yellowstone procedures were not ideal. Pressures were measured only at the wellhead before completion of each hole. Wellhead pressure is mainly responsive to the aquifer of highest head in the hole, provided that permeability in this aquifer is also high; this aquifer is normally not specified by the data and need not be near the bottom of the hole. Wellhead pressure also reflects the density of the fluid in the hole, which in turn is a function of temperature distribution and the amount of entrained vapor. If a gas cap is present within the casing, the measured pressure will be too high depending on the height of the gas cap. In most cases the gas cap bled off as a thermometer or other instrument was lowered into a drill hole, with a proportional drop in measured pressure to a steady level when water rather than gas began to leak from around the wire that suspended the instrument.

Pressure profiles were made after a hole was completed using equipment devised by Fournier and Truesdell (1971). A long flexible stainless-steel tube is inserted into the hole and maintained full of nitrogen from a gas cylinder. At any given depth the pressure outside the tube is balanced by the pressure of inert gas in the tube. Pressure is accurately measured with a pressure gage mounted between the tube and the gas cylinder.

Recovery of cores was an important objective of the drilling operation. After retrieval of the core barrel from the drill string, the core was carefully extracted, the pieces arranged in correct orientation and sequence in a core tray, and each piece immediately marked with an arrow pointing in the original "up" direction. The core was then marked and labeled at each foot before being transferred to cardboard core boxes. The core was described and logged at the drill site. A representative sample of about 20 percent of the core was selected for detailed laboratory study in Menlo Park, Calif. The remainder was stored in government facilities.

Fluid sampling was conducted several times for each accessible well. Wellhead samples were collected immediately upon well completion, even though they were generally much contaminated by drill water. At intervals of months or years thereafter, additional samples were collected, both at the wellhead and at depth, using a down-hole sampler designed by Fournier and Morgenstern (1971). This sampler allows the fluid at depth to be sampled in situ and raised to the surface without loss by boiling or exsolution of gas.

DEFINITION OF TERMS

Fluid pressure.—Total fluid pressure observed at any specified point of measurement, most commonly at the wellhead; does not distinguish between liquid and vapor. Either psia (pounds per square inch absolute) or psig (pounds per square inch gage) is specified in this report.

Water table.—The free-standing level of water in porous ground that communicates directly to the atmosphere; in fine-grained or dense fractured material, the level that water attains in an open hole or in a wide fracture. Thus, effects of surface tension and the capillary fringe are minimized. All depths below ground surface are shown as negative, thus permitting water levels above ground (and positive pressures) to be shown as positive values.

Static water level.—The level that water attains in an open hole under steady-state conditions with no change in subsurface temperature or proportion of vapor to liquid; in actual practice, a "static water level" may involve competing effects from two or more aquifers, and probably no part of the system being measured is strictly static. With increasing depth in a geothermal system, the static water level generally rises up to and then above the ground surface. High positive levels are generally not measured directly but are computed from positive wellhead water pressures; for convenience in this report, a single factor of 1 psi = 2.4 ft of water is used, but where greater precision is required, the factor depends on the vertical distribution of temperatures and densities of water and vapor in the part of the system being measured.

Wellhead fluid pressure.—Observed gage pressure (psig) at the wellhead. In practice, generally measured 1 to 5 ft above ground, with difference from ground-level pressures neglected in this report. Does not discriminate between liquid and vapor pressure.

Wellhead water pressure.—Observed gage pressure (psig) at the wellhead with the hole filled with liquid water; the latter qualification generally can not be confirmed but is assumed valid if water without vapor bubbles leaks from valves or other fittings (exsolution of vapor bubbles from liquid after leakage does not invalidate the assumption).

Gas-accumulation effects.—The vapor pressures of all gases, including H_2O, are commonly high enough for vapor to separate from liquid at the top of a capped hole, depressing the water level until a steady state is attained; as the water level is depressed below gage level, the wellhead pressure increases, by the rough conversion factor 1 psi = 2.4 ft of water.

Reference boiling-temperature curve.—The variation of temperature with depth in many vigorous, high-temperature geothermal systems can be approximated by the reference boiling-temperature curve for pure water. This curve, calculated from laboratory experimental data for pure water (Keenan and others, 1969), is based on the following relationships: (1) the boiling temperature of water increases with pressure, and (2) the increase in pressure with depth is due to the weight of the overlying water.

Calculations such as those of White (1968, p. C56), Haas (1971), and Manuel Nathenson (written commun., 1973) assume a column of water, the top of which is at ground level (for Yellowstone, about 7,500 ft, equivalent to a boiling temperature of 92.4°C, and temperatures everywhere just at boiling, considering the weight of overlying water. The reference boiling-temperature curve takes into account the differences in density of water with increasing temperature. Points that plot to the left of the curve are characterized by water. Points that plot to the right of the curve (where the assumptions are valid) are characterized by steam. Points that plot on the curve are characterized by the coexistence of steam and water, but with so little dispersed vapor that density is that of the liquid. Other reference curves, not considered here, have been calculated for different altitudes, salinities, cold columns to point of boiling, and lithostatic pressures (White, 1968; Haas, 1971).

Throughout this paper drill-hole measurements are compared with this boiling-temperature curve. In actual fact, no single curve is appropriate for all situations because the temperature of formation of a vapor phase at a given depth depends on (a) the salt content of the fluid (increased salinity raises temperature of boiling, but this effect is negligible for Yellowstone waters), (b) the dissolved gas content (increased gas content lowers temperature of vapor formation), (c) the proportion of dispersed vapor in the column, (d) the surface altitude, (e) the depth of the water table, and (f) the artesian or thermoartesian pressure (to be defined). With a water table below ground surface, the boiling-temperature curve should be lowered an equivalent distance. A static water level above ground, on the other hand, requires that reference curve be raised by an equivalent distance.

Obviously, no single reference curve can apply to all geothermal wells in the same area, or even to a single well at different depths because aquifers differ in gas content, static water levels, and salinity. Accordingly, our standard reference, the boiling-temperature curve, assumes pure water, everywhere just at boiling at the prevailing pressures, and with a free surface at ground level. This curve is useful for reference purposes and does not specify whether vapor is present at the depth of each measured temperature. Discrepancies are particularly important with respect to gas content, static water levels above ground, and actual temperatures and densities of overlying water that differ from those assumed for the reference curve.

Reference boiling-pressure curve.—The pressure curve equivalent to the boiling-temperature curve. Changes in boiling pressure with depth are nearly linear.

Equivalent depth.—The measured depth corrected for the static water level. Use of equivalent depth rather than measured depth allows all measured temperatures to be compared to a single reference boiling-temperature curve. For positive static water levels, equivalent depth is greater than measured depth; for negative static water levels, equivalent depth is less than measured depth.

Water overpressure.—A qualitative term referring to water pressures in excess of the reference boiling-pressure curve; also used quantitatively with in-hole pressure measurements at specific depths.

Eruption.—Many drill holes discharge water and steam just like an erupting geyser (White, 1968), especially if static water levels are above ground surface. Opening a valve or disconnecting a drill tool lowers pressure at the wellhead and throughout the hole, causing water to flow from the hole. The temperature of discharge may be low at first, but it then rises, eventually exceeding the boiling point at existing atmospheric pressure. Part of the water "flashes" into steam as pressure decreases in the hole. The violence of an eruption depends on initial temperature, wellhead water pressure, and permeability of rocks penetrated by the drill hole.

Thermoartesian pressure.—Effects in a hydrothermal system similar to artesian pressure in nonthermal systems, and caused by thermal expansion of water and consequent decrease in density with increasing temperature. The term "thermo-artesian" pressure was first used by Studt (1958, p. 707); such pressure may be superposed on artesian pressure. In Yellowstone both kinds of artesian pressure are probably present.

Self-sealing.—Outflow channels of hydrothermal systems of high temperature tend to decrease in permeability due to deposition of minerals in open spaces. Deposition results from decreases in temperature and pressure upward, and reactions of fluids and wallrock. Silica minerals (quartz, chalcedony, cristobalite, and opal), zeolites, and calcite are especially common deposits in outflow channels (White and others, 1956; Honda and Muffler, 1970).

Water pressure gradient.—(1) Vertical pressure gradient, as measured by changes in static water level with depth in a drill hole. In Yellowstone, static water levels normally increase with depth; that is, the water pressure gradient is positive upward and can be expressed as the fraction by which the hydrostatic gradient is exceeded. (2) Horizontal pressure gradient is measured by comparing static water levels in two or more holes when drilled bottoms are at approximately the same altitude. The difference in static water levels divided by the distance between the holes provides the horizontal gradient.

ACKNOWLEDGMENTS

Our hydrothermal studies in Yellowstone could not have been conducted without the strong support of the National Park Service. We are indebted to former Superintendent J. S. McLaughlin and Superintendent J. K. Anderson; to Dale Nuss and Lynn Williamson, former and present West District Rangers; and to J. M. Good and W. W. Dunmire, Chief Naturalists during and soon after completion of our drilling program. John Douglas and John Stockert, former and present West District Naturalists, and Dr. George Marler, retired geyser specialist, have all provided invaluable support for these nontraditional and at times hazardous research activities.

The drilling contractor throughout the program was Sprague and Henwood, Inc. We wish here to express our appreciation to Sprague and Henwood and their personnel for unstinting cooperation in this research effort. Many aspects of the Yellowstone drilling were new to us and to the contractor. The success of the drilling experiment was due in large measure to the contractor's cooperation and the skill, diligence, and willingness of the drilling personnel to adapt to new situations and to devise new methods.

We thank our many colleagues of the U.S. Geological Survey for their cooperation, interest, and advice, specifically Terry E. C Keith, Keith Bargar, Mike Thompson, Reba Fournier, and James Mattinson. R. L. Christiansen, Frank Olmsted, Manuel Nathenson, and W. H. Diment have been especially helpful in providing data and critical reviews of this report. Nathenson has checked many of our calculations and has provided temperature-profile data from Y–7 and Y–13, using thermistor and thermocouple gear that he assembled.

UPPER BASIN AND UPPER FIREHOLE RIVER

Y–1 (BLACK SAND BASIN) drill hole

SITE SELECTION

Y–1 was our first research drilling into Yellowstone hot-spring systems. The site selected was in Black Sand Basin, a subdivision of Upper Geyser Basin 1.2 mi west of Old Faithful Geyser; the site is also about 0.9 mi west-northwest of Carnegie I drill hole and 62 ft lower in altitude. It was chosen in part because of accessibility via a snowplowed secondary road, and in part because we anticipated relatively favorable conditions for introducing our contractor and crew to the problems of drilling in hot-spring areas. The specific site is not presently recognizable from surface evidence; it is 47 ft S. 75° E. of Whistle Geyser, and 5.5 ft below the crest of Whistle's cone.

PHYSICAL MEASUREMENTS

Data from Y–1 are summarized in table 2, and summary data on altitudes, depths, maximum temperatures, pressures, and other data from this hole and all other Yellowstone drill holes are shown in table 3. Temperatures considered to be the most significant are

TABLE 2.—*Temperatures, pressures, and other observations from Y–1 (Black Sand) drill hole, Upper Basin, Yellowstone National Park*

Date and time 1967		Observation depth, ft[1]		Temp, °C[1]		Thermometer No.	Static water level, ft[1 2]	Wellhead pressure, psig[1]	Comments
4/18	1015	6.2		(17)			(−4.8)		5 min shutdown.
	1325	18.5					**−4.9**		1 hr shutdown, then drilled at −21 ft.
	1540	20.5		(37.5)					1 hr after 4-in. casing set and cemented to −21 ft.
	1650	19.8		(76.2)					2 hr after; temperatures may be too high from setting of cement?
	1920	15.5		(65.0)					5 hr after.
4/19	0730	**12.8**		**48.6**					17 hr after (cement in hole; probably best of shallow temperatures).
	1030	22.5					−2.0		~10 min shutdown; good water level?
	1130	30.5					−1.8		~10 min shutdown; good water level?
	1220	35		(83)					½ hr after circulation.
	1410	60					(−3.1)		
	1645	79.7		(103)			(−2.7)		1 hr after drilling to −80 ft.
4/20	0735	**79.6**		**125.9**		15	**−1.4**		Drilled to −100 ft at 1125.
	1930	99.3		(129.1)		15	(−1.7)		8 hr after circulation.
4/21	0720	99.3		133.6	**134.1**	15	**−0.7**		100 ft of 3-in. casing set and cemented 1030.
				134.6		14			
	1445	43.4		(84)					In cemented hole.
4/22	0800	**43½**		**97.0**					In cemented hole. Drilled out cement, then to −185 ft. at 1540. Lost circulation drill water −178 to −182 ft; with no discharge or wellhead pressure evident.
4/23	0921	**183.4**		157.6	**158.1**	4	(+15½)	6½	17½ hr after circulation.
		183.5		158.6		7		7½	
	1835	**183.5**		159.1	**159.0**	4	(+17½)	7¼	27 hr after circulation.
				158.9		7		7½	
4/24	0726	182.8		158.6	**159.2**	4	17	**7**	38 hr after circulation. Then drilled to −215 ft at 1315; first eruption from hole when core barrel removed (see text).
		182.9		159.2		7			
				159.3		4		7½	
				159.7		7			
4/25	0727	**214.6**		**169.6**		4	(+74)	**31**	31 psig wellhead water pressure. Thermometer No. 7 lost in hole; 14½ hr after circulation.
4/26	0738	**214.6**		170.6	**170.7**	4	(+71)	**29½**	38 hr after circulation. In effort to control water flow, hole filled with cement but bottom probably not sealed.
				170.7		8		30½	
4/27								24	After pumping cold water in hole for 40 min. Redrilled hole diverged from cement at about −115 ft. Drilled on to −130 ft with positive pressures and discharge at depths below about −110 ft, contrasting with first drilling 4/22.
4/28	0716	128.5	128.4	146.7	**146.8**	4		8½	Wellhead pressure. Then drilled to −180 ft, cemented in new attempt to control flow.
	0731	128.3		146.9		8		8	
	1333	169.0		(96.4)		14			38 min after circulation.
	1348	168.75		(103.2)		14		6½	53 min after circulation.
	1455	~156		(123.9)		14			2 hr after circulation.
4/29	0725	**152.8**		**155.0**		4			On cemented bottom, no pressure obtained. Then drilled to −194 ft: still discharging so cement not effective.
4/30	0937	190.9	**190.7**	163.7	**163.7**	4	(+30)	13	Pressure above 4/23–24 at −183 ft even though very permeable from −183 to −191 ft.
	0951	190.6		163.6		4		**12.5**	
5/1	0734	**190.7**		163.3	**163.4**	4	(+33½)	17	Slight temperature decrease from 4/30? 40 hr after circulation. Then drilled to −211 ft at 1130.
	0747	189.7		163.6		8		**14**	
	1130								Erupted trying to get back into hole; more gas than previously
	1415								Decided to terminate drilling.
	1545							50	Pressure much above 4/25–26. Why? (see text).
	1600							60	Pressure still rising steadily. Decided to cement hole.

[1]Data in boldface considered most reliable; data in parentheses, least reliable.
[2]Relative to ground surface; positive levels calculated from wellhead pressures considered to be water pressures least affected by vapor.

plotted versus depth in figure 8; most but not all of these are probably close to original ground temperature.

The measured bottom-hole temperatures (fig. 8, curve B) intersect the reference boiling-temperature curve (A) at −128 ft and exceed the curve at all greater depths. The rather regular increase in temperature with depth is interrupted at −183 ft, where the temperature is about 4°C lower than expected. From −178 to −182 ft no drill water returned to the surface, and the core recovered from this zone is highly permeable sandstone and vuggy conglomerate. The break in temperature gradient may be due to intersection of a local channel of relatively cool water, but is more likely to be explained by local convective circulation within the permeable zone.

The water table was first identified 4.8 ft below ground. As the hole was deepened the static water level in the hole changed in response to changing subsurface pressure conditions, rising to ground level when the hole was about 100 ft deep. With continued deepening, positive wellhead fluid pressures were measured, with pressure rising to 6½ psig at −183 ft and 31 psig at −215 ft; corresponding static water levels are +15½ ft and +74 ft. These pressures are interpreted to be wellhead water pressures, that is, we conclude that either a separate vapor phase was not present in the hole, or vapor had minimal effects.

Curve C of figure 8 shows equivalent depths corrected for differences in static water levels, all adjusted to ground level by amounts shown in column 6 of table 2. Temperatures at equivalent depths of curve C nowhere exceed the reference boiling-point curve (A) and are generally 1° to 5°C below it. This departure is probably related to the effect of dissolved gases in lowering the temperature of vapor formation; a partial pressure of other gases of 5 to 10 psi can explain these differences. The effects of gases are considered in more detail in holes for which more complete data were obtained.

ERUPTION PROBLEMS

Previous drilling experience at Steamboat Springs, Nevada, where wellhead fluid pressures were generally low, had suggested that eruption tendencies of the Yellowstone test holes could be controlled by cold drilling water, a stuffing box around the drill rods, and a valve on the casing. We had not anticipated that wellhead

TABLE 3.—*Summary of physical data of all research drill holes in Yellowstone National Park*

	Total depth, ft	Altitude of surface, ft	Depth to "bedrock," ft[1]	Altitude of "bedrock," ft[1]	Casing depths in ft below ground				Maximum measured temp., °C and depth, ft	Depth of water table below ground, ft	Altitude of water table	Depth of hole in ft., when water level first to surface	Rise in static water level, ft	Maximum pressures			
					4-in	3-in	BX	AX						Near-bottom fluid pressure, psia	Wellhead water pressure, psig	Wellhead fluid pressure, psig	Vertical pressure gradient[2]
Upper Basin																	
Y-1	215	7,294	211½	7,082	21	100			170.7 @−215	4.9	7,289	~100	79	(3)	~30?	>60	0.37
Y-7	242	7,266	173	7,093	21	102			143.1 @−235	5.0	7,261	242	~3	(3)	[4]−1.3	0	.01
Y-8	503	7,272	181	7,091	20	93			169.8 @−342	3.1	7,269	~25	~95	231	~35	86	.19
Carnegie I	406	7,356	220	7,136			[5]44		180 @−406	[2]~1	~7,355	(3)	?	(3)		57	?
Lower Midway Basin																	
Y-2	516	7,372	104	7,268	29	128	408	'450	203 @−516	3.5	7,369	~83	~103	[6]233	~42	214	.20
Y-3	514	~7,195	138½	~7,057	32	90	200		196.0 @−494	~8?	~7,187	~75?	~60	217(?)	~20?	72	.12
Y-4	691	~7,205	0.4	~7,205	21	120			195.8 @−689	17.8	~7,187	~80	~207	366	79	96	.30
Y-5	538	~7,228	32	~7,196	32	102			170 @−248	8.1	~7,220	~65	100	260 @−528′	38	84	.19
Y-13	465	~7,220	61	~7,159	21	72	227		203.4 @−465	3.5	~7,216	62	~219	226 @−460′	~90?	180	.47
Upper Firehole																	
Y-6	500	~7,640	69½	~7,570	50	118			180.8 @−499	3.2	~7,637	~170	53	228	21?	76	.11
Mud Volcano																	
Y-11	347	7,709	64	7,645	20	90			191.4 @−347	7.5	7,702	~190?	?	~188?	?	170	?
Norris Basin																	
Y-9	813	7,584	4	7,580	21	100			195.7 @−813	28.8	7,555	~230	~150?	357	~50	140	.18
Y-12	1,088	7,538	0	7,538	21	110	530		237.5 @−1,088	17.9	7,520	~505	~138	425 @−1,079′	~50?	50	.13
Carnegie II	265	7,519	0	7,519		?	60?		205 @−246½	~15?	~7,504	~70?	?	(3)	(3)	297½	?
Mammoth																	
Y-10	370	6,742	253½	6,488	22	86			~73 > 50 ft to bottom	11.8	6,730	[1]~70	~110	125 psia @−192′	~39	78	.30

[1]"Bedrock" is the uppermost lava or ash flow of each hole.
[2]Rise in static water level/total depth; difference between ground and water level ignored.
[3]Not measured.
[4]Psig equivalent of depth of water level below surface.
[5]Depths and diameters of casing not specified.
[6]233 psia at −488 ft; point B of figure 18 suggests bottom-hole pressure of at least 254 psia at −516 ft.

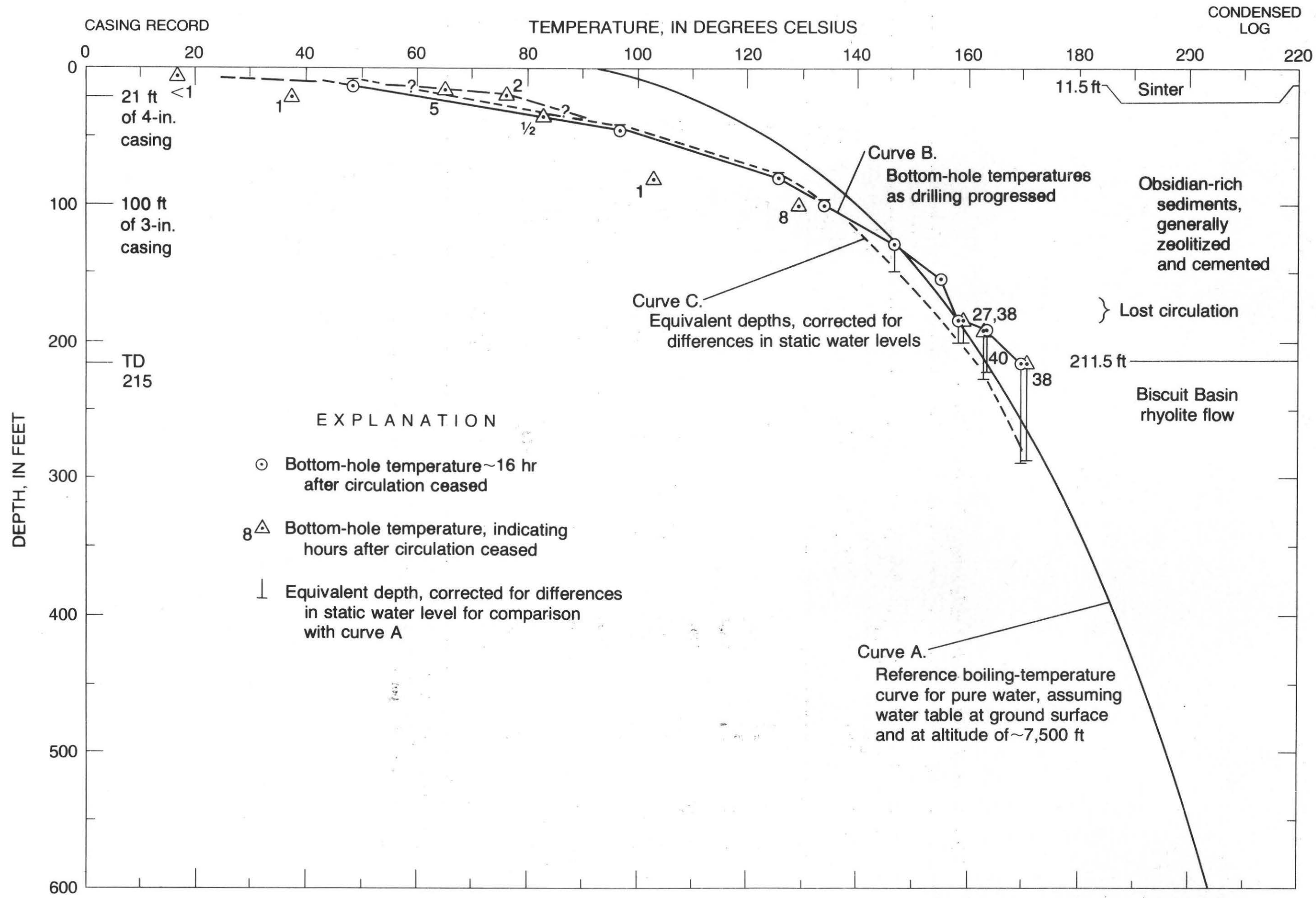

FIGURE 8.—Temperatures and other data, Y–1 (Black Sand) drill hole, Upper Geyser Basin.

water pressures at Yellowstone would be so much higher than at Steamboat Springs. Eruption tendencies of Y–1 first became evident near −180 ft but were easily controlled to −209 ft where the core barrel was retrieved from within the drill rods without difficulty. But when the core barrel was withdrawn from −215 ft, cool drill water gushed from the rods in response to the high wellhead water pressures. The drillers did not have the time or sufficient experience with potentially erupting wells to maneuver the drill chuck back over and into the rods in order to control the hole. Within a few seconds the top cool water was followed by a mixture of boiling water and steam, and the well surged into violent eruption—a shattering experience for all of us! The eruption had the "bursting" characteristics of many geysers of high temperature and abundant water supply (White, 1967, p. 661). Boiling water and steam covered the drilling platform and concealed the control levers used for maneuvering the drill chuck.

The eruption continued unchecked, with some decrease in bursting but little decrease in discharge. Clearly, the permeable rock in the uncased hole below −100 ft could deliver ample thermal water to continue the eruption indefinitely. After about 30 minutes, however, visibility improved enough for the driller to maneuver the drill chuck into the erupting column and down into the drill rods. The chuck was then screwed to the rods, cold water was pumped into the hole, and the eruption was terminated.

Three subsequent eruptions occurred during withdrawal of the drill rods from the hole, in spite of intermittent pumping of cold water. A maximum wellhead water pressure of 31 psig was measured on April 25; this is equivalent to a static water level about 74 ft above ground surface. This was our introduction to the high wellhead fluid pressures that were later found in all but 1 of the 13 Yellowstone drill holes.

In order to increase the density of water in the hole and thereby decrease the wellhead pressure, on April 26 cold water was pumped down the hole for 40 minutes. By this procedure the wellhead pressure was decreased from its previous ~30 psig, but only to 24 psig. High wellhead pressures were clearly to be a continuing problem. We then tried to lower formation permeability by pumping 10 sacks of cement into the hole, using a maximum pumping pressure of 550 psig. We had expected to redrill the cement in the old hole, but found that it was harder than the adjacent porous hydrothermally altered rock (Honda and Muffler, 1970); deflection started to occur near −105 ft, and was in new ground with no cement in core below −115 ft. The new hole (called Y−1x for comparison) exhibited high pressure by discharging water when core was retrieved from −115 ft and the rate of discharge increased irregularly at successively greater depths. It was particularly high from −170 to −180 ft, so cement was again pumped into the hole in an effort to plug the most permeable rock. Drilling continued without new problems until −211 ft, when another eruption took place through the rods. Although about as violent as the eruption of April 24, this new eruption was quickly controlled by moving the drill chuck over and down onto the rods.

After withdrawing the rods, we reluctantly concluded that cement had not reduced permeability enough for drilling to continue safely. We decided to move the rig to another site, planning to return to Y−1 after we had developed more skill and better equipment for combating the high pressures.

The drillers were dismantling the rig for moving to a new site when a pressure gage was put on the hole. To our surprise, wellhead fluid pressure was already 50 psig or nearly 20 psi above the previously observed maximum. During the next 15 minutes pressure rose steadily to 60 psig with no signs of stabilizing. This was yet another problem not anticipated from previous experience. The drill crew was about to quit for the day; should we let the hole rest overnight, with the possibility of a continuing rise in pressure, perhaps exceeding the 125 psi rating of the valve? We decided to fill the hole with cement.

During later drilling with improved equipment and more experience, we found that somewhat higher pressures could be controlled safely, and we then regretted our decision to cement Y−1. This not only prevented deepening the hole and collecting fluids from depth, but also prevented observations aimed at understanding the high pressures in Y−1x.

The terminating eruption at −211 ft in Y−1x differed from the terminating eruption at −215 ft in Y−1 in that, even with cold water just pumped into the hole, Y−1x surged almost instantly into eruption. The explosive discharge of Y−1x suggested that so much gas was entrained in the water in the drill rods that the average density and physical behavior were very different from that of Y−1 at the same depth.

Observations on subsequent Yellowstone drill holes support our conclusion that the main difference in behavior between Y−1 and Y−1x was due to the greater content of gases in the fluids of Y−1x. The high wellhead pressures measured just before Y−1x was cemented were almost certainly caused by accumulation of gases beneath the valve, with a resultant depression of the water level in the hole, as illustrated by figure 9. The rising water near the center of upflow may have already started to form vapor bubbles at depths and temperatures considerably greater than those of Y−1. We assume in figure 9 that Y−1x intersected such a channel of upflowing water and vapor, just missed by Y−1. Another explanation assumes that the lower part of Y−1 was not filled with cement and that the "short-circuit" provided by the open hole permitted rapid flow of water from near or below −215 ft to higher levels. This hotter water when tapped by Y−1x would boil more vigorously and produce more gas than the water in Y−1 (see later discussion of Norris Basin holes).

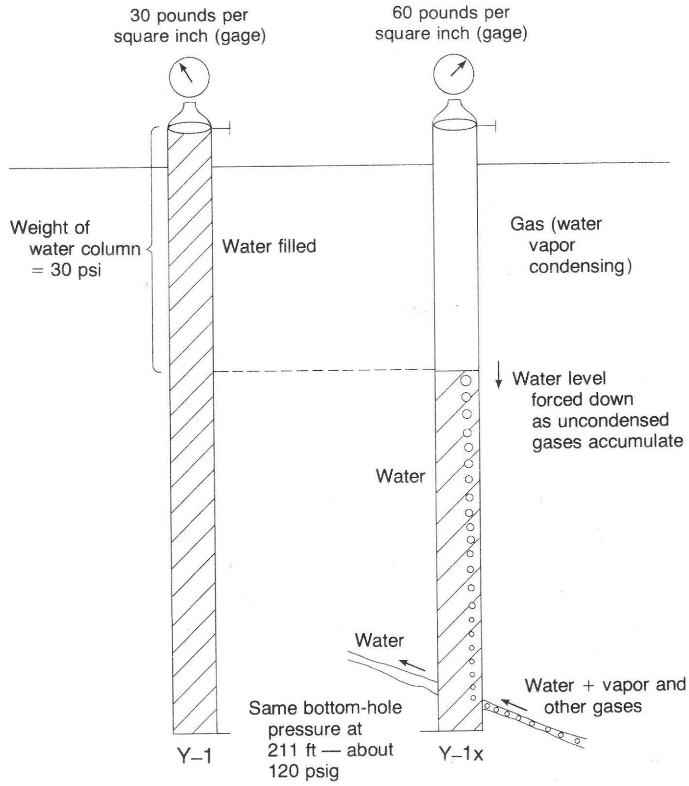

FIGURE 9.—Preferred explanation for differences in gage pressure recorded in Y−1 drill hole and its redrilled lower segment, Y−1x (here shown for simplicity as a separate hole).

Y−7 (BISCUIT BASIN I) DRILL HOLE

SITE SELECTION

Two drill holes, Fenner's Carnegie I and our own Y−1, had explored the southern part of the Upper Basin, but the subsurface relationships were still not adequately known. A site near the north end of the basin was selected as the best available for providing more data. The site is just north of the loop road at the north end of the Biscuit Basin parking area.

PHYSICAL MEASUREMENTS

The physical data from Y–7 are summarized in table 4; temperatures and other pertinent data are shown in figure 10. Drilling was so trouble-free and rapid that only a few measurements were obtained (figure 10, curve B). Decreases in thermal gradient probably occurred just below the water table and also somewhere near −60 ft at the top of a permeable zone in which circulation was lost. All temperatures are far below the reference boiling-point curve (A of figure 10).

Water-level measurements (table 4) are also significant. The water table was first identified at about 5 ft below ground, at an altitude almost identical with that of the Firehole River north and northwest of the hole. The water level declined to about 6 ft below ground when the drilled depth was near −60 ft, probably because of cooling by drill water with consequent increase in density of water in the hole relative to predrilling densities. The water level then rose to 3.8 ft below ground when the hole was first drilled to −242 ft. The relatively low temperatures and the absence of static water levels above ground surface are marked contrasts with all other research holes in Yellowstone, and indicate that Y–7 is outside the main zone of upflowing hot water. Thus, drilling was terminated at −242 ft.

POSTDRILLING MEASUREMENTS

A thermistor temperature series was obtained from the surface to −110 ft, 11 days after Y–7 was completed (fig. 10, curve C), and a second series with a longer cable was measured to the bottom in June 1968, 9 months after completion (curve D). A third series obtained on September 4, 1969, was similar to but slightly lower than curve D, as was a fourth series on September 23, 1971, and a fifth series on September 16, 1973 (by M. Nathenson). Seasonal fluctuations in water levels seem to occur, with highest levels during spring runoff (table 4). These may be accompanied by slight fluctuations in temperature in Y–8 with higher temperatures in the spring and somewhat lower temperatures in the fall. This possibility has not yet been confirmed (by measuring a spring temperature profile) since curve D was obtained.

After initial temperature recovery, the static water level averaged about 3 ft below ground, or ~2 ft above the water table (−5 ft). This represents an upward hydraulic gradient of about 2 ft over 240 ft or ~0.008 (table 3); this is equivalent to a positive fluid pressure at the water table of about 0.83 psi from the bottom zone.

Temperatures continued to rise for some weeks after drilling ceased. This may be due to further recovery of temperature after cooling by drill water, but a more likely explanation, based on the water-level data and experience with other Yellowstone drill holes, is that hot water flowing slowly up the hole and into permeable ground heated the ground slightly above predrilling temperatures, with consequent slight rise in the average static water levels.

This slow increase in bottom-hole temperature over a long period of time is unique in our Yellowstone drill holes and indicates that drilling resulted in increased flow from surrounding hotter ground. This is a mild example of the pronounced changes to be described in Norris Basin drill holes.

Each series of thermistor readings shows a relatively

TABLE 4.—*Temperatures, water levels, and other observations from Y–7 (Biscuit Basin I) drill hole, Upper Basin*

Date 1967	Time	Observation depth, ft[1]	Temp. C°[1]	Thermometer No.	Static water level, ft[1]	Comments
9/6	1410	10.0	(20.5)		−4.9	Drilled depth 11 ft; after shutdown of 10 min; a minimum temperature; lost circulation 10–11 ft.
	1420	10.0	(20.8)		**−5.0**	After 20 min shutdown; probably best indication of water table.
	1505	(13)	(22)		−4.9	
	1545	(17.6)	(26.5)		−4.8	Then drilled to −21 ft at 1615; cased and cemented.
9/7	0900	**8**	**34**			In cemented hole. With drilling, intermittent lost circulation.
	1510	44.0	(41.5)		−4.4	25 min after drilling to −52 ft; hole caving; drilled to −67 ft at 1630.
9/8	0800	**62.0**	**86.0**		−5.7	Hole caved to 58 ft; 4 ft into fill.
	~0815	(25.0)	(50.0)			Much above bottom. Then drilled to −102 ft at 1300, cased (3″) and cemented. Lost circulation −65 to −102 ft.
9/9	0840	(65.4)	(77.8)			In cemented hole, much cooled by drill water.
	1455				−6.4	Lost circulation 148–167 ft; uncemented sand and gravel from −162 to −172 ft? Drilled to −172 ft, 1350.
9/10	1030	171.1 } **170.8**	112.0 } **111.9**	4	−3.7	20 hr after circulation; note rise in water level with heating.
	1045	170.6 }	111.7 }	8		
9/11	0800	**170.7**	**116.7**	8	−3.35	41 hr after circulation; good core recovery below −192 ft; drilled to −242 ft; ~ 1230, hole terminated.
9/12	1105	**240.1**	**140.9**	8	−3.80	~22 hr after circulation.
9/13	0843	**239.6**	**141.8**	8	−3.37	44 hr after circulation.
9/22					−3.05	Thermistor temperatures to −110 ft; see fig. 10, curve C.
6/13/68	1140	**231**	**142.3**		−1.3	Thermistor temperatures to bottom, fig. 10, curve D.
9/4/69		**235**	**141.7**		−2.88	Thermistor series not shown on fig. 10; nearly identical to curve C to −56 ft, then slightly below curve D to bottom.
			143.1	13 & 14		
9/23/71		237.1	142.2		−2.42	Thermistor series, not shown on fig. 10.
			143.4	12		
9/16/73			141.6		−2.64	Thermistor series measured by M. Nathenson, not shown on fig. 10; similar to curve D but slightly lower from −30 to −160 ft.

[1]Data in boldface considered most reliable; data in parentheses, least reliable.

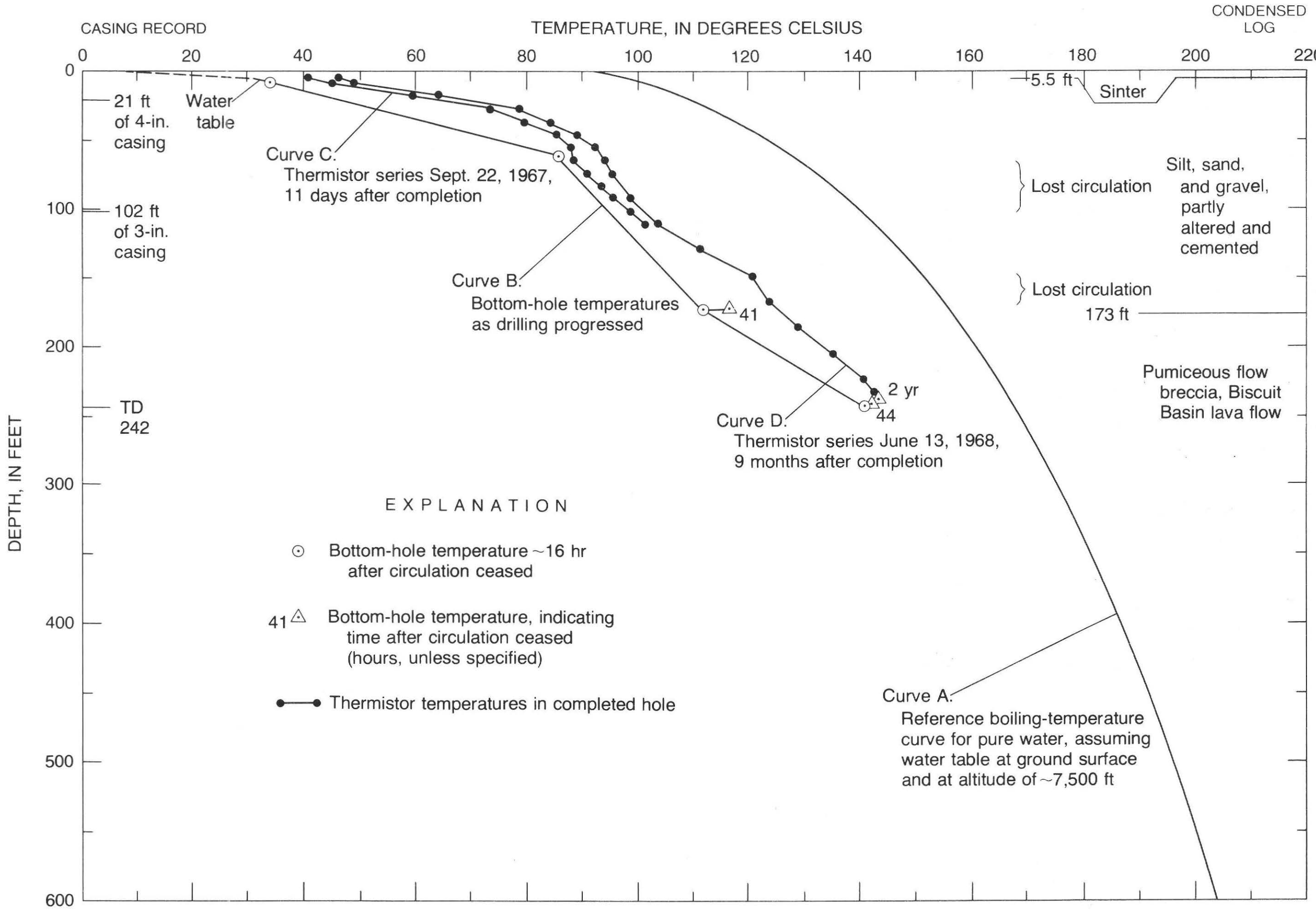

FIGURE 10.—Temperatures and other data from Y–7 (Biscuit Basin I) drill hole, Upper Basin.

low gradient in the permeable zones from about −60 to −100 ft and −150 to −170 ft, where circulation losses were noted during drilling. Local convective circulation is likely to occur in each permeable zone, which would tend to equalize temperatures and result in low thermal gradients. The hole was cased and cemented to −102 ft, which is near but probably not below the bottom of the thickest permeable zone. Permeability of rocks adjacent to the casing was high enough, however, for hot water from below to flow up around the casing, thus causing higher temperatures within the casing. This increase in upflow was indicated at least as high as −55 ft, perhaps with some influence to −30 ft.

Some convection also occurs within the NX casing, tending to raise temperatures in the upper part. Positive evidence for convection was identified by Manuel Nathenson on September 16, 1973, using a thermocouple and a portable strip-chart recorder. Fluctuations of as much as 1.5°C occurred in 10 minutes, and temperatures in individual eddies changed as much as ~1°C.

Y–8 (BISCUIT BASIN II) DRILL HOLE

SITE SELECTION

Temperatures and pressures in Y–7 were relatively low compared with other holes already drilled elsewhere in Yellowstone National Park. However, the chemical compositions of water from nearby springs suggested that subsurface temperatures in the immediate area were at least as high (~200°C), as found in previous holes. Accordingly, a second drill site was selected in Biscuit Basin about 425 ft south of Y–7 and 6 ft higher. The site is within a cluster of discharging springs, 48 ft northwest of a small geyser informally called "Rusty" (Marler, 1973, p. 25).

PHYSICAL MEASUREMENTS AS DRILLING PROGRESSED

The physical data from Y–8 are summarized in table 5; temperatures, the casing record, and a condensed log of the rocks are shown in figure 11. Some data on temperatures and depth of the water table were obtained close to the surface, but no reliable temperatures were obtained from 6.4 to 163 ft in depth because of the combined effects of casing, cementing, and rapid drilling.

The water table was first identified at about −3 ft when the hole was 5½ ft deep. The hole started to discharge at a drilled depth of 28 ft when the drill stem was opened for core recovery, so a static water level above ground was first noted at this depth or a little higher. The wellhead water pressure was 8 psig at −163 ft and then rose abruptly to ~29 psig at −181 ft, where the first strong eruption tendencies were recognized.

A zone of high permeability (indicated by partial loss of drill water) was noted from about −150 to −172 ft, evidently nearly isolated by partial self-sealing from a deeper permeable zone of much higher wellhead water pressure below −180 ft. This deeper aquifer is near the upper contact of a flow breccia of the Biscuit Basin flow (R. L. Christiansen, written commun., 1974). Temperatures increased only slightly with greater depth, reaching a measured maximum at −261 ft, and then decreased slightly to the bottom of the hole.

POSTDRILLING MEASUREMENTS

Measurements made in June 1968 and October 1969 indicate that since drilling was completed, hot water under high pressure has been flowing up the hole into the permeable sediments of lower water pressure, at least up to the bottom of the casing at −93 ft. Consequently, temperatures and pressures at depths of less than −180 ft have increased significantly.

Curves C and D of figure 11 cannot represent original ground temperatures. For example at −163 ft, where wellhead water pressure was ~8 psig (table 5), the predrilling ground temperature might have been as high as 158°C, or 5°C above the observed temperature and 4°C above the reference boiling-point curve; this is the maximum temperature consistent with the observed wellhead water pressure. The postdrilling temperature of about 167°C at the same depth must be accompanied by a wellhead water pressure of at least 33 psig. Wellhead fluid pressures (largely if not all water) of about 35 psig (table 5) were observed during the month after completion of the hole. Vapor bubbles in the liquid, separating in part because of the partial pressures of other gases and thereby decreasing average density, may account for the discrepancy of about 2 psi in pressure at the wellhead. Predrilling overpressures below −180 ft were probably higher than 35 psig.

Downhole pressure measurements were made in 1969 and 1971 (fig. 12). In Y–8, after the hole was capped for a sufficient time, the water level was dis-

TABLE 5.—*Temperatures, pressures, and other observations from Y–8 (Biscuit Basin II) drill hole, Upper Basin*

Date and time 1967		Observation depth, ft[1]	Temp. °C[1]	Thermometer No.	Static water level, ft[1 2]	Wellhead pressure, psig[1]	Comments
9/12	1525	2½			(−2.3)		Drilled depth 3½ ft; drilled on to −7½ ft at 1545.
	1605	5.5	(17)		(−1.4?)		
9/13	0800	**5.5**	**51½**		**−3.15**		Temperature at sand level; few gas bubbles.
	0815	**6.4**	**72**				Thermometer 9 in. into sand.
	1325	17.5			−1.75		Drilled to −20 ft at 1425, cased (4 in.) and cemented.
9/14	0825	8.3	(64)		(−1.0)		On cement; much cooling by lost drill water.
	1050	**28**	**>84**		Above ground		Hole discharged 6 gpm at −28 ft; discharge temperature 84°C. Drill water muddied spring 50 ft to southeast, and Rusty Geyser less active. Drilled to −93 ft at 1545; set casing (3 in.) and cemented.
9/15	1000	11.7	(72)				On cement. Drilled to −163 ft at 1540. Rusty active again.
9/16	0820	**162.9**	**153.1**	8	(+19)	**8**	Only partial drill water return from −163 to −173 ft.
	1205	181			(+70)	**29**	Pressure increased near −180 ft. Drilled to −211 ft at 1440.
	1530	**211**	**166.0**	8		29½	~1 hr after circulation.
9/17	1315	**211**	**168.1**	8	(+74)	**31**	Approximate wellhead water pressure 22 hr after circulation.
9/18	0758	**211**	**167.9**	8		30½	40 hr after circulation. Well first erupted 0915; Drilled to −261 ft at 1530.
	1600					28½	
9/19	0800	~**261**	169.4 } **169.6**	4	(+74)	**31**	Drill rods dropped 2 ft at −320 ft; soft, or a cavity. Drilled to −342 ft at 1520.
		~261	169.8	8			
9/20	0755	**341.6**	**169.8**	8	(+78)	**32½**	Thermometer not insulated. Drill rods fell 1 ft at −371 ft; cavity? Drilled to −423 ft at 1600.
9/21	0806	**423.6**	169.1 } **169.3**	4	(+79)	**33**	Wellhead water pressure. Thermometer not insulated so temperature reversal? Drilled to −503 ft at 1520.
	0821	**423.6**	169.4	8		33	
9/22	1235	**500.6**	166.4 } **166.9**	4	(+80)	33½	Thermometer insulated for first time; note slight temperature reversal.
	1420		167.3	8		34	
10/17		500.7	(169.0)	9	(+84)	72 to **35**	Not insulated. Bottom pressure 235±3 psig.
10/22		499.7			(+84)	**35**	Top pressure (after gas bled off).
							Bottom pressure 225 psig (probably low due to leaking check valve at bottom of tube).
6/12/68		(275)	(167.8)		(+98)	84 to **41**	Pressure decreased as gas bled off. Thermistor temperatures (curve C, fig. 11).
		494	**166.0**				
9/15/69		498					Bottom pressure 230 ± 0.5 psig.
10/4/69						86 to 47	Maximum-thermometer series, curve D, fig. 11, to check thermistor series of 6/12/68; maximum temperature (uninsulated), 169.6°C; probably near −250 ft ≪1 gal. water during series.
5/28/71					(+95)	**39.5**±0.5	
		499					Bottom pressure 230 ± 0.5 psig.
9/23/71		496	**165.5**		(+89)	78 to **37**	
		494					Bottom pressure 230 ± 0.5 psig.
9/27/71		496			(+89)	78 to **37**	Bottom pressure 231 ± 0.5 psig

[1]Data in boldface considered most reliable; data in parentheses, least reliable.
[2]Relative to ground surface; positive levels in parentheses, calculated from wellhead pressures considered least affected by vapor; assumed factor of 2.4 is somewhat high.

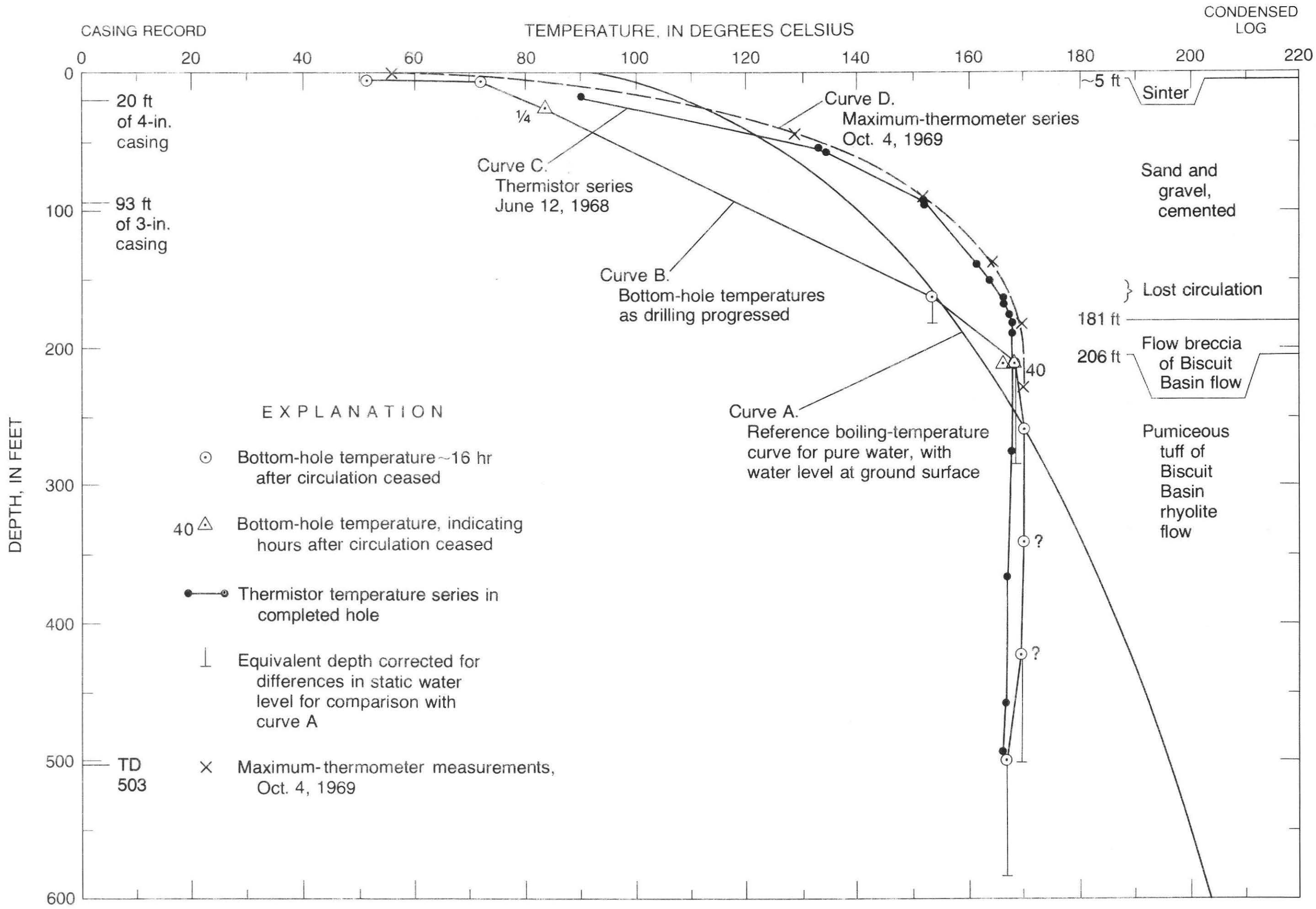

FIGURE 11.—Temperatures and other data from Y–8 (Biscuit Basin II) drill hole, Upper Geyser Basin.

placed to a depth of about 96 ft. The pressure and temperature measurements of figure 12 were made after the accumulated gas had been bled from the well. Gas accumulated in Y–8 so rapidly that, during the measurements, a small amount of leakage was allowed to insure a maximum content of water in the hole. The linear array of pressure data indicates nearly complete success in this effort.

The upper part of the postdrilling temperature profile (curve D) can be interpreted as reflecting a combination of convection, adiabatic boiling, and conduction. The inflection point at about −180 ft probably is due to the influx of gas-bearing water from the aquifer at −181 ft. From this point to about −130 ft the approximate congruence of curve D with the reference boiling-temperature curve (B) suggests that boiling is occurring. From −95 to −20 ft, linear gradients suggest cooling by conduction through the NX casing. The much lower but still linear gradient from −20 ft to the surface may reflect the greater mass of highly conductive iron in the double strings of casing there. If adiabatic boiling is assumed in the zone from −130 to −180 ft, pressure readings can be compared with the boiling pressures for pure water at corresponding depths and temperatures, determined from steam tables (curve E, fig. 12). The calculated pressures are all at least 8 psi below the measured pressures; the discrepency is most reasonably explained by the partial pressures of other gases. When a vapor phase is present, the measured pressure is equal to the partial pressure of water vapor plus the sum of the partial pressures of all other gases. If we assume that the proportion of vapor in the column was so low that average density was not decreased significantly, the partial pressure of all other gases (mainly carbon dioxide) is calculated to be about 8 psi or 0.54 atm. This assumption is supported by the fact that curves A and C of fig. 12 are nearly parallel, and both are slightly concave downward as they should be. Curve G, a near-surface modification of pressure curve C, indicates the assumed effects of gas accumulation after a shutdown time long enough for the water level in the hole to be depressed to the bottom of the casing.

EVIDENCE FOR NEAR-SURFACE SELF-SEALING IN Y-8 DRILL HOLE

Pressures observed at the surface or calculated from water levels are shown in figure 13 relative to drill-hole depth at the time of each measurement. Wellhead water pressures clearly increase greatly downward, especially between depths of −163 and −181 ft (near 7,100-ft altitude). A major decrease in permeability with time in

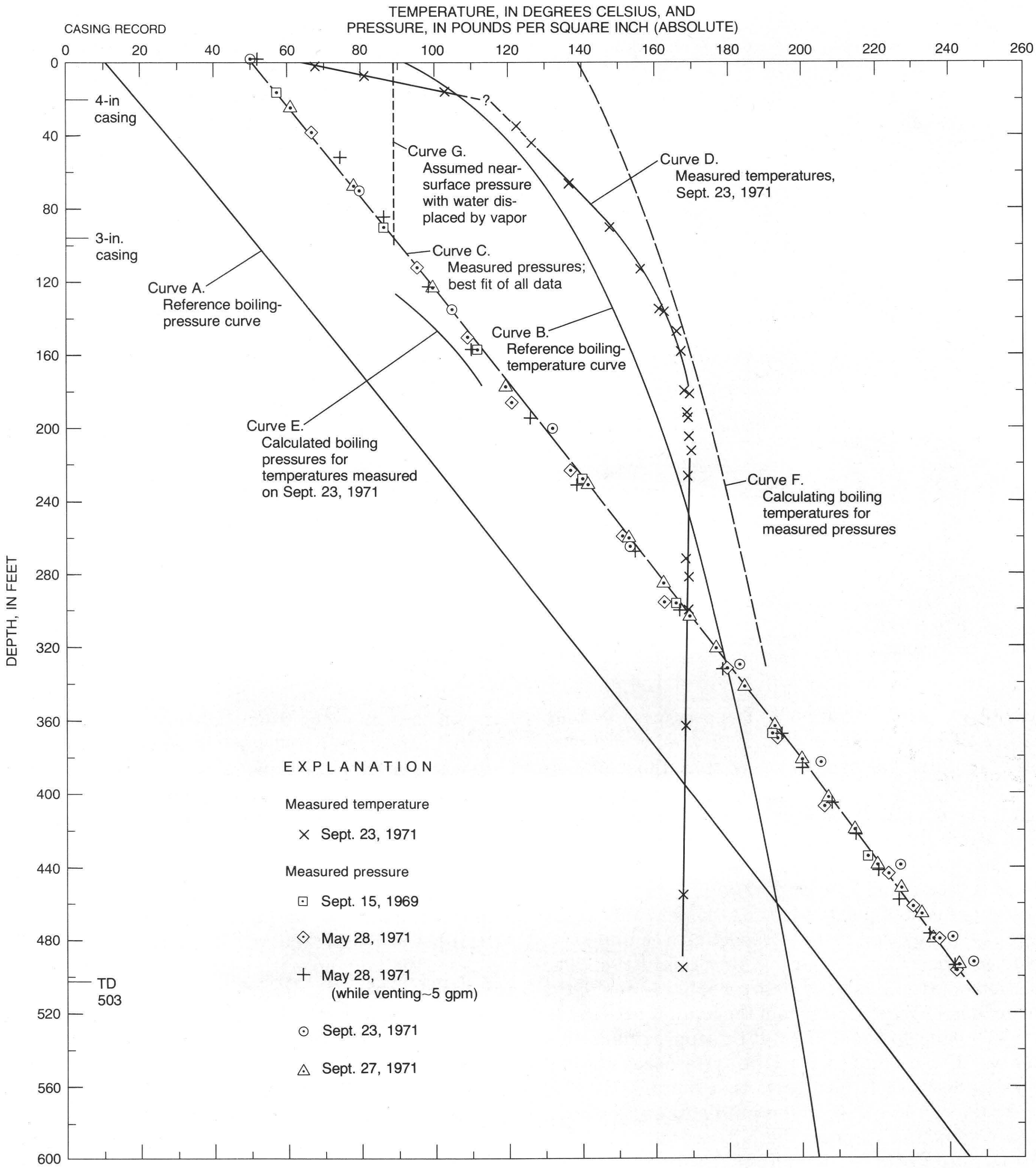

FIGURE 12.— In-hole temperature and pressure, Y–8 drill hole after completion, with other reference curves.

response to hydrothermal activity is required to explain these pressure differences. The sediments are now well cemented and probably date from the late Early Pinedale glacial stage less than 25,000 years ago. The original stream sediments were mainly coarse grained and sufficiently well sorted to have had high porosities and permeabilities. However, only about a gallon per minute of water was discharging from the spring 50 ft south of the drill hole (fig. 13), and probably no more than 20 gpm in total was discharging from all springs within 200 ft of the drill hole. Obviously, in spite of the high vertical water pressure gradient from −180 ft to the surface, only a little water can actually flow upward. The only reasonable explanation is that originally high permeabilities have decreased greatly in response to deposition of hydrothermal minerals in pore spaces and fractures. Petrographic and X-ray study of the cores from this hole (Terry E. C. Keith, written commun., 1973) indicates abundant hydrothermal quartz, chalcedony, analcime, and calcite throughout most of the hole, especially within the 10-ft interval from −170 to −180 ft, where the pressure gradient is highest. Subordinate montmorillonite, celadonite, and mordenite also occur. The drill hole evidently provides an effective hydraulic "short-circuit" across this self-sealed zone. The large increase in upflow in response to this short-circuit explains the major differences between curves B and C of figure 11. The increase in upflow also resulted

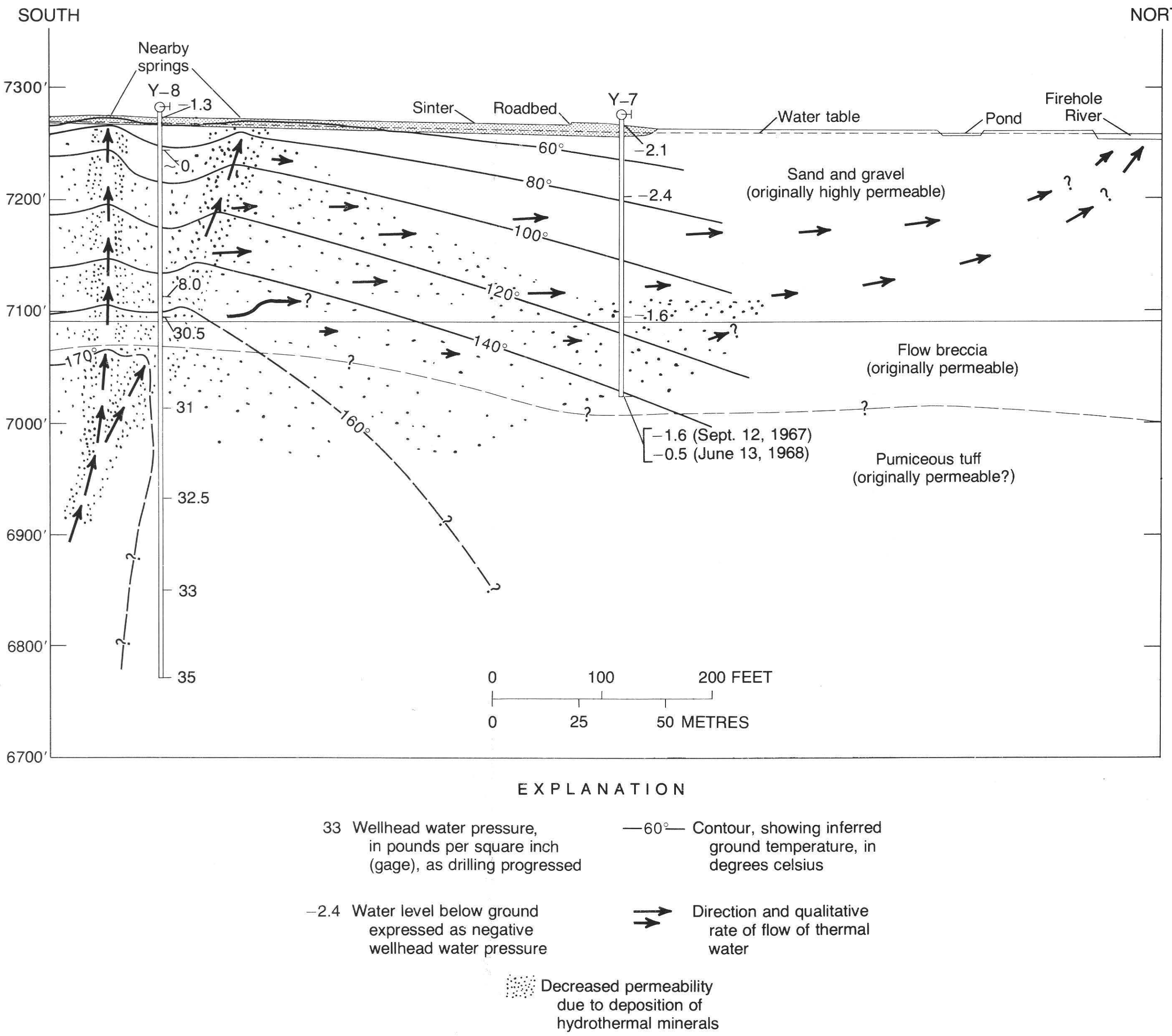

FIGURE 13.—Section through Y–7 and Y–8 drill holes, showing pressures, temperature contours, and deduced self-sealing by deposition of hydrothermal minerals in originally permeable ground.

in much greater pressures at all depths above −180 ft, and the high initial temperature of the upflowing water (~169°C) eventually raised all shallow temperatures.

The in-hole fluid pressures measured in 1969 to 1971 (curve C, fig. 12) all indicate wellhead water pressures significantly above the ~30 psig measured when the hole was being drilled through the zone of maximum temperature near −120 ft. The wellhead pressures measured as drilling progressed were generally slightly low because of the cooling effects of drilling water, but the measurements of September 16–18, 1967, suggest rapid recovery from this effect, at least near −211 ft. In contrast, postdrilling in-hole pressures may be higher than original pressure because of extensive upflow and heating with consequent expansion of water in the hole at all levels above −181 ft. The natural fluid pressure at about −181 ft before disturbance by the drill hole cannot be determined from our data but was probably about 32 psi above curve A of figure 12, rising perhaps to 35 psi at the bottom of the hole.

HORIZONTAL "SELF-SEALING" AND CIRCULATION PATTERN BETWEEN Y-8 AND Y-7 DRILL HOLES

As discussed above, the increasing wellhead fluid pressures with depth in Y–8 are related to self-sealing by hydrothermal minerals. The original sediments, as displayed in the cores, contain no strata likely to have been initially fine grained and low enough in permeability to account for the observed vertical pressure differences. Equally strong evidence for horizontal self-sealing by hydrothermal alteration and mineral deposition is the contrasts in wellhead water pressure that exist between Y–8 and Y–7 at equivalent depths.

Many individual beds were originally well-sorted permeable steam sands and gravels, and original hydraulic gradients must have been exceedingly low when hot water first started to flow through these sediments. The water table as identified in Y–8 and Y–7 differs in altitude by about 8 ft (table 3), sloping downward to the north at a gradient of 0.019. In contrast, the present horizontal hydraulic gradient in sediments near −170 ft in both holes is now about 7 psi per 100 ft (32 psi less ~2 psi for difference in altitude, table 3, divided by 425 ft), or about 0.17. For comparison, the hydraulic gradient of the water table from Y–7 to the Firehole River is about 0.01. Pressure in Y–7 is clearly more closely related to a normal rate of increase with depth below a free-standing water table than to the hydrothermal system tapped by Y–8.

Horizontal temperature gradients per 100 ft from Y–8 to Y–7 are about 4°C at −50 ft, 5°C at −100 ft, 7½°C at −150 ft, 8 ½°C at −200 ft, and 5°C at −250 ft. Note that the calculated horizontal temperature gradients are 6 to 12 times the vertical gradient for conductive heat flow in "normal" nongeothermal areas. All temperatures in Y–7 are much too low for a vapor phase to form. Temperatures are concluded to decrease for the most part from Y–8 to Y–7 because of slow northward flow of water through an imperfectly sealed zone, with upward conductive cooling of the water.

Our interpretation of temperature contours and circulation patterns along a vertical section that includes Y–7 and Y–8 (fig. 13), involves the following concepts:

1. Vertical or steeply dipping fractures probably control the upflowing water discharged from springs near Y–8.
2. Temperature contours bulge upward on and near these upflowing channels.
3. Except for such modifications, temperature contours from 60°C to 140°C are controlled by data from Y–7 and Y–8.
4. Positions of the indicated 160° and 170°C contours are much less certain and are controlled entirely by data from Y–8. We are confident that 170°C does occur in or very close to Y–8 (169.6°C was measured at −261 ft after 16½ hr without circulation, so original ground temperatures probably exceeded 170°C).
5. The slight reversal of temperature below −400 ft in Y–8 is best interpreted as the intersection of the drill hole with the edge of a convecting cell that "mushrooms" outward. Location of the center of the cell is not known, but subsurface temperatures of ~200°C are indicated from silica contents of springs to the west, south, and east of Y–8.
6. The principal upflow is shown in figure 13 as occurring in zones of most extensive mineral deposition, which occurs in initially permeable walls of fractures as hot water escapes. Eventually the channels and their immediate walls are thoroughly sealed, and either new channels form or local flow declines and then ceases.

CARNEGIE I DRILL HOLE, MYRIAD GROUP

SITE SELECTION

The Myriad springs, a rather inconspicuous group 1,500 ft west of Old Faithful, were selected by Allen, Day, and Fenner of the Geophysical laboratory of the Carnegie Institution of Washington for their first research drill hole in Yellowstone in 1929, here called Carnegie I. Reasons for selection of this site were not specified, but a typical "alkaline-water" area clearly was desired. Other factors evidently considered included proximity to Old Faithful, accessibility to housing, and a convenient supply of drill water, which was piped from Old Faithful Inn. The specific site is now marked with an inconspicuous concrete pad 100 ft northwest of Round Geyser and near the center of the Myriad Group.

PHYSICAL MEASUREMENTS AND INTERPRETATIONS

Physical data from Fenner (1936) are summarized in table 6, supplemented by previously unpublished data from Fenner's field notes. The most significant temperatures are shown in figure 14. Obvious differences are evident between the temperature data of Carnegie I and corresponding data from our drill holes in Upper Basin and elsewhere. The measured temperatures in Carnegie I (fig. 14) are consistently below reference temperature curve A, in contrast to Y–1 (fig. 8), where all temperatures below −120 ft plot on or above the reference curve. The Carnegie I data suggest that C–I is comparable to Y–7 (fig. 10), which is in the border of a thermal system, rather than to Y–1 (fig. 8) or Y–8 (fig. 11), which penetrate upflowing systems. In fact, however, Carnegie I was sited near the center of the Myriad Group in which numerous steam vents, springs, and a few geysers are distributed throughout an area approximately 1,000 ft in diameter. Thus, we would expect Carnegie I to be even more centrally located in an upflow system than either Y–1 or Y–8; conductive heat loss cannot in our opinion explain Carnegie I's characteristics.

Thus, the data from Carnegie I need to be reexamined, utilizing our present knowledge of hydrothermal systems to determine whether the anomalies can somehow be reconciled. Although Fenner's published record contains no detailed data on drilling procedures or methods of measuring temperatures and pressures, his field notes indicate that Carnegie I was drilled using two shifts per day, in contrast to our single shift of 8 hr. The duration of each shift was not specified, but each is likely to have been at least 10 hr long, with continuous drilling probably from 8 a.m. of one day to 4 a.m. of the next.

Until September 28, 1929, temperatures were measured at about 8 a.m., thus providing only 4 to perhaps 8 hr for recovery from the cooling effects of previous drilling. On September 28, 1929, and generally thereafter, temperatures were measured during the day, at times only an hour or so after drilling had ceased. An armored thermometer was usually lowered to within 1 or 2 ft of the bottom of the hole. Some temperatures were measured soon after the hole had been opened and allowed to erupt. The decrease in confining pressure during eruption usually results in boiling and consequent cooling as heat is transferred to water from the rocks (table 6, series of Sept. 23, 1929), just as in an erupting geyser (White, 1967). Both the rate of drilling and rate of circulation of drill water were evidently much lower than in our holes. All these considerations other than rate of circulation should have resulted in measured temperatures relatively lower than ours. In figure 5, note that temperatures measured 4 to 7 hr after drilling, rather than our usual ~16 hr, would have been low by 6° to 14°C (except in a high-pressure aquifer where original ground temperatures recover rapidly because of inflowing water).

Fenner's pressure measurements cannot be compared directly with ours or evaluated with confidence in terms of wellhead water pressures and gas-accumulation effects; instead, they are clearly wellhead fluid pressures

TABLE 6.—*Temperature, pressures, and other observations, Carnegie I drill hole, Myriad Group, Upper Basin* (reported by Fenner, 1936)

Date and time[1]		Drilled depth, ft	Temp. °C[2]	Wellhead fluid pressure, psig[2]	Comments[1]
Sept. 14	1929				Drilling started; two shifts per day.
16		[1]42			Cased and cemented; depth of casing not stated, but evidently −42 ft where coring started.
19	0600	62			First steam, encountered suddenly.
21	0800	95	125½	13	Chopping bit −97.7 to −113.8 ft (except "for a short time").
23	0800	104.3	129	12	
				(27½)	After blowing for a few minutes.
			(127½)	(27)	After blowing 3rd time.
24	0800	139	132	25	
				(30)	After blowing.
25	0800	148	145	32½	
	1700			(37½)	After blowing.
26	0800	156	147	(37)	Drilled to −161.7 ft first shift (2 ft more on 2d shift). Thermometer down after blowing.
27	0800	167 ([2]168.3)	(146)	(37)	Thermometer down after blowing (but may have hung up at −121 ft—not confirmed).
28	0830	195	(146½)	27½	Thermometer only to −121 ft—hung up. Thermometer on drill rods, 2 ft off bottom (an hour or so after circulation ceased?).
	1400	205	155	28	
				(33)	After blowing 20 min.
29	0800	220	(141)	32½	Before blowing; thermometer only to −121 ft, jerking by steam?
				(37)	After blowing.
	1445	226	159½	------	(Time after circulation ceased not noted.)
30	0800	242	------	31	Before blowing; 40 psig after blowing, then to 42½, finally to 37 psig.
Oct. 1	1100	264	164½	(39)	After circulation? Pressure after blowing.
2	1500	292	171	(42½)	Temperature after blowing, with thermometer 1½ ft off bottom; pressure after blowing.
6	1400	313	175	42½ (?)	At −300 ft, hole erupted for 1 hr but no effect on pools 50 to 75 ft away.
7	1420	343	173½	43	After drilling; thermometer 1½ ft off bottom.
10	1010	379	172	35 (?)	At −375 ft, hole erupted many hours, some slight surface effects; pool 50 ft away became turbid. Thermometer to bottom on drill rods.
11	1610	406	180	49	Thermometer 1½ ft off bottom several hours after circulation. Pressure before blowing; up to 57 psig after blowing.
Aug. 29	1930				"Spring nearest drill hole now overflows and has overflowed since later stages of drilling; formerly rose and fell about 22 inches before drilling begun."

[1]Largely from Fenner's original field notes. [2]Data in parentheses considered less reliable.

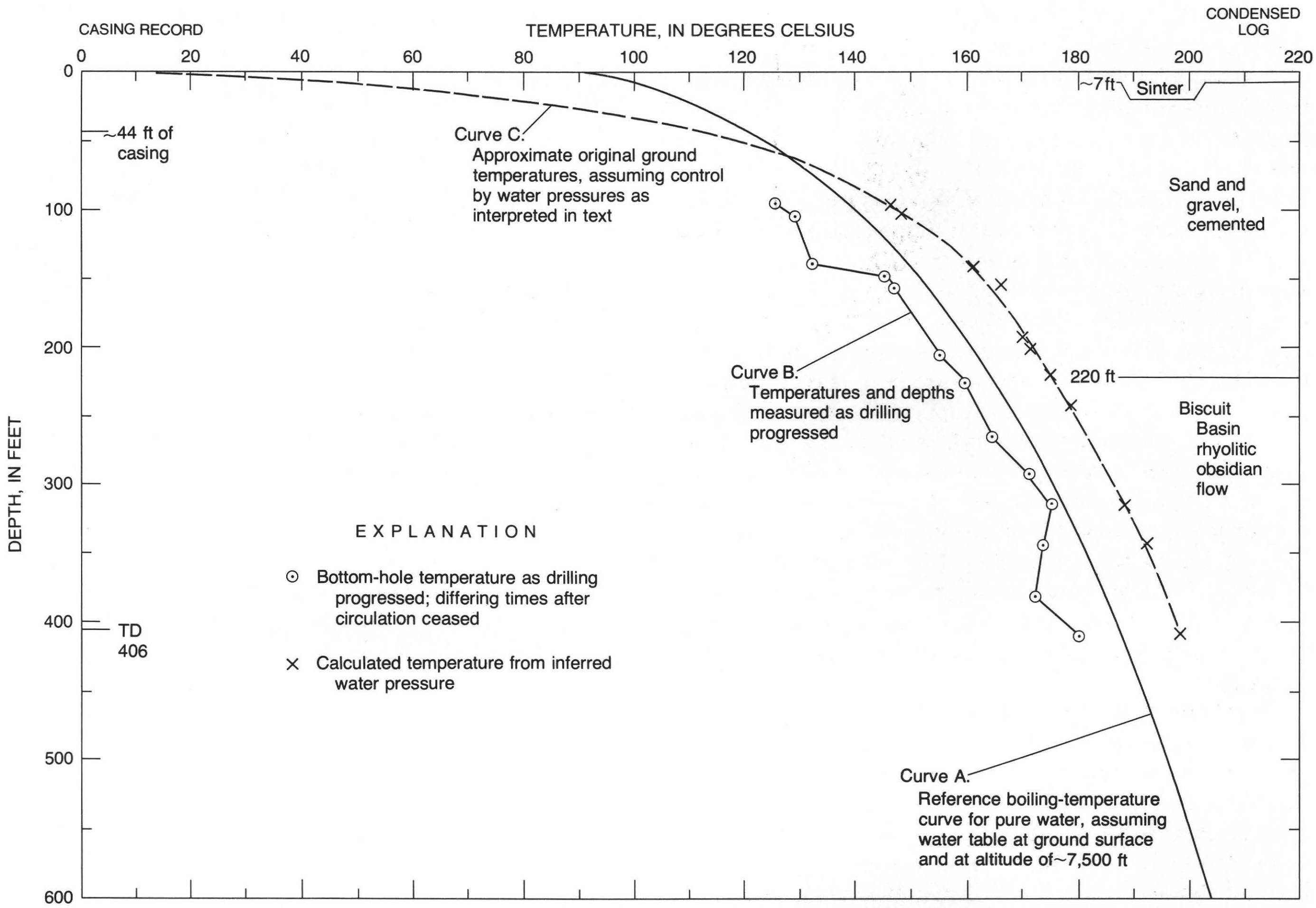

FIGURE 14.—Temperatures and other data from Carnegie I drill hole, Myriad Group, Upper Basin (Fenner, 1936).

in which effects of liquid and vapor cannot be distinguished. The pressure data of table 6 that are not enclosed in parentheses are most nearly comparable to our wellhead water pressures. If we assume equivalence, wellhead water pressures were about 12 psi near −100 ft, 25 to 31 psi from about −140 to −240 ft (and possibly deeper), and perhaps as much as 40 to 50 psi at depths below −250 ft. If the observed 49 psig of October 11, 1929, was wellhead water pressure (which would have increased to 50 psig in a heated hole), and if the true bottom-hole temperature was directly related to this pressure, the original ground temperature may have been as high as 198°C rather than the observed 180°C. Curve C of figure 14 shows temperatures calculated from the most reliable pressure data of table 6. Each temperature thus calculated is likely to be a few degrees too high, but in our opinion curve C is much closer to original ground temperatures than curve B. Temperatures probably exceeded the reference boiling-point curve (A of fig. 14) at most or all depths below −62 ft, where "steam" was first encountered (table 6). Fenner's indicated changes in temperature gradient near −140 and −380 ft probably have no significance. Additional evidence that subsurface temperatures in the Myriad system are at least as high as 205°C is based on silica content of 363 ppm in the spring nearest the drill hole (White and others, 1963), using the curves of Fournier and Rowe (1966).

We emphasize here that the above comments are in no way either direct or implied criticism of Fenner or his drillers. On the contrary, we acknowledge our great indebtedness to these early pioneers. Carnegie I was the world's first research hole to be drilled into a high-pressure hot-water system. Drilling equipment was primitive by present standards, and the effects of circulation of drill water and of induced eruption ("blowing") on bottom-hole temperatures were not yet understood. The principal previous drilling experience of the crew and of the Carnegie scientists had been in the vapor-dominated system of The Geysers, California (Allen and Day, 1927), where the most reliable temperatures and pressures were obtained after blowing (See White and others, 1971, for differences between hot-water and vapor-dominated systems.)

Fenner's previously unpublished comments on changes that occurred in nearby springs after the hole was completed (table 6) are similar to some of our observations. The increase in spring discharge probably resulted from "short-circuiting" of aquifers by the drill hole, with consequent increase in upflow of hot water into spring vents.

Y–6 (LONE STAR) DRILL HOLE, UPPER FIREHOLE RIVER

SITE SELECTION

Many hot springs of rather low discharge occur along and near the Upper Firehole River from 2 to 3½ miles south of Old Faithful. The only named thermal feature of this group is Lone Star Geyser. Allen and Day (1935, p. 51) estimated a total hot-spring discharge of 0.06 ft³/sec (25 gpm) from the area. An isolated drill site was needed for the last part of the 1967 summer tourist season; this isolation was provided by a locked gate on the service road to the Upper Firehole, half a mile southwest of Lone Star Geyser. The selected site was 350 ft north of the footbridge of the Howard Eaton trail over the Upper Firehole, 7 ft above river level, and 125 ft northeast of the Firehole River, and thermal springs are absent.

Our objectives were to obtain data on a rather inconspicuous hot spring group and to determine, if possible, its relation to the major Upper Geyser Basin 3 miles to the northwest. The altitude of the drill collar of Y–6 is about 7,640 ft; this is about 270 ft above Old Faithful's vent and 170 ft above Solitary Geyser, the highest thermal feature having a salinity similar to the other major springs of Upper Basin.[6]

PHYSICAL MEASUREMENTS AS DRILLING PROGRESSED

The physical data of Y–6 are shown in table 7 and figures 15 and 16. Temperatures were relatively low in near-surface uncemented sands and gravels, probably because of southeastward flow of cold water through these sediments to the Firehole River. The water table was first identified at a depth of −3.2 ft, which is about 5 ft above the mean level of the Firehole River 125 ft to the southwest.

Evidence for high wellhead water pressure was first noted at −172 ft (table 7). From that depth to the bottom of the hole, most of our data indicate an almost constant

[6]The Hillside Springs in the northwestern part of Upper Basin are more dilute than the geyser waters and are now depositing travertine rather than sinter; their highest altitude is nearly that of Solitary Geyser (7,470 ft), but old sinter from former springs in both the Hillside and Solitary areas occurs as high as 7,480 ft.

TABLE 7.—*Temperatures, pressures, and other observations from Y–6 (Lone Star) drill hole of the Upper Firehole River*

Date and time 1967		Observation depth, ft[1]	Temp. °C[1]	Thermometer No.	Static water level, ft[1,2]	Wellhead pressure, psig[1]	Comments
8/17	1315	21.1	(17)				Drilled to −50 ft at 1245; caving.
	1400	21.1	(15)				Set 50 ft, 4-in. casing. Cemented, 14 sacks cement.
8/18	1000	**22.0**	**20**				On cement; drilled to −78 ft at 1550.
8/19	1630	**51.4**	**28.8**		**−3.2**		On 26½-ft cave; temperature low from lost drill water.
8/21	0740	**51.3**	**33.9**				Temperature probably close to original after 64 hr standing; drilled to −118 ft at 1425.
	~1500	93.2	(42.0)		−3.1		Just after rods pulled; 25-ft cave; 3-in. casing set to −118 ft; cemented.
8/22	0900	**94.5**	80 } **79.6**				In cemented hole. Drilled to −182 ft at 1710 with first positive pressure noted at −172 ft.
		94.5	79.2				
	1750	**182.5**	**103.8**	14	(+41)	**17**	½ hr after circulation.
	1815	**182.4**	**108.7**	15		17	¾ hr after circulation.
	1822	**182.4**	**111.6**	14		16¼	1 hr after circulation.
8/23	0740	**182.5**	129.1 } **128.8**	4		37 to 18½	Much gas at initial pressure.
		182.4	128.4	8	(+23)	18 to **9¾**	Frothy water discharged at final pressure; drilled to −242 ft at 1715.
8/24	0749	**242.2**	141.6 } **141.6**	4	(+38)	**16** to 16¾	
		242.3	141.6	8		16¾	Then drilled to −302 ft at 1705.
8/25	0740	**302.3**	147.9 } **147.9**	4	(+37)	**15½**, 15½	Leakage all water, no gas; all water pressure.
		302.3	148.0	8		16	Then drilled to −350 ft at 1530.
8/26	0833	349.7 } **349.8**	(155.8 bumped)	4	(+36)	**15**	All water pressure.
	0853	350.0	**157.7**	8		15	
8/27	0804	**349.6**	**160.0**	8	(+38)	**16**	Leakage all water exsolving gas bubbles; all water pressure. ~40 hr since circulation.
8/28	0737	349.5	160.1 } **160.1**	4	(+38)	**16**	~64 hr since circulation.
	0757		160.2	8			Then drilled to −383 ft, 1600.
8/29	0737	382.9 } **382.9**	(159.8 bumped?)	4	(+38)	**16** to 16½	
	0755	382.9	**161.7**	8		16½	Then drilled to −393 ft at 1430; quit for new bits.
8/30							No morning measurements; drilled to −463 ft at 1725.
8/31	0736	**463.3**	173.4 } **173.9**	4		12 down to 0	All gas at 12 psig, then to 0; no excess water pressure.
	0751	**463.3**	174.4	8	−15.4		Note depth to water in open drill rods.
					−20.7		Water level in drill rods after gas bled off outside rods; drilled to −500 ft at 1530.
9/1	0902	499.7 } **499.6**	178.9 } **179.3**	4	(+40)	**16½**	Note return of pressure, constant.
	0923	499.5	179.6	8		16½	Hole terminated at −500 ft.
9/2	0845	499.4 } **499.4**	179.6 } **179.8**	4	(+40)	**16¾**	Leakage, all water.
		499.3	180.0	8		16¾	
9/4	0942	**499.0**	**180.7**	8	(+41)	**17** to 18¾	Leakage at first all water, exsolving gas, then water and gas as temperature of discharge increased.
9/5	0752	499.1	**180.8**	8	(+41)	22 to **17**	Pressure down, then up to 19½ psi.
10/16	1117	500	**180.2**	4	(+50?)	55 to **21**	At first gas, then to all water exsolving gas. Bottom pressure 210 ± 5 psi; overpressure ~11 psi.
6/27/68		496	179.9 } **179.7**	12	(+55?)	26 to **23**	Thermistor series; see figure 15.
			179.4				
9/7/69		499			(+61?)	75 to **25½**	Bottom pressure 228 psia, 21 psi overpressure?
9/22/71		494.2	**179.2**	12	(+50)	76 to **21**	In-hole pressure and temperature series, with 227½ psia recorded at −493 ft.

[1]Data in boldface considered most reliable; data in parentheses least reliable.
[2]Relative to ground surface; positive levels in parentheses, calculated from wellhead pressures considered least affected by vapor; assumed factor of 2.4 is somewhat high.

wellhead pressure of 16 psig. Fluid leaking from wellhead fittings during measurements was generally liquid water, commonly evolving a little gas only after leakage to atmospheric pressure. However, we observed puzzling pressure changes not recognized in other Yellowstone drill holes. At −182 ft on August 23 (table 7) after much leakage of gas and water, pressure fell to 9¾ psig, notably less than the 16 psig generally found elsewhere in the hole. On August 31 at a drilled depth of −463 ft, gage pressure fell to 0 as accumulated gas escaped. Surface fittings were removed, and depth to water inside the drill rods was then measured at −15.4 ft; when gas was also bled from the space between drill rods and well casing, the water level inside the rods declined to −20.7 ft, or about 13 ft below the level of the nearby Firehole River! By the next day, the well head water pressure was again near the normal 16 psig that characterized most of the hole.

Temperatures near the surface were about 90°C below the reference temperature curve (fig. 15, curves A and B). The difference between the two curves decreased rather regularly to about 17°C at the bottom of the hole.

SUMMARY OF DRILLING PROBLEMS

Y–6 was one of our easier drill holes to complete; fluid pressures and temperatures presented no problems that were not easily solved with the experience and drilling equipment available. The highest wellhead pressure observed during drilling was only 37 psig, and all pressures above about 20 psig were clearly caused by accumulating gas. Some minor drilling difficulty was encountered in penetrating the shallow glacial sands and gravels, which tended to cave in the open hole.

POSTDRILLING MEASUREMENTS

A thermistor temperature profile was obtained on June 27, 1968, nearly 10 months after completion of the hole (curve C, fig. 15), and a nearly identical second series was measured on September 22, 1971 (curve D, fig. 16), more than 3 years after completion. In-hole pressure measurements were made in September 1969,

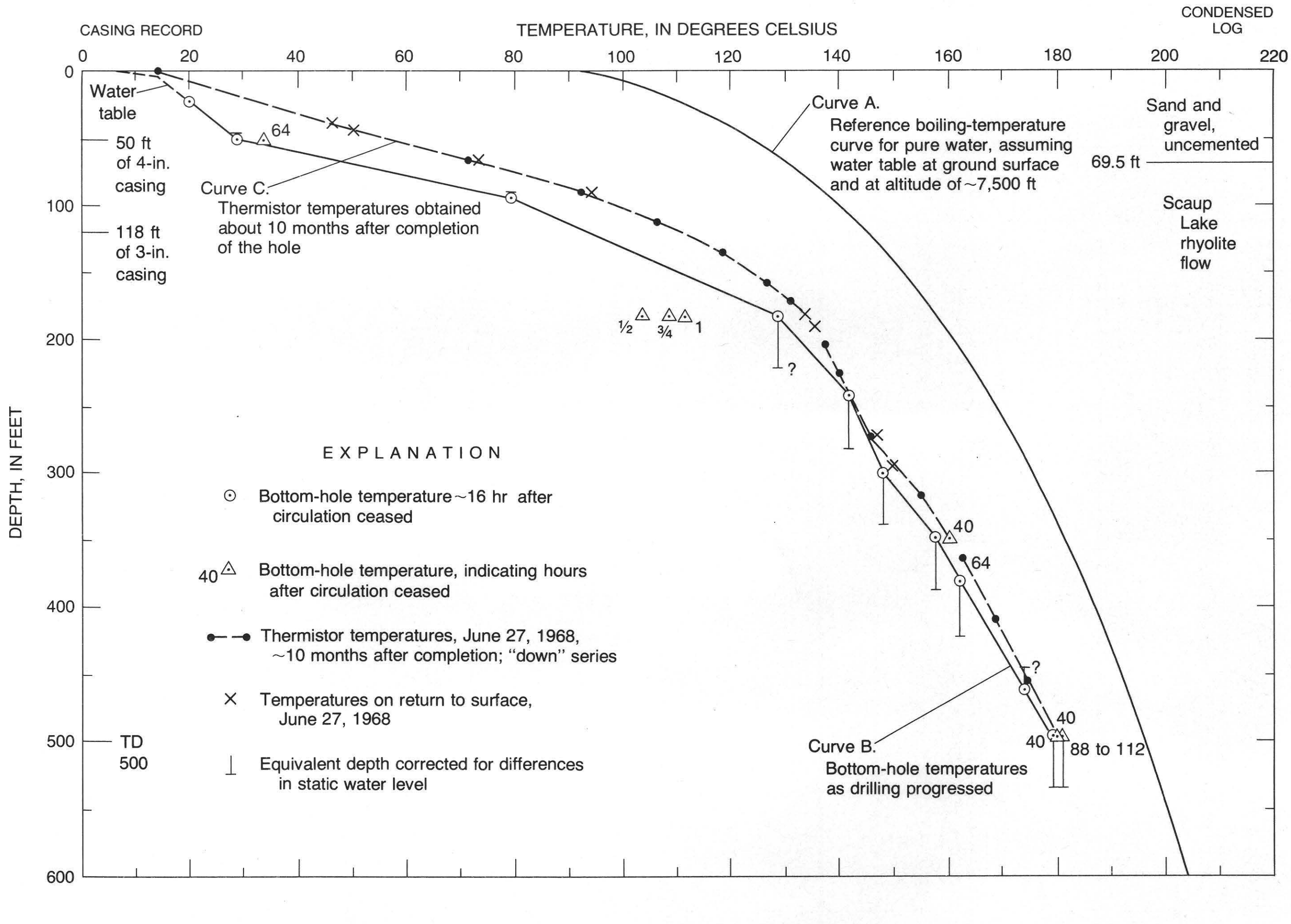

FIGURE 15.—Temperatures and other data, Y–6 (Lone Star) drill hole, Upper Firehole River.

and again on September 1971, with results plotted in figure 16.

INTERPRETATION OF DATA

Temperatures measured as drilling progressed (curve B, fig. 15) are well below the reference boiling-temperature curve A at all depths, indicating that heat is dissipated largely by conduction and by convection of water. Low-discharge nonboiling hot springs and sinter deposited by former springs occur from 175 to 300 ft to the southwest, south, and southeast of the drill hole, but

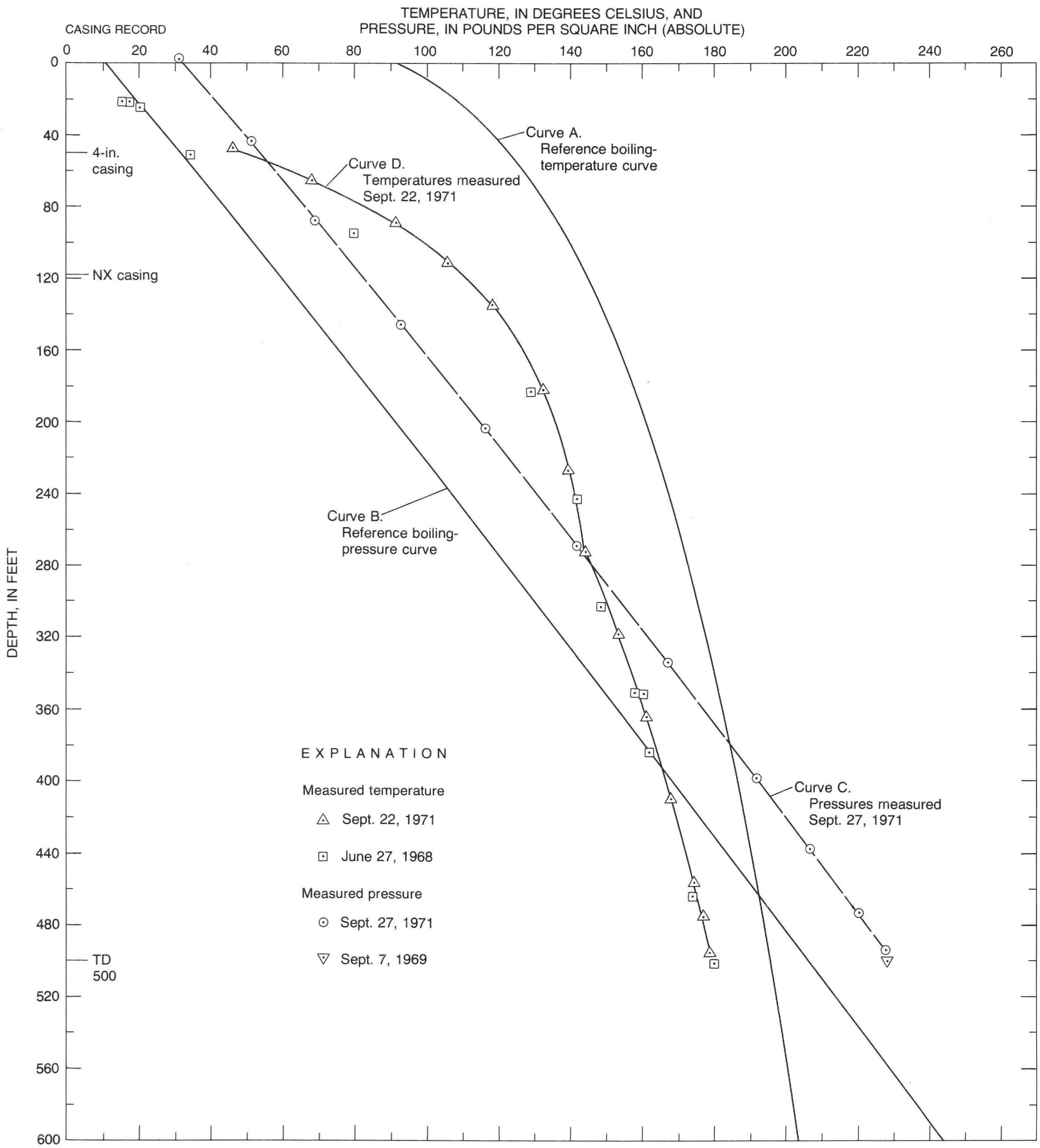

FIGURE 16.—In-hole temperatures and pressures of Y-6 drill hole after completion.

are absent to the north and west; the drill hole is on the edge of a convection system. The upflowing water of the system, however, has a temperature at least as high as the 180°C measured in Y–6. These facts indicate that conduction of heat must be an important near-surface process in the area. Vertical conduction of heat, however, does not account for the general similarity between original ground temperatures (curve B) and the reference curve (A) of figure 15; the temperatures of curve B at depths near and below −200 ft occur nearly 125 ft below equivalent temperatures on curve A. The same puzzling relationship was observed in Y–4, which is also on the border of a convection system. This relationship in both holes may be best explained by boiling in the hottest upflow, with some water then being diverted horizontally and then downward on the borders of the systems in convective circulation. The springs south and southwest of Y–6 may indicate the center of an upflowing system, now much impeded by self-sealing.

Thermistor temperatures (curve C of fig. 15) below −240 ft are nearly identical with the original ground temperatures, which are probably several degrees above curve B. Note that measurements, made ~16 hours after circulation ceased at −349.5 ft and −499 ft, were only about 2°C below temperatures measured at the same depths after an additional 2 days or more without disturbance. Temperatures at depths above −200 ft increased because of hot water flowing up the hole and out into ground below the 3–in. casing at −118 ft. Most of the hot water probably flows into the hole near −240 ft and out into adjacent rocks near and above −200 ft. Very little water seems to be supplied from depths below 240 ft, as indicated by lack of disturbance of predrilling ground temperatures below this depth. The nearly constant wellhead water pressures measured for depths below −200 ft are undoubtedly a key factor in accounting for this stability.

What is the explanation for the unusual changes in pressure noted near −182 ft and especially near −463 ft, where wellhead pressure was 0 and water levels were then recorded as much as 13 ft below the nearby Firehole River? Nearly all drill core from −350 to −410 ft is remarkably fresh, with only a few hydrothermal veinlets, considerable iron oxide, and no pyrite. We suggest that these zones of anomalous fluid pressures are not controlled by the upflowing hot water of the system or by any relation to river level; the latter evidently is not the effective base level for all ground water of the area. Some parts of the thick Scaup Lake lava flow are isolated (by self-sealing?) from the high-pressure thermal upflow, but have permeable channels leading to low-lying ground of Upper Basin more than 2 miles to the northwest. The Upper Firehole River has a very low gradient for 1½ miles downstream from Y–6, so subsurface response to a base-level control anywhere along this stretch cannot satisfy the demands imposed by our data.

After completion of the hole, the wellhead water pressure remained nearly constant at 16½ to 17 psig for at least 5 days. All pressure measurements made more than a month later indicate higher wellhead pressures—21 to 25 psig. This increase in pressure is largely if not entirely due to heating of the upper part of the hole, with consequent expansion of the water and increase in thermoartesian pressure. The down-hole pressure measurements indicate water pressure of 21 to 23 psi above the reference boiling-pressure curve (B of fig. 16).

All thermal features of Upper Geyser Basin and the Lone Star area could be fed by liquid water from a single large hydrothermal system characterized at depth by a common pressure regime. Under this model, high near-surface impedance to flow produced by self-sealing would allow some thermal water to discharge in the Lone Star area, some 270 feet above the floor of Upper Geyser Basin. The model requires that just below the self-sealed zone in Upper Geyser Basin, the sum of artesian and thermoartesian pressures would have to be greater than at a similar position in the Lone Star area. The difference would have to be at least equivalent to the hydrostatic difference between the two areas (270 ft/2.4 ft/psi = 112 psi). Assuming that water overpressures in the Lone Star area do not exceed the measured 17 psi, overpressures at depth under Upper Geyser Basin would have to be at least 129 psi. Such overpressures were not noted in our Upper Basin drill holes, but the holes (particularly Y–1) may not have been deep enough. Overpressures of at least 90 psi were found in the Lower Basin drill holes, however, so high overpressures are not precluded for Upper Basin.

In summary, the data from Y–6 and from Upper Geyser Basin are compatible with the hypothesis of a single system but are inadequate to confirm it. Overpressures in Y–6 were only half those measured in Upper Geyser Basin and showed no tendency to increase with depth. In addition, the similarity in water chemistry between Upper Geyser Basin and the Lone Star area supports the model. We suspect that extreme overpressures do not occur at depth in the Lone Star area, and that this system may indeed be part of a system that is much larger than Upper Geyser Basin.

LOWER AND MIDWAY BASINS

Y–2 (FIREHOLE LAKE) DRILL HOLE

SITE SELECTION

Problems that developed during the drilling of Y–1 in

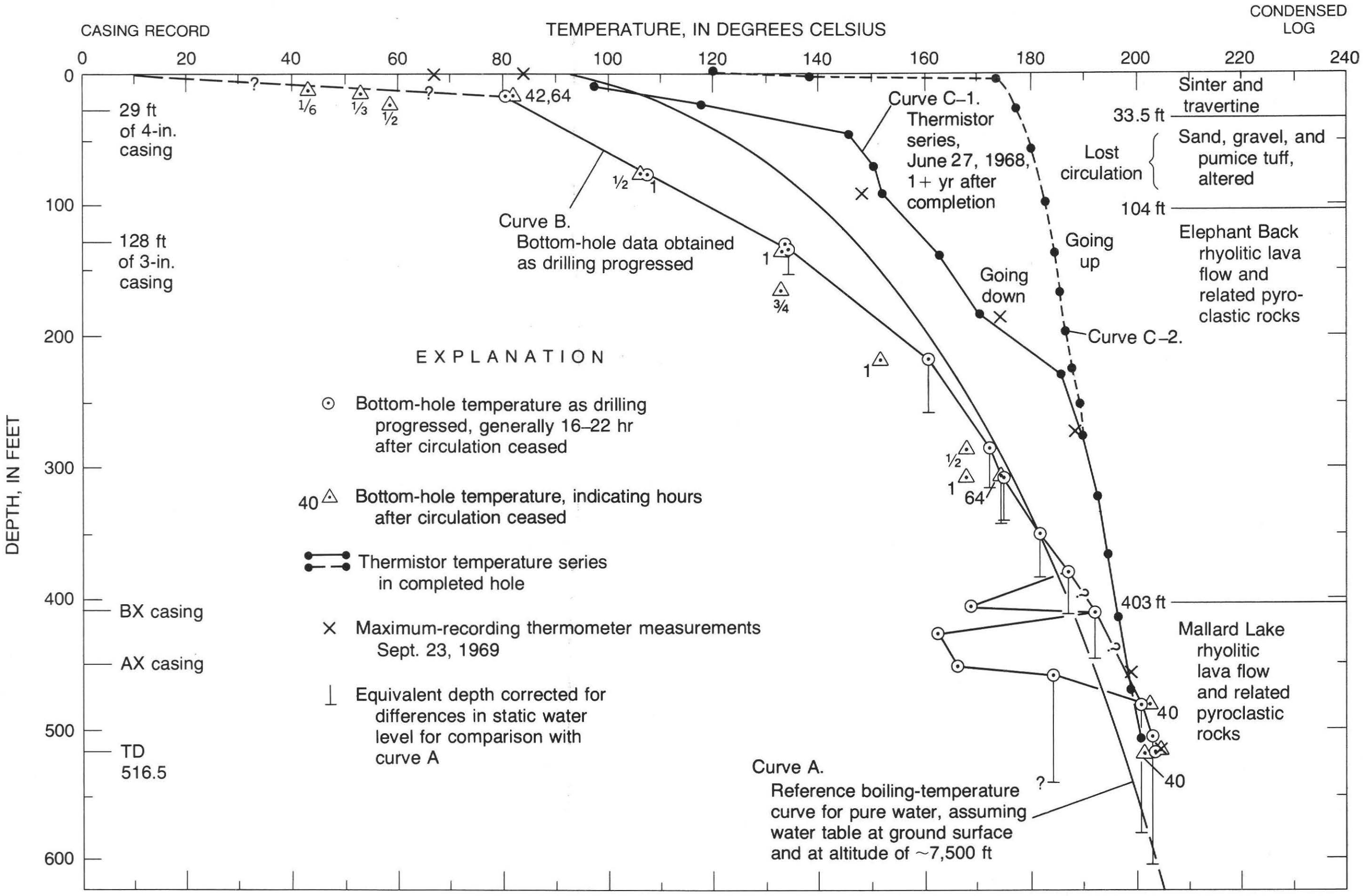

FIGURE 17.—Temperatures and other data, Y–2 (Firehole Lake) drill hole, Lower Basin.

Black Sand Basin of Upper Basin were related for the most part to wellhead pressures that were much higher than expected. Our second hole, Y–2, was selected partly in the hope of easier drilling under low-pressure conditions to provide us and the drill crew with more experience and time to devise new equipment for later more difficult holes that were expected. Firehole Lake, Hot Lake, and Steady Geyser of easternmost Lower Geyser Basin are characterized by waters of relatively low silica content (less than 200 ppm), suggesting a subsurface temperature of about 170°C (Fournier and Rowe, 1966). High discharge rates (about 3,500 gpm for the group, according to Allen and Day, 1935, p. 53), spring temperatures mostly below surface boiling, and copious deposition of travertine (White, 1970) also indicated low subsurface temperatures and perhaps low pressures.

On the other hand, we were also aware that extensive aprons of sinter from formerly active springs extend down to Hot Lake and Firehole Lake, isolated remnants of old sinter deposits occur on slopes of nearby hills at altitudes as much as 90 ft above the Y–2 drill site, and active sinter-depositing springs high in silica occur about 2,500 ft to the west in the Shelf-Pink Cone group. Old travertine, presumably deposited from springs similar to those of the present, also occurs as much as 28 ft above the drill site. Thus, another objective in selecting this site was to clarify the unusual alternation between sinter and travertine in the Firehole Lake area.

PHYSICAL MEASUREMENTS AS DRILLING PROGRESSED

Physical data are shown in table 8 and figure 17 (curve B). The near-surface data are not very satisfactory, largely because of restrictions imposed by casing and cementing. Bottom-hole temperatures evidently increase along a nearly linear conductive gradient from near −17 ft to about −130 ft. Fluid pressures were relatively low in the upper part of the hole. The water table was identified near −3.5 ft, and the first significant increase in static water level was near −83 ft. Wellhead fluid pressure first became pronounced at −134 ft and increased irregularly to the bottom of the hole. Measured temperatures first exceeded reference curve A of figure 17 near −350 ft, but wellhead water pressures of about 15 psig prevented boiling from occurring above about −380 ft in the natural system.

At and below −380 ft, most of the measured temperatures, when corrected for pressure and plotted at equivalent depth, are very close to reference curve A; however, some natural exsolution of gas-enriched vapor was probably occurring near and below −380 feet before drilling.

Puzzling combinations of temperature and wellhead pressure were found at depths of 406, 426, 451, and 458 ft. At each of these depths the measured temperature was much lower than the general trend in the hole, but pressures were generally higher than elsewhere (table 8); none of these pressures was clearly due to high wellhead water pressure except perhaps at −458 ft. Most of these pressures were strongly influenced by the accumulation of gas in the hole. The temperature measured at −451 ft is clearly not a significant indication of original ground temperature. The thermometer gear was lowered very slowly through separated sections of casing near −138 ft (May 28, 1967, table 8), where a slight downdrag on the gear seemed to occur. The same thermometer was again lowered and left on the bottom while a valve was opened slightly to permit some eruptive discharge. The observed temperature (167.8°C) was significantly above the previous measurement with the same thermometer (166.3°C). We conclude that reversed circulation was occurring in the hole before the first measurement; water was flowing up from the deep part of the hole outside the casing and was boiling as pressure decreased upward. At the casing break, vapor separated and accumulated in the top of the hole as the adiabatically cooled water flowed through the break and then back downward inside the casing. The slight eruptive discharge during the second temperature measurement caused some flow of water directly up the casing. Similar fluctuations in temperature, also interpreted as results of circulation reversal, were noted in

TABLE 8.—*Temperatures, pressures, and other observations from Y–2 (Firehole Lake) drill hole, Lower Basin*

Date and time 1967		Observation depth, ft[1]	Temp. °C[1]	Thermometer No.	Static water level, ft[1 2]	Wellhead pressure, psig[1]	Comments
May 3	1000	4.0	(40.5)				Drill water intake 42°C. so temperature not significant.
	1038	8.5	(41.5)		−3.3		11 ft drilled; lost circulation at −11 ft.
	1110	10.8	(40)		−3.4		Then drilled to −16 ft.
	1145	13	(43)		−3.4		10 min after circulation; on 3-ft fill; drilled to −21 ft.
	1245	14.9	(53)		**−3.5**		20 min after circulation; on 6-ft fill.
	1450	22.8	(58.9)		−3.45		29 ft drilled; 35 min after circulation.
	1645	29.0	(46)				Set 29 ft of 4-in. casing and cemented; into unset cement.
4	1330	52.5	(61.9)		−5.2		After drilling to −54 ft; lost circulation at −51 ft.
	1402	58.1	(64)		−4.5		After drilling to −59 ft.
	1625	76.8	(105.6)	8			After drilling to −78 ft; 25 min after circulation.
	1650	76.3	(106.1)	8	−3.9		50 min after circulation.
5	0742	76.3	106.8	8			No significant change in water level from −11 to −78 ft; lost circulation at −51 ft. Thermometer emplaced below lead weight, increasing observation depth. Drilled to −83 ft.
		77.4	107.9 } **107.3**	4	−3.47		
		77.4	107.2	4			
	0915	83			−0.5		Increasing fluid pressure first becoming evident; some gas.
	1005	88.7	(107.5)		+3		After drilling to −88 ft; water very gassy.
	1135	96.9	(106.1)				After drilling to −98 ft.
	1210	103			−6.45		After drilling to −103 ft; lost positive pressure. Water levels 3½ to 6½ ft below ground from about −100 to −125 ft; lost circulation near −113 ft. Then drilled to −128 ft at 1425.
	1600	128			+9.8		No drill water return from −51 to −128 ft. Then cased to −128 ft, cemented from top and bottom but pressured (to 400 psi) only at top.
6	1050	**17.1**	**80.4**				Slight gassy bubbling in casing; on cement; 19 hr after circulation.
	1620	16.9	81.6				24 hr after circulation.
7	0945	16.9	82.2				42 hr after circulation.
	1633	16.9	81.8				49 hr after circulation.
8	0757	**16.9**	**81.8**				64 hr after circulation; temperature considered very reliable even though in cemented hole. Drilled to −134 ft at 1534.
	1645	134.3	132.9	8	(+20)	**8½**	70 min after circulation.
	1700	134.4	133.3	8	(+19)	**8**	85 min after circulation.
9	1000	**134.4**	**134.4**	8		5	Then drilled to −164 ft (reported) at ~1430; pressure and discharge increased.
	1500	164.9	(132.5)	8		12¼	
	1515	164.0	(132.3)	4	(+29)	**12¼**	
	~1600						Cemented hole to replace leaky valve.
10	0752	**128.1**	133.9 } **133.7**	8			On cement.
	0807	128.1	133.6	4			No cement retained in hole from −141 to −164 ft (horizontally washed?).
	1622	219.0	(151.6)	4	(+40)	16½	Drilled to −219 ft at 1515; 1 hr after circulation ceased.
11	0741	**218.9**	160.9 } **160.9**	4		**16½**	All water overpressure.
	0753	218.9	161.0	8		16½	Then drilled to −289 ft at 1615.
	1632	286.2	(167.9)	4		17½	~½ hr after circulation ceased.
12	0730	**285.5**	171.7 } **172.1**	4	(+44)	**18½**	
	0748	285.5	172.4	8			Then drilled to −309 ft at 1530; much gas; surging pressure.
	1626	309.0	(167.9)	8		34 to 39	~1 hr after circulation ceased; valve leaking.
13	0902	**308.8**	174.3 } **174.8**	4	(+34)	**14** to 17	
	0917	308.8	175.3	8		14 to 23	No drilling May 13 or 14.
14	0927	**307.8**	(171.8; bumped?)	4	(+29)	**12** to 19	
	0954	307.8	173.3(?)	8		14½	Temperature lower than May 13 and 15?
15	0847	**307.4**	174.4 } **174.5**	4		13¼ to 16	Valve leaking so hole cemented; removed leaking valves and found adapter cracked.
			174.7	8		15	
16							Replaced adaptor and valve; drilled to −339 ft at 1630 but new valve would not close; cemented again.
17							Removed valve—seats had rotated; installed another valve, drilled to −354 ft at ~1400.
18	0733	350.0 } **349.9**	181.4 } **181.9**	4	(+34)	43 to **14**	After escape of gas; 4 ft of caved ground.
	0750	349.8	182.3	8		33 to 14¾	Gas accumulated rapidly, then bled off; drilled to −382 ft, when rods sheared off at −210 ft; all recovered.

See footnotes on facing page.

greater detail by White (1968, table 30, Sept. 12–13, 1950) in drill hole GS–4 at Steamboat Springs, Nev.

The relatively low temperatures recorded at −406 and −426 ft can also be explained by reversed circulation. The measurement at −458 ft, however, is more difficult to explain. Shortly before this measurement, AX casing had been installed to −449 ft and was cemented under pressure at top and bottom, thus eliminating this particular reversed circulation. Reversed circulation could have occurred outside the BX casing, with conductive cooling of water inside the casing.

An obvious alternative explanation is that one or two zones of real temperature reversal are related to inflowing water of lower temperature, similar to reversals recognized at Steamboat Springs (White, 1968, p. C51, C53). Sharp local reversals of this type are lacking in all other Yellowstone drill holes, and temperature profiles in the completed Y–2 hole failed to provide any suggestion of temperature reversals. The temperature of 192.2°C at −409 ft is so close to the projection of reliable data points of curve B above and below the questioned zones that real reversals seem unlikely. Because of the uncertainties, however, the predrilling ground temperatures from −380 to −480 ft cannot be affirmed from available data, and alternative trends in temperature are shown in figure 17.

SUMMARY OF DRILLING PROBLEMS

Y–2 proved to be the most difficult hole to drill. In contrast to our hopes, high wellhead pressure first became evident at −134 ft and was an increasingly serious problem with increasing depth, especially below −400 ft. This greatly exacerbated other drilling problems, which included valves that did not seat properly, casing that was difficult to emplace and cement, and couplings and drill rods that failed.

TABLE 8.—*Temperatures, pressures, and other observations from Y–2 (Firehole Lake) drill hole, Lower Basin* —Continued

Date and time 1967		Observation depth, ft[1]	Temp. °C[1]	Thermometer No.	Static water level, ft[1 2]	Wellhead pressure, psig[1]	Comments
May 19	~0800	**379.4**	186.8 } **187.3**	4		15¼ to 13½	
			187.8	8	(+31)	**13** to 13¾	Then drilled to −408 ft; rods sheared off again at about −230 ft.
20–23						55 to 106	Fishing difficult because of high pressure and temperature; attempted use of heavy mud without success and finally recovered lost string.
24	~0800	~**406**	168.6 } **168.7**	4	?	47	Some effect of gas accumulation on pressures and temperatures? BX casing then set to −408 ft, forced in under pressure with bottom length plugged.
			168.9	8		46	Cemented *only* at top, with cement forced between AX and BX casings, pressuring to 800 psig.
25							Drilled out cement plugs in top and bottom lengths of casings.
26		**409.4**	192.3 } **192.2**	8		30 to 15½	
		409.3	192.1	4	(+35)	**14½**	Steady pressure; wellhead water pressure? Drilled to −426 ft at 1540.
27	0615	425.3 } **425.9**	162.8 } **162.8**	4	?	80 to 64	Leakage of gas without water; gas accumulation effect.
		426.5	162.8	8		76	Uncemented bottom of BX casing spun off at −138 ft drilled through separated casing to −451 ft at 1340.
28	1400	~**451**	**166.3**	4		76	Slight down-pull on in-hole equipment below separation? Downflowing water accounts for low temperature?
		~451	**167.8**	4	?	77 to 63	Temperature remeasured with hole discharging slightly at top in attempt to reverse circulation, resulting in *higher* bottom-hole temperature.
29							Temperatures and pressures unreliable since 5/19, except for 5/26; decided to install AX casing.
31							Preparing for AX casing. Slight leakage of gas outside all casings first noted; then increased.
June 1						72	Temperature of dry gas leakage outside casing 93½°C, but seemed stabilized. Installed 449 ft AX casing under pressure with cement plug in bottom length, and through separated BX. Cemented top and bottom (plug drilled out) until pressured.
2	~1600				(+91)	**38** to 45	Drilled cement and new hole to −458 ft at 1500; pressure after drilling.
3	0700	**457.6**	**184.4**	4	(+86)	37 to **36**	Wellhead water pressure near 36 psig?
	~0730	457.6	181.8(?)	8		40 to 48	Cause of erratic temperature not known. Then drilled to −479 ft at 1430.
	1545	478.3	(176.0)	4		82	1 hr after circulation.
4	0950	**479.2**	(199.6)	4		58	First discharge all gas, then water and gas.
	1027	**479.1**	**201.1**	8		68 to 78	Hole then erupted to flush out drill water.
5	0725				(+100)	**42**	Initial fluid only water; wellhead water pressure?
	0740	**479.0**	203.1 } 202.8	8		46	
	0755		202.6	8		55	Drilled to −506 ft at 1625.
6	0840	~**505½**	**203.1**	8	(+100)	**42** to 46	Only water at first—water pressure? Erupted hole—water-steam changed to dry steam at 110°C and 8–12 psig. Drill rods vibrating and wearing rapidly; drilling terminated at −516 ft, 1300.
7	0820	**516.5**	203.1 } [3]**203.1**	8		60 to 57	
			203	1 (200–500°F)		59 to 128	Hole erupted through ½-in. vent; water and steam, changing to dry steam, maximum 128 psig (vapor pressure of 174½°C).
8	0828	**516.3**	201.0 } **201½**	8	(+134?)	**56**	
	0850		201.4	8		58 to 60	Bottom temperature definitely less than on 6/7.
			[3]202	1 (200–500°F)			
July 28	1630	(443)	[3](201½)	3 (200–500°F)		130 to 100	High-temperature upflow from bottom? Pressure rise to 130 psig maximum, then down to 100, leaking water.
Aug. 1		488				92	In-hole pressure 233 psia at −488 ft, or about 30 psi of overpressure relative to curve A, figure 18.
June 27, 1968		515	201.1		(+132?)	**55** up to 130	Thermistor series, plotted on figure 17. Some leakage during measurements; see text for probable effect.
Sept. 20, 1969						214	Initial wellhead pressure, with vapor in casing to about −449 ft.
		517				214 to 128	In-hole pressure 158 psig.
Sept. 23, 1969		**515**	**204.2**	12		82 down to 75, steady	Hole degassed 9/22 and early 9/23 to insure maximum water in hole; negligible leakage during series by maximum thermometer. Data points plotted on figure 17. After series, hole filled with 12 sacks cement, pressured to 200 psi.

[1]Data in boldface considered most reliable, data in parentheses, least reliable.
[2]Relative to ground surface; positive levels in parentheses calculated from wellhead pressures considered to be water pressures least affected by vapor.
[3]Pressure-corrected.

The drill crew, contractor, and scientists had not yet devised equipment and procedures to correct equipment failures while controlling high-pressure fluids at all times. A new expensive type of high-pressure valve proved to have seats that rotated out of correct position because of friction from the drill rods (table 8, May 15 comment). Because of the possibility of pollution, we were reluctant to use lubrication on drill rods; consequently, wear on the drill rods was excessive, and the rods sheared off twice in quick succession (May 18 and 19). Fishing for the lost string was difficult, especially after the second loss when wellhead fluid pressures ranged from 55 to 106 psig. On May 24 BX casing with a wooden bottom plug was successfully emplaced; after drilling out the plug, the casing was hung in the hole but was not cemented at the bottom. With further drilling and friction of rotating rods on the top-cemented casing, a spinoff of most of the casing string occurred on May 27. AX casing was then emplaced through the separated section and was cemented at top and bottom under pressure; as we shall see, postcompletion measurements indicate that cement does not fill much of the space between the AX and BX casings at intermediate depths, or between the separated BX casing and the surrounding rocks.

MEASUREMENTS IN COMPLETED HOLE AND INTERPRETATION

Postdrilling temperature and in-hole pressure measurements are summarized in table 8 and figures 17 and 18. These measurements were complicated by the fact that permeability around the open hole below the AX casing was so low that even slight discharge or leakage through our gear at the surface was only slowly replaced by new inflow.

A series of thermistor temperature measurements made on June 27, 1968 (see table 8 and curves C–1 and C–2, fig. 17) demonstrates the drastic changes in temperature and wellhead pressure that occur where permeability is so low. Initial leakage from pipe fittings was nearly all liquid water (estimated as a few gallons in total), but wellhead pressure increased from 55 to 130 psig during the series. Temperatures were first measured proceeding down the hole (fig. 17, curve C–1) and then, to check the effects of leakage and increasing pressure, temperatures were measured from −276 ft up to the surface (curve C–2). Differences between the two curves raised questions about the magnitude of changes that presumably occurred immediately before and during the initial series; these questions could not be answered immediately because our thermistor soon failed.

The thermistor gear was again inoperative when needed for Y–2 in 1969, but a few temperatures measured at selected depths by maximum thermometer on September 23 (indicated by X's on fig. 17) provided some confirmation for the qualitative reliability of curve C–1. An improved packing gland and revised procedures for securing the pressure chamber to the wellhead prevented leakage from the unthreaded joints and from around the thermometer cable, except for an estimated quarter gallon that escaped each time the thermometer was removed. Total leakage of water from the hole during the temperature series was estimated as less than 3 gallons. Much accumulated gas had been discharged during the in-hole pressure measurements made 3 days earlier, and additional gas was discharged on September 22 and early in the morning of September 23. Accordingly, at the beginning of the maximum thermometer series about 2 hr later on the 23d, the hole was nearly filled with liquid water. Initial water level was about −17 feet, as estimated by changes in surface fluid pressure from 82 to 75 psig as the temperature series was made. Upflow into a cooler environment accounts for the modest decrease in temperature from 84°C (first entry) to 67.5°C (final entry).

Thus, the C–1 thermistor temperatures are concluded to be near but not identical to rock temperatures immediately adjacent to the hole on June 27, 1968, and thus are as much as 52°C higher (at −45 ft) than our best data for predrilling ground temperatures. We conclude that these large increases resulted from upflow of high-pressure water outside the imperfectly cemented AX and BX casings during the year after the hole was completed, and that the C-series of temperatures measured on June 27, 1968, cannot be close to original ground temperatures. This is clearly indicated by measurements near −77 ft, where a reliable temperature close to 107°C was obtained as drilling progressed; the water level at the time was about 3½ ft below the ground surface. In contrast, the postdrilling temperature of about 150°C near the same depth demands a static water level at least 68 ft above ground level, equivalent to a wellhead water pressure of about 28 psig.

Our best estimate of the maximum water pressure originally present in rocks penetrated by Y–2 is about 40 psi above reference pressure curve A of figure 18. The wellhead pressure measured on June 5 and 6, 1967, with water at the top of the hole, was 42 psig. The in-hole temperature of 202.8°C measured on June 5, 1967 (point A of fig. 18 at a drilled depth of 79 ft) demands a water-vapor pressure of 239 psia. This pressure is shown as point B on figure 18. With respect to the reference boiling pressure curve, point B is overpressured by about 40 psi.

The C–1 thermistor series of June 27, 1968, if accepted as approximating existing temperatures at the time in rocks adjacent to the hole, is interpreted as follows:

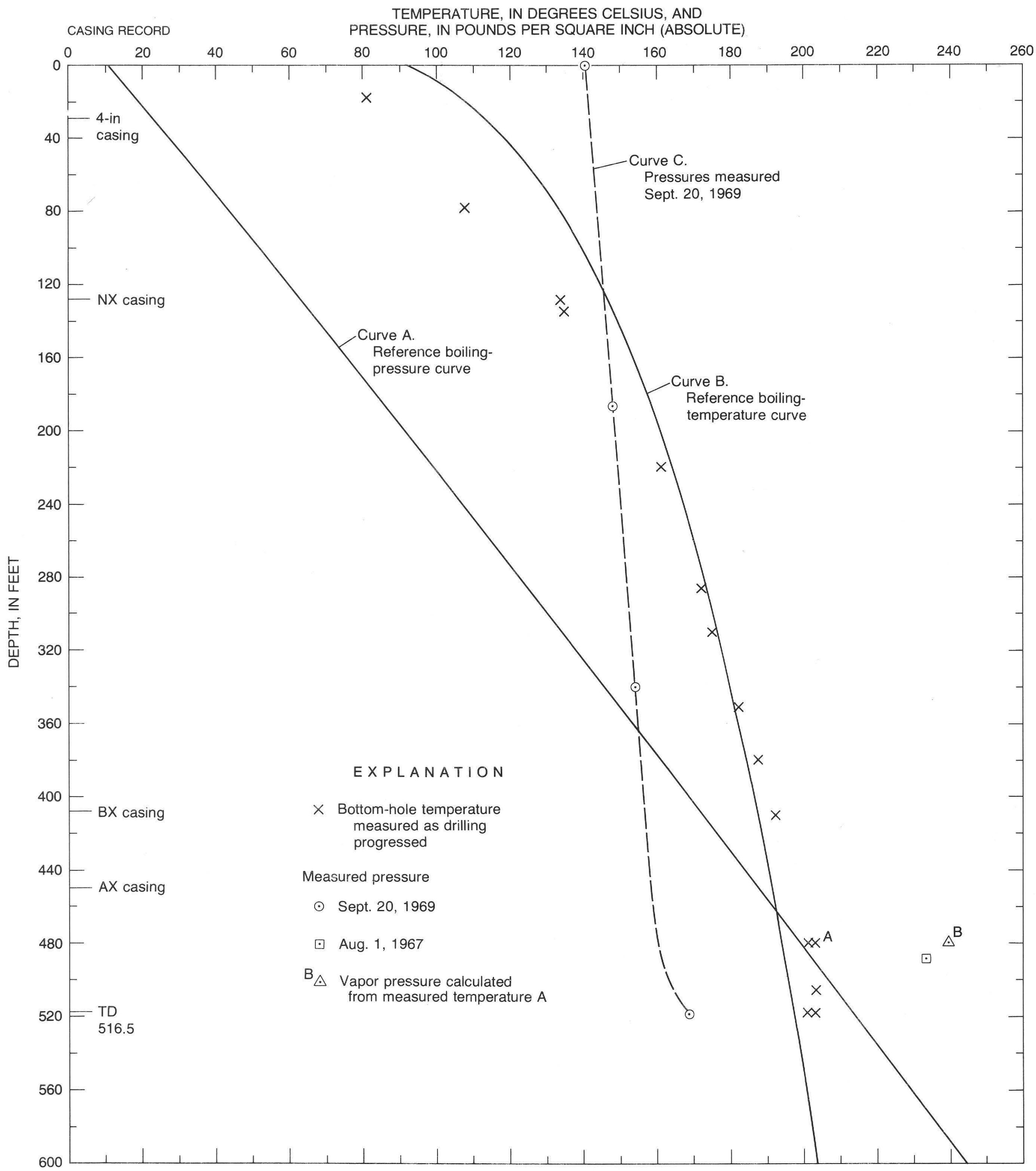

FIGURE 18.—In-hole pressures of Y–2 drill hole after completion, compared with other data.

The nearly constant but nonvertical slope of the curve from about −230 ft to the bottom of the hole suggests that hot water is flowing up inside the BX casing and is boiling as pressure decreases upward. At the break in the BX casing near −230 ft, liquid and vapor separate. The liquid fraction flows down outside the casing to produce uniform temperature changes in all fluid fractions, reflected in the uniform slope and not evident in original bottom-hole temperatures as drilling progressed. Upflow above the bottom of the NX casing at −128 ft probably does not occur within the cemented hole but is more likely to occur in adjacent rocks up to the high-permeability zone of lost circulation from about −50 to −90 ft. Wellhead water pressures in the latter zone are likely to have changed from about −1.4 psig (initial) to at least +15 psig; the latter is required by the 148°C measured at −89 ft on September 23, 1969 (fig. 17).

The in-hole pressure measurements of September 20, 1969 (fig. 18), when the hole was initially nearly filled with vapor at a wellhead pressure of 214 psig, demonstrate the effects of low permeability. Point B of figure 18, calculated from a measured temperature, is at least 40 psi above reference pressure curve A, but the bottom-hole pressure of September 20 was only 158 psig, and the actual pressure gradient of curve C was much less than that of curve A. Evidently, the leakage of fluid from the hole before and during this series of measurements resulted in boiling, cooling, and transfer of heat from the rocks to the limited available water; the permeabilities of the rocks are so low that inflow into the hole was less than losses by leakage (not measured, but low).

The significant physical changes induced by the drilling of this hole, with its faulty casing and cementing, were entirely unanticipated and, in fact, could not have been prevented after the AX casing was emplaced and cemented. The temperature changes also indicate that having casing in a hole does not guarantee original rock temperatures because short-circuited flow paths may occur outside the casing. The record of Y–2 is considered here in some detail because it provides dramatic evidence of the consequences of inadequate techniques in drilling high-pressure areas.

A slight but detectable leakage of gas around the casing into our concrete box provided the basis for cementing and abandoning the hole on September 23, 1969, even though further scientific study was desirable. The cementing stopped most but not quite all of the gas leakage, but the upflow of hot water at high pressures responsible for the leakage should eventually become negligible through deposition of silica, decreasing permeability by the self-sealing process. By July 1971 the flow of gas had almost completely ceased.

Y–3 (OJO CALIENTE) DRILL HOLE

SITE SELECTION

Major objectives of Y–3 were to clarify subsurface relations near the Pocket Basin hydrothermal explosion crater of late Pleistocene age (Muffler and others, 1971) and to obtain general information on the stratigraphy and distribution of temperatures in Lower Basin, the largest of Yellowstone's geyser basins. Y–3 also was the closest permissible site to the western part of Lower Basin. The specific site was next to a parking area (since relocated) about 1,000 ft west of the Pocket Basin explosion crater and about 250 ft northwest of and 7 ft above the largest spring of the area, Ojo Caliente.

PHYSICAL MEASUREMENTS AS DRILLING PROGRESSED

Physical data from Y–3 are shown in table 9 and figures 19 and 20. Good data were not obtained in the shallow zone to −140 ft because drilling was rapid and was complicated by the setting of two strings of casings. Thereafter in this and in other holes we generally limited drilling to about 50 ft per day to insure a better record of temperatures and pressures. Our experience at Y–3 demonstrated that at least one good set of data, uncomplicated by the setting of casing and cementing, is essential at depths from about 20 to 90 ft, and two sets of good data are very desirable.

Temperatures in Y–3 increased so rapidly that the hole erupted from −90 ft when only 32 ft of 4-in. casing was in the hole. The temperature at −90 ft was not measured, but it was probably above reference temperature curve A, with a corresponding high wellhead water pressure to account for the high eruption potential. Temperatures from −90 to −140 ft cannot be deciphered with certainty from our data, but below −140 ft they increased steadily to near the bottom of the hole (fig. 19, curve B).

No reliable data concerning static water levels were obtained as drilling progressed, generally because gas accumulated rapidly in the casing. Wellhead water pressure of the aquifer near −100 ft is at least 6 psig (table 9, June 13, 1967). At greater depths, wellhead pressures during measurements of temperature commonly ranged from 30 to 40 psig, but at these pressures gas was always the dominant escaping fluid. A few measurements obtained when discharge from the gear was mostly water suggest that water overpressures were near 18 to 22 psig at depths of −220 to −450 ft, and then decreased to about 16 psig near the bottom of the hole.

SUMMARY OF DRILLING PROBLEMS

Because drilling from −32 to −90 ft was easy and fast, no temperatures were obtained and we had no warning of the very high temperature gradient and eruption potential. When eruption did occur from −90 ft, our planned NX casing was not yet in the hole, and the drill chuck was not large enough to accept pipe of such large diameter. With much difficulty the casing was manually forced down by winch into the erupting hole, and the drillers used gear for protection from the hot water. Fortunately, the first casing string to −32 ft proved to be well cemented and adequate.

TABLE 9.—*Temperatures, pressures, and other observations from Y–3 (Ojo Caliente) drill hole, Lower Basin*

Date and time 1967		Observation depth, ft[1]	Temp. °C[1]	Thermometer No.	Static water level, ft[2]	Wellhead pressure, psig[1]	Comments
6/8	1540	22.7	(23.5)		(−1.3)		Drilled to −32 ft at 1520; 20 min after circulation. Then cased to −32 ft, cemented.
6/9	0745	**25.1**	**59.5**		(−1.9)		In cemented hole. No reliable water level data but best estimate −8 ft to depth of −70 ft, with some lost circulation. Drilled to −90 ft at 1430, when hole erupted; controlled with difficulty.
	2000	**79.4**	**131**	4	−8 ?	26½	
6/10	0730	79.1	132.4 } **132.4**	4		35 to 32	After measurements, set 3-in. casing to −90 ft through erupting hole; cemented by 1330.
		79.5	132.3	8			
6/11	1400	17.1	(60)				In cemented hole, but temperature still decreasing from eruption—see 6/12.
6/12	0745	**17.1**	**54**				42 hr after hole cemented; temperature probably good. Drilled out cement to −86 ft.
6/13	0800	(84.7)	(93.3)				On cement; why is temperature so low? Drilled to −135 ft at 1335.
	1355	(127)	(138.3)	4	(>14)	6	Wellhead water pressure 10 min after circulation; hole not yet heated.
6/14	0740	**124.6**	140.1 } **140.1**	4		36 to 38	Some gas accumulation; hole caving; attempted cementing, but only 2½ sacks, not pressured.
	0755	**124.6**	140.0	8		39	
	1145	102.4	140.0			21	On cement 2 hr after circulation. Temperature at least 140°C. Drilled out cement; then to −144 ft at 1645.
6/15	0745		140.1 } **140.1**	4		31	Much gas. Hole has caved 8 ft. Drilled to −184 ft at 1420. Started leaving drill rods in hole overnight.
	0800	**136.0**	140.1	8		31	
6/16	0738	**184.6**	153.3 } **153.3**	4		30 to 31	Much gas.
	0750	184.6	153.4	8		32	Then drilled to −224 ft at 1630.
6/17	0752	224.2 } **224.1**	**164.2**	4		32	Much gas.
	0807	223.9	(161.8)	8		32	Then drilled to −256 ft at 1530.
6/18	1032	(195.4)	(160.0)	4	(+44)	22 to **18½**	Wellhead water pressure ~18 psi; ~60 ft off drilled bottom; caving. Temperature unreliable.
	1041	(196.3)	(160.0)	8		19	
	2100					30	Gas and water.
6/19	0740	(142.6)	(151.1)			36 to 21	Upflow of hot water thru 113 ft of caved fill?
	2045	**264.7**	**172.2**	4	(+45)	**19**	6 hr after drilling to −274 ft; wellhead water pressure; temperature fairly reliable.
6/20	0750	264	(162.8)	4		62 to 42	Gas; thermometer snagged, temperatures less reliable than 6/19 p.m.
	0755	**264**	(170.0)	8		38 to 37	Thermometer snagged. Drilled to −309 ft at 1600.
	2105	307.7 } **307.7**	176.7 } **177.0**	4		44 to 39	Much gas; 5 hr after circulation.
	2112	307.7	177.2	8		41 to 40	
6/21	0745	**307.7**	176.7 } **177.0**	4		52 to 44	Gas accumulation; cemented to −106 ft and drilled out, with open hole found below −147 ft.
	0803	307.7	177.2	8		45 to 46	
6/22	0742	**307.0**	176.7 } **176.7**	4		42 to 38	Then drilled to −354 ft at 1600; only ~1/5 drill water returned during day.
	0809	307.0	176.7	8		38	
	2035	352.7	(180.0)	4	(+53)	26 to 22	~4 hr after circulation; thermometer snagged; some gas accumulation so wellhead water pressure ~22 psi.
6/23	0734	**352.2**	**185.6**	8		38 to 36	Gas and water. Then drilled to −399 ft at 1525; about 30 percent of drill water returned.
6/24	0723	(141)	(150.6)	4		57	Gas and water. Hole blocked at −141 ft; drilled to −444 ft at 1435; low water return all day.
	2122	**441**	193.3 } **193.3**	4		71 to 22	Gas and water; 6 hr after circulation stopped. Wellhead water pressure ~22 psi?
	2138	440	193.3	8	(+53)	**22**	
6/25	0956	441	(191.1)	4		72 to 42	Gas and water.
	1018	**441**	**194.4**	8		46 to 47	Gas and water; best temperature.
6/26	0739	438	(189.5)	4		56 to 38	Gas to gas and water.
	0758	**438**	**193.3**	8		44 to 43	Gas; then drilled to −494 ft at 1545.
	2113	494.7	(194.5)	4		37 to 39	Gas and water ~5 hr after circulation.
	2132		**196.0**	8		39	Very gassy water.
6/27	0745	493.8	(193.4)	8		59 to 49	Gas and water; thermometer snagged.
		493.7	**195.6**	8		58 to 51	Gas, no water out. Then drilled to −514 ft at 1445.
6/28	2110	125.6	(149.5)	4		56	Caved to −126 ft—Ojo Caliente started geyser eruptions.
7/16/68							BX casing hung in hole to −200 ft, tight below −128 ft, to clear blockage and to terminate interference with Ojo Caliente.
7/19/68		514.9	**173.4**	14	(+38)	**16** to 22	16 psi wellhead water pressure? Pressures then increase with slight leakage during series. Data of curve C, fig. 19, measured with maximum thermometer (thermistor cable inoperative); temperatures below −277 ft suggest reversed circulation.
9/25/68		158.5	159.6			32 to 34	Thermistor series of temperature measurements. Data shown in curve E, fig. 20. Thermistor failed below −158.5 ft.
9/17/69		512				35 to 40	Bottom-hole total pressure was 217 psia, indicating water overpressure of only about 6 psi, curve D, fig. 20.
9/23/69		512	**189.6**	12		41 to 29	Temperature series, maximum thermometer (see fig. 19, curve D); casing leaking below main valve so 11¼ sacks cement pumped in hole.

[1]Data in boldface considered most reliable; data in parentheses, least reliable.
[2]Relative to ground surface; positive levels in parentheses calculated from wellhead pressures considered least affected by vapor.

Very permeable caving ground from −90 ft to about −138 ft continued to cause serious problems during the drilling of the hole (and throughout the next 2 years). With hindsight, we realized that BX casing should have been set to −150 ft in the initial drilling, but having been forced to case at −90 ft, we were reluctant to case again so soon. Instead, we attempted, unsuccessfully, to control the caving by pumping cement down the hole into surrounding ground.

After the hole was completed at −514 ft and the drill rig was dismantled, caving prevented measurements at depths below −126 ft. Also, on the day after removal of the rig, Ojo Caliente, although having no previous record of geyser activity, started to erupt as a geyser. Almost certainly this change in activity was caused by flow of water and steam up Y–3 to the permeable zone from −90 to −138 ft, and then laterally to the hot spring. The cooling effect of drill water probably explains why Ojo Caliente did not erupt during the middle and late stages of drilling, but we had looked for specific evidence (such as turbidity) that drill water was entering the spring and failed to detect any.

In the early summer of 1968, Y–3 site was reoccupied and BX casing was hung in the hole to a depth of −200 ft in order to clear the persistent blockage near −126 ft and to terminate or dampen any influence of Y–3 on Ojo

Caliente. With difficulty the casing was forced down through the caving zone. Ojo Caliente is not known to have erupted as a geyser since this casing was emplaced.

During the following year a leak developed between the BX casing and the main valve. In September 1969 we applied a temporary clamp to shut off the leakage and then filled the hole with cement.

POSTDRILLING MEASUREMENTS

Postdrilling temperature and pressure measurements could be made in the lower part of Y–3 only after the BX casing was hung in 1968 to make the hole accessible. Our thermistor equipment failed on September 25, 1968 (curve E, fig. 20) and was inoperative during most of 1969, so a detailed temperature profile was not obtained throughout the completed hole. However, two maximum-thermometer series were obtained; the series of July 19, 1968 was measured only 3 days after the BX casing was installed and is shown as curve C of figure 19 and C of figure 20; a second series measured 14 months later is shown as curve D of figure 19. The thermistor series of September 25, 1968 (curve E, fig. 20) tends to confirm the zone of nearly constant temperature suggested by the bottom-hole temperatures (curve B, fig. 19) at about −140 ft. The postdrilling maximum-thermometer series C and D of figure 19 are similar down to about −180 ft, but the spacing of data points is too wide to detect the zone near −140 ft. Curve C (fig. 19) showed an unexpected decrease from original ground temperatures (curve B) at depths below about −260 ft, where measured temperatures were nearly identical (173.3°C, 173.4°C, 173.4°C) at three different depths. We suggest that cold water introduced into the hole just before the BX casing was installed may have cooled the hole enough to induce a downward flow of relatively dense (cooler) water from an aquifer near −260 ft (and overpressured by 18 to 22 psi) into an aquifer of lower overpressure (16 psig) but of initially higher temperature near the bottom of the hole. Significantly, the in-hole pressures measured on September 17, 1969 (table 9) indicated a bottom-hole water pressure of only 6 psig (fig. 20, curve D). Presumably the downflow in response to this pressure gradient con-

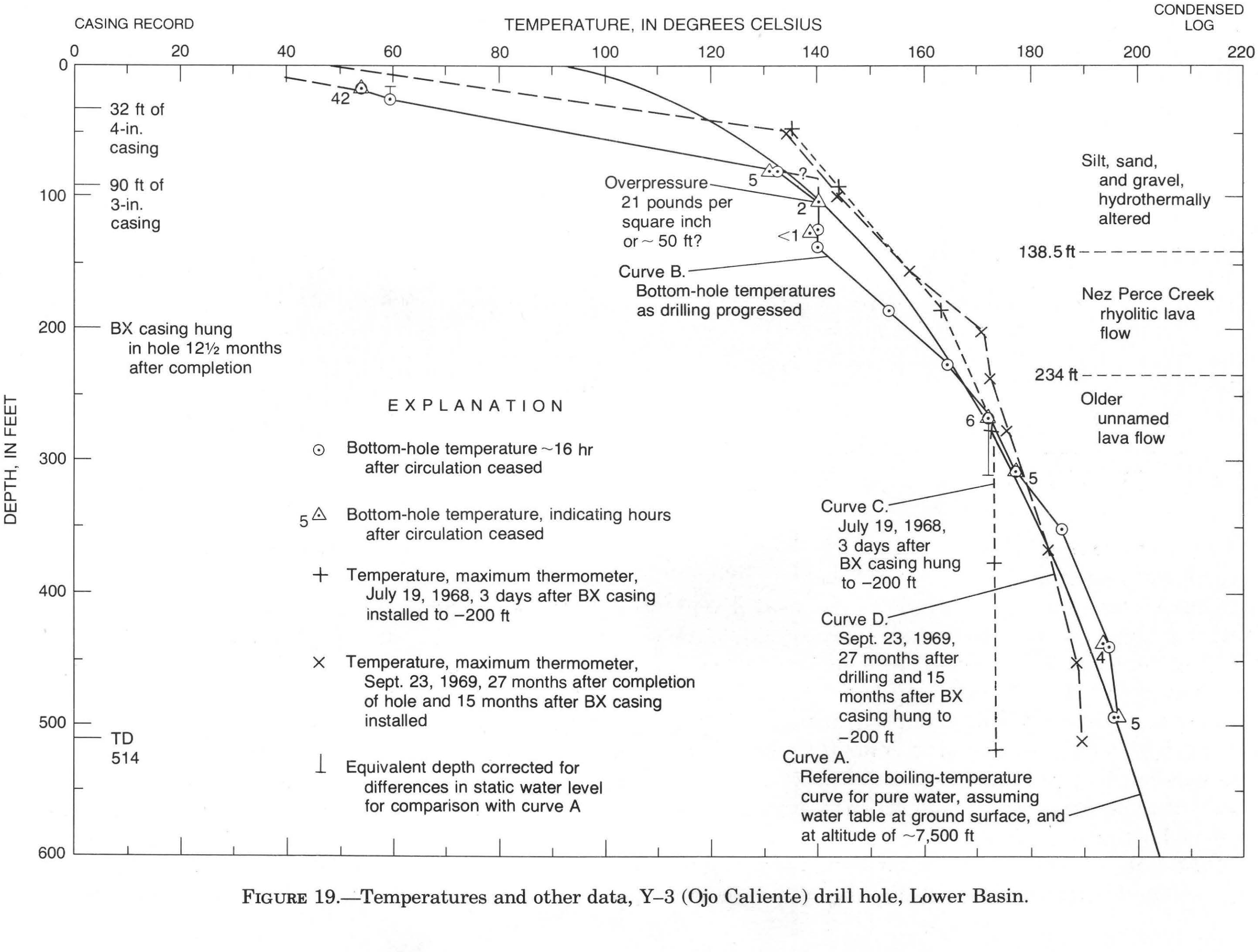

FIGURE 19.—Temperatures and other data, Y–3 (Ojo Caliente) drill hole, Lower Basin.

tinued for many days or weeks, being supplied by water near −260 ft at a temperature near 173°C.

The hypothesized downflow, if real, decreased in rate with time. By September 1969 (curve D, fig. 19), temperatures near the bottom had increased significantly, but were not yet as high as predrilling ground temperatures (curve B, fig. 19).

Gas leaked from the hole before and during the in-hole pressure measurements of curve D, figure 20. The low pressure gradient between −260 ft and the bottom

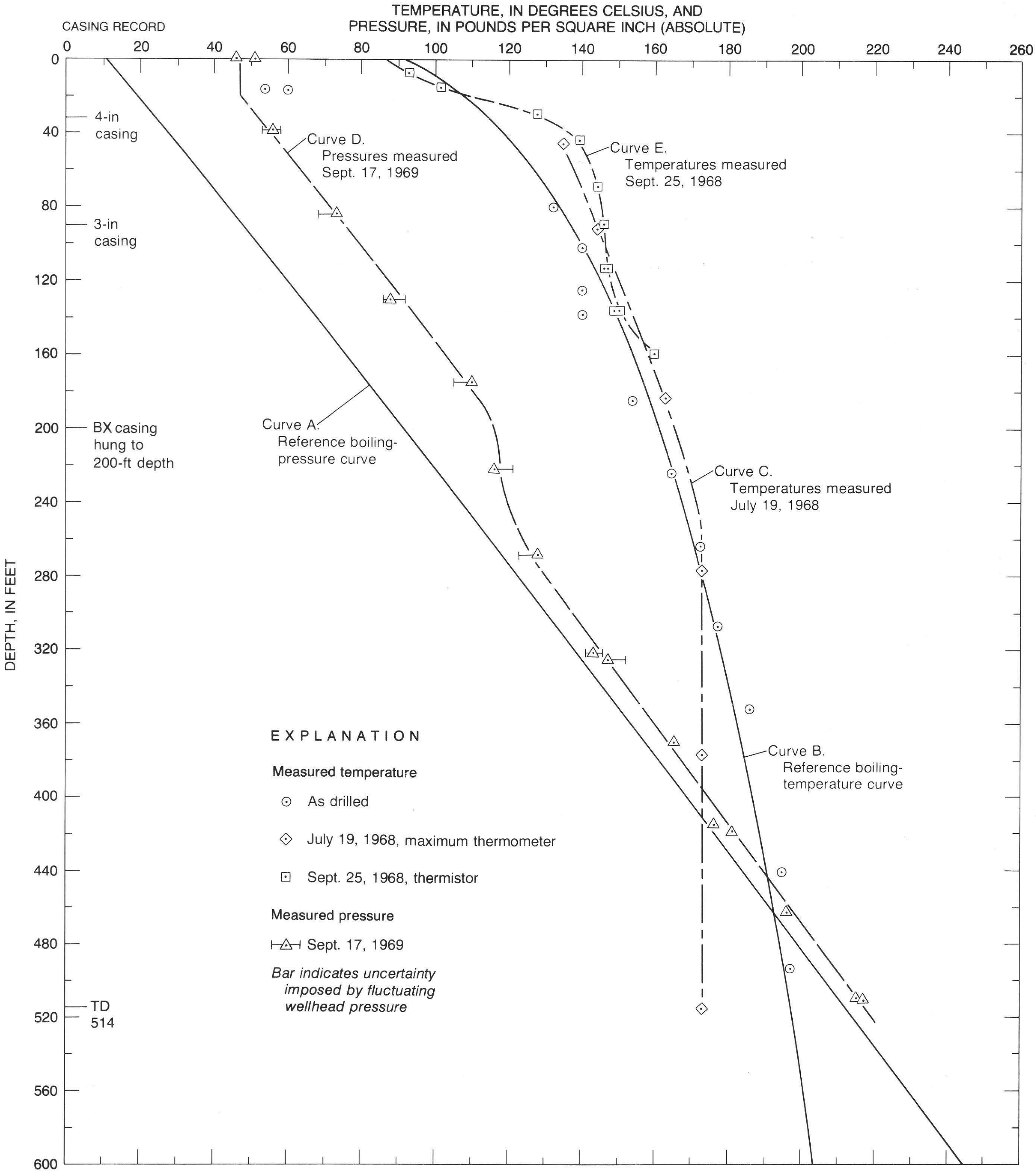

FIGURE 20.—In-hole temperatures and pressures of Y-3 drill hole after completion.

of the casing at −200 ft clearly shows that vigorous boiling was occurring throughout the interval. Presumably at −200 ft the steam either condensed or, more probably, was diverted outside the casing. Noncondensable gas filled approximately the upper 20 ft of the casing. During the measurements sudden changes in wellhead pressure of about 5 psig occurred, suggesting uneven flow in the system, probably from the zone near −260 ft.

Y–4 (NEZ PERCE) DRILL HOLE

SITE SELECTION

Y–4 was selected as the best accessible site on the bedrock margin of Lower Geyser Basin at an appreciable distance from prominent surface activity, in order to gain a better understanding of the borders of major geothermal systems. The site is in an abandoned gravel quarry where several feet of glacial gravels were removed many years ago and the underlying rhyolitic bedrock, the Nez Perce Creek flow, was exposed (R. L. Christiansen and J. D. Obradovich, written commun., 1974; age ~140,000 yr). A service road with a locked gate provided the isolation we and National Park Service officials desired for our activities during the 1967 mid-summer tourist season. The site is in a mature strand of lodgepole pines that show no evident effect from any thermal activity. The drill collar is about 30 ft above Nez Perce Creek and 650 ft N. 21° W. of the nearest known thermal spring, which is on the north bank of the creek. This spring is an inconspicuous feature with seeping discharge and a temperature of 44°C.

A secondary objective was to clarify the subsurface volcanic stratigraphy, but the hole served only to demonstrate the great thickness and lack of internal structure of the Nez Perce Creek lava flow.

PHYSICAL MEASUREMENTS AND INTERPRETATIONS

Physical data obtained from Y–4 are shown in table 10 and figures 21 and 22. The temperature gradient is linear to about −250 ft, where the first significant fluid flow occurs in an iron-stained zone between −249 and −251 ft. Upward projection of this constant gradient

TABLE 10.—*Temperatures, pressures, and other observations from Y–4 (Nez Perce Creek) drill hole, Lower Basin*

Date 1967	Time	Observation depth, ft[1]		Temp. °C[1]		Thermometer No.	Static water level, ft[1 2]	Wellhead pressure, psig[1]	Comments
6/30	0930								Started drilling, bedrock floor of old gravel quarry; drilled to −21 ft, installed and cemented 4-in casing.
7/1									Drilled out cement, new hole to −55 ft at 1530.
7/5	0800	**49.7**		**29**			**−17.8**		After 3½ days rest; then drilled to −95 ft at 1545.
7/6	0800	(45)		(26)			−18.0		Thermometer snagged on bit? Then drilled to −121 ft at 1345; installed and cemented 120 ft NX casing, 8 sacks cement, not pressured.
	~1400	121					−17.7		
7/7									Drilled out cement; new hole to −149 ft at 1525.
7/8	0745	**148.7**		**73.9**			−19.0		Then drilled to −204 ft at 1515.
7/9	1000	**203.4**		**99.3**		4	−19.9		
7/10	0748	203.8		(95.0)		18	**−19.8**		Thermometer snagged near −175 ft coming out; could not get back down. Drilled to −259½ ft at 1600.
7/11	0735	**258.9**	**259.0**	122.6	**122.5**	4	−20.2		Then drilled to −304 ft at 1545.
	0755	**259.2**		122.3		8			
7/12	0714	303.5	**303.4**	128.9	**128.9**	4	−20.5		Then drilled to −351 ft at 1540; losing some drill water.
	0729	303.2		128.9		8			
7/13	0715	350.5	**350.5**	143.6	**143.6**	4	−21.9		Then drilled to −380 ft at 1540, with increasing loss of drill water.
	0731	350.5		143.6		8			
7/14	0728	379.6	**379.6**	149.0	**149.0**	4	−22.0		Then drilled to −424 ft at 1555, with almost no water return.
	0740	379.6		149.1		8			
7/15	0718	**423.4**		159.9	**160.0**	4	−22.3		Then drilled to −454 ft at 1440.
	0735			160.2		8			
7/16	0917	**451.2**		166.8	**166.8**	4	−21.9		
	0933			166.9		8			
7/17	0730	**451.1**		167.6	**167.6**	4	−20.7		Note 1.2-ft rise in water level from heating of hole; then drilled to −514 ft at 1540 with ~15 percent water return.
	0749			167.7		8			
7/18	0730	**513.2**		172.0	**172.2**	4	−21.9		Then drilled to −561 ft at 1545, with poor water return.
	0745	~514		172.3		8			
7/19	0715	560.4	**560.4**	179.9	**180.2**	4	−21.8		Then drilled to −597½ ft at 1440, with fair water return.
	0732	560.4		180.4		8			
7/20	0720	(579.7)		(168.9)		4	−20.1		Core barrel left in rods.
	0828	**596**		**182.8**		8			After core barrel removed. Then drilled to −611½ ft at 1445.
7/21	0712			(177.8)		4	−21.8		Bumped at drill bit; unreliable.
	0748	(608.1)		(181.6)		4			Bumped, unreliable; then drilled to −641 ft at 1520.
7/22	1005	**640.8**		**188.4**		8	−21.9		Temperature after core barrel retrieved. Then drilled to −691 ft; first positive pressure (and pyrite) near −680 ft. Pressure much greater downward.
7/23	~1000	(141.5)		(168.4)		4	(+190)	**79½**	All water pressure; hole blocked at −141.5 ft. Note effect of water flow up hole, increasing temperature at −141 ft about 96°C above original.
7/24	0800	(141.5)		(166.7)		4	(+189)	**79**	Hole still blocked. Hole then erupted and successfully cleared. Probably best indication of maximum over-pressure prior to drilling—79 psi.
	0906	**690.5**		**195.6**		4		80½	All water pressure. Drilling terminated.
7/25	1128	689.0	**689.1**	195.5	**195.8**	4	(+202)	**84**	All water, no gas.
	1155	689.1		196.1		8		84½	All water, no gas; top temperature 27°C.
7/29	1400	**690.0**		**193.9**		4	(+208)	**87**	All water, no gas; note temperature decline.
10/22		**690.2**		188.9(?)		11	(+216)	**90**	All water, no gas; bottom pressure 366±3 psia; calculated natural over-pressure at bottom 76 psi.
6/14/68	1100	686						94 to 96	Thermistor temperature series, curve C, figure 21.
7/9/69		690					(+216)	**90** to 94	Bottom pressure 363 psia; calculated overpressure at bottom, 75 psi.
9/17/69		688					(+216)	**90** to 94	In-hole pressure series, curve E, figure 22. Bottom pressure 363 psia. Calculated overpressure at bottom 75 psi.
5/24/70		685						93 to 94	In-hole pressure series, curve E, figure 22. Bottom pressure 363 psia.
9/24/71		685		193			(+218)	**91** to 94	In-hole thermistor and pressure series (curves C and E, fig. 22). Bottom pressure 361 psia.
				194.2		12			

[1]Data in boldface considered most reliable; data in parentheses, least reliable.
[2]Relative to ground surface; positive levels in parentheses calculated from wellhead pressures considered to be least affected by vapor.

through the dense homogeneous lava to the ground surface suggests a mean annual surface temperature of ~6°C.

A second segment of lower but nearly constant gradient extends from −250 to −450 ft, with minor variations that are related either to very slight flow or to errors in measurement. A third segment, also of nearly constant gradient, extends from −450 ft to the bottom of the drill hole at −691 ft.

Fluid pressures were nearly constant to a depth of −650 ft, with measured depths to water ranging from −17.8 to −22.3 ft (table 10). The tendency for the depth

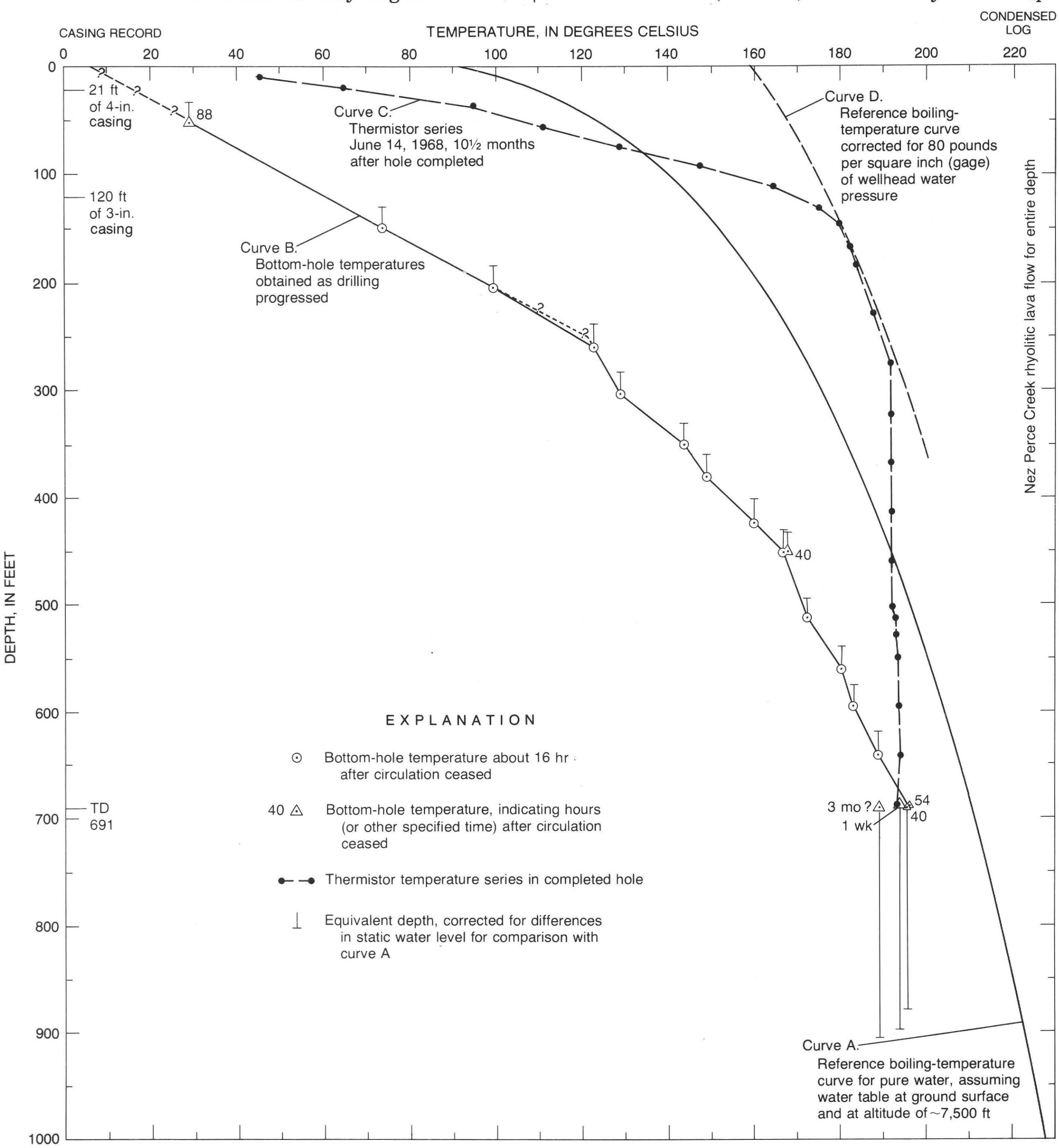

FIGURE 21.—Temperatures and other data, Y-4 (Nez Perce) drill hole, Lower Basin.

to water to increase slightly as the drilled depth increased is mainly related to the cooling effects of drill water over an increasing depth range. Rocks high in the hole had been cooled by days or weeks of intermittent drilling, and in the absence of upflow from hot aquifers, original ground temperatures did not recover rapidly. Note, for example, the rise in water level of 1.2 feet from July 16 to 17 (table 10) while drilled depth remained constant and the bottom-hole temperature increased only 0.8°C. This rise in water level must have been due largely to thermal expansion of water at intermediate levels in the hole in response to conduction of heat from the walls.

The first major change in fluid pressure became evident when the core barrel was retrieved from −681 ft and water rose for the first time above ground level. The actual change probably started to occur during the previous run near −679 ft, where the shallowest fresh

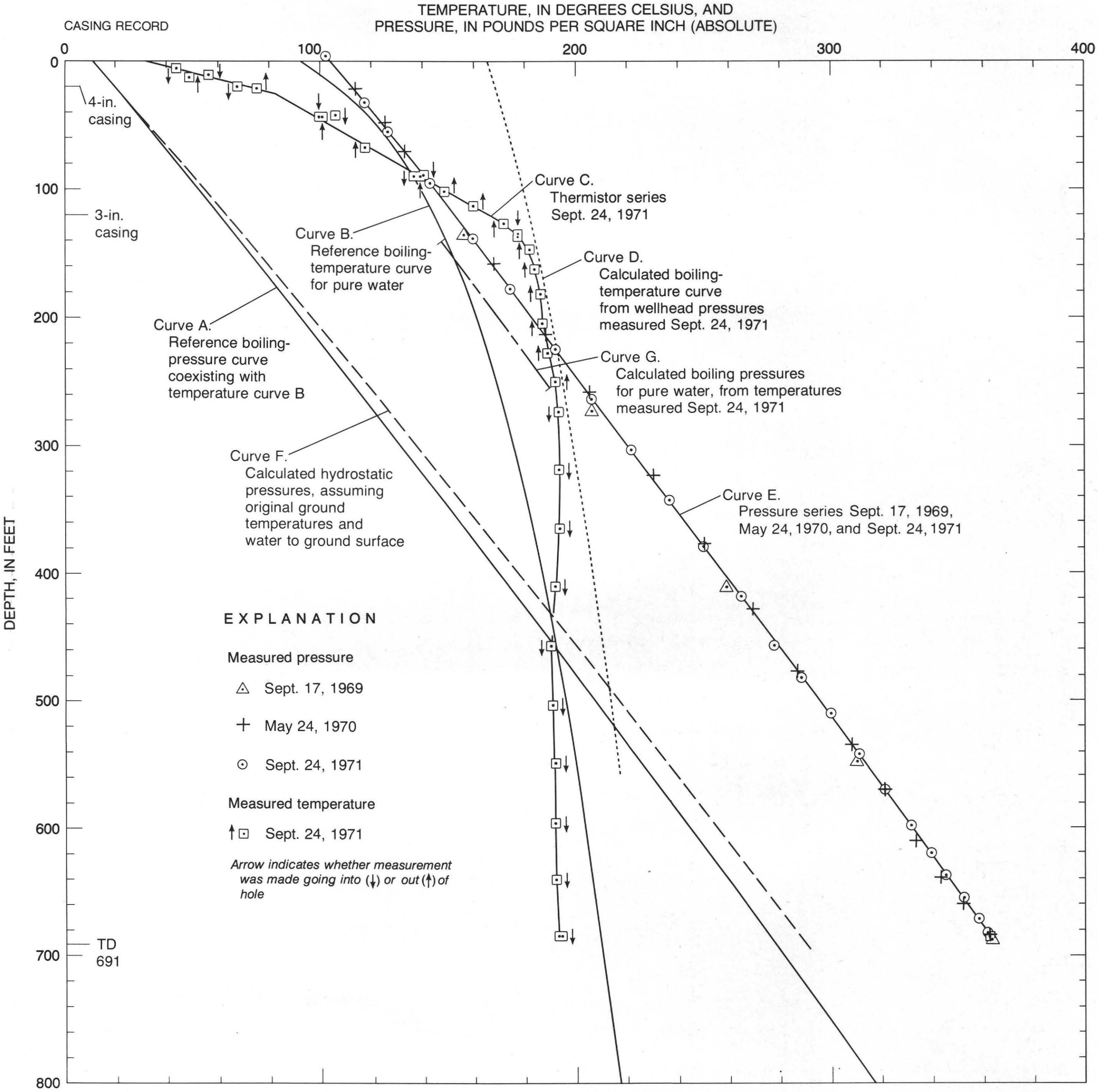

FIGURE 22.—In-hole temperatures and pressures of Y–4 drill hole after completion, compared with other data.

pyrite found in the hole occurs in fractures in drill cores. At −691 ft, nearly 80 psig was measured at the surface (table 10). The static water level had increased from about −22 ft at −641 ft to the equivalent of about +190 ft at −691 ft, and the hydraulic gradient through this 50 ft interval averages 4¼ ft of water per foot of depth; between −671 and −691 ft the probable average gradient is close to 11 ft of water per foot of depth. Such hydraulic gradients are possible only in rocks of extremely low permeability. The temperature record provides no evidence for any predrilling upward flow of fluid from the high-pressure aquifer near −681 ft. This aquifer obviously communicates with deeper levels of much higher pressure, but not with the surface.

SUMMARY OF DRILLING PROBLEMS

Y–4 was one of our easiest holes to drill. By July 1967 the drill crew was experienced in handling many difficult problems, and satisfactory methods and equipment had been developed to drill into relatively high-pressure environments. However, the high pressures suddenly encountered near −680 ft forced us to terminate drilling at −691 ft. At this depth the wellhead water pressure of about 78 psig was exceeded in only one other drillhole (Y–13).

POSTDRILLING MEASUREMENTS

Two series of temperature measurements were made in Y–4 using thermistor equipment. The first was on June 14, 1968, 10½ months after completion of the hole (curve C, fig. 21) and the second on September 24, 1971 (curve C, fig. 22). These curves clearly indicate that Y–4 short-circuited the aquifers that it intersected. The hole allows hot water to flow from the high-pressure aquifer near −681 ft, then up and into aquifers of low initial pressure at intermediate and shallow depths, as indicated by loss of drill water during drilling. The upper part of the hole has been heated to temperatures above those of the original rocks. Also, in response to the upward decrease in hydrostatic pressure, the upflowing water at ~195°C starts to boil near −275 ft and continues to boil up to about −145 ft. The change in gradient in curve C (fig. 22) near −148 ft suggests that high-temperature water is flowing out into a zone of fractures noted in drill cores from −138 to −149 ft. The slight irregularities in temperature below about −300 ft shown in curve C, figure 21, and in curve C, figure 22, probably resulted from slow convective circulation of water in the hole during the measurements.

Two months after completion of the hole, wellhead pressures increased from 79 psig to 91 psig (table 10). The fluid that leaked from the hole during all those measurements was liquid water with some vapor exsolving after leakage. The increase in wellhead pressure must have resulted from heating of the hole.

In-hole pressure measurements clarify the actual conditions at depth. The pressures measured on September 24, 1971 (E of fig. 22) were used to calculate a boiling-temperature curve (D of fig. 22). This calculated curve has an average temperature of ~3°C above a parallel segment of temperature curve C (fig. 22), measured in the hole immediately before the pressure measurements. The parallelism indicates that a vapor phase was present from −260 to −140 ft, but the temperature difference between the curves indicates vapor pressures of water that were significantly below the total pressure (that is, the water contained bubbles of exsolved gas). Curve G, figure 22, shows the partial pressures of water calculated at the measured temperatures in the interval −260 to −140 ft. This curve is almost exactly parallel to and about 13 psi lower than curve E (the measured pressures). Therefore, the sum of the partial pressures of gases other than steam was ~13 psi or ~0.88 atm.

Comparison of postdrilling in-hole pressure measurements (table 10 and curve E, fig. 22) and a calculated pressure curve appropriate for the predrilling subsurface temperatures at the Y–4 site (curve F, fig. 22), indicates 75 to 76 psi of water overpressure. This is very close to the 79 psig first measured at the wellhead after drilling. Later surface pressures measured when only liquid was leaking from the hole ranged from 80 to about 94 psig. All these higher wellhead fluid pressures resulted from heating of the hole at all levels about about −681 ft, probably with some effect from vapor bubbles in a slowly convecting "boiling" segment near −200 ft.

Y–13 (PORCUPINE HILLS) DRILL HOLE

SITE SELECTION

Y–13, our final research drill hole, was planned for a depth of 500 ft. Our main objective was to obtain more information from the center of a hot upflow system. Yellowstone contains many geologically suitable sites, but nearly all were eliminated for one of three reasons: (1) no access by present road, (2) too close to major thermal features that might be irreparably changed, (3) too close to tourist traffic, involving possible danger and risk of accidents. For these reasons more of our previous drill holes were sited on the borders of upflow systems than we desired. For Y–13, however, we found a suitable site that was relatively isolated but accessible by a service and fishing road up the south side of Nez Perce Creek in northeastern Lower Geyser Basin.

The Y–13 site is in a cluster of thermal springs of low discharge on a nearly horizontal terrace between the two western Porcupine Hills at an altitude about 45 ft above Nez Perce Creek and 15 ft above the nearest drill hole, Y–4 (table 3). The hottest spring of the group was slightly superheated, with discharge of 1 to 2 gpm and located 70 ft northeast of Y–13; the drill site is on the slope of the sinter cone of this spring and 3 ft lower in altitude. Chemical data (Fournier and Truesdell, 1970) suggest that subsurface temperatures in the vicinity are slightly above 200°C, and that the ratio Cl/HCO_3 of springs near the drill site is the highest of Lower Basin, indicating a major upflow zone. The lack of vigorous discharge from all springs of the group was assumed to result from extensive self-sealing of outlet channels. Wellhead water pressures of at least 33 psi were suggested by the existence of discharging springs and hot spring sinter of former springs at various places in Porcupine Hills at altitudes as much as 80 ft above the drill site.

PHYSICAL MEASUREMENTS

Physical data from Y–13 are shown in table 11 and figures 23 and 24. The water table was identified at about −3½ ft (~6½ ft below the outlet of the

TABLE 11.—*Temperatures, pressures, and other observations from Y–13 (Porcupine Hills) drill hole, Lower Basin*

Date and time 1968		Observation depth, ft[1]	Temp. °C[1]		Thermometer No.	Static water level, ft[1 2]	Wellhead pressure, psig[1]	Comments
6/25	1202	(~21.9)	(<19)			(−4.3)		After drilling to −22 ft; then set 4-in casing to −21 ft.
	1300	(21.9)	(22.8)			**−3.5**		45 min after circulation; then cemented; best shallow water level.
6/26	0810	**15.7**	**52**			(−5.5)		On cement; then drilled to −61½ ft at 1230.
	1640	61.6	124.2		14?	−0.1		4 hr after circulation.
6/27	0730	**61.6**	128.1 129.2 129.2	**128.9**	9 11 12	**−0.3**		Temperature on boiling point curve, so drilled to −72 ft at 0935; set 3-in. casing to −72 ft, cemented bottom and top, securely.
6/28	~0730	**37.8**	**87.3**			(−0.2)		On cement; note straight-line gradient, figure 23. Then drilled to −133 ft at 1600, with hole discharging below −117 ft.
6/29	0730	**133.1**	153.3 152.4	**152.9**	11	(+21)	**9¼**	Water pressure. Then drilled to −177 ft at 1545.
6/30	0850	~**177**	165.6 166.7	**166.1**	9 11	(+36)	17 to **15** 16 to 17	Water pressure 15 psi?
	1930					(+50)	**21** to 22	All water pressure?
7/1	~0730	~177	166.1 166.8	**166.5**	9 14		27 to 28½ 27 to 28½	Permeability high. Then drilled to −207 ft at 1530.
7/2	0755	**207.1**	166.3 166.1	166.2(?)	9 4	(+51)	**21½**	Not insulated; water pressure?
	0815	**207.1**	161.4		13		21½	Insulated; probably most reliable temperature but not certain. Then drilled to −227 ft at 1330; problems with caving.
7/3	0845	~221	(169.8)			(+72)	37 to **30**	Water pressure? Thermistor ~4°C low, failing?
	0930	**223.5**	173.3 173.7 174.0	**173.7**	12 12 9		41 to 38	Then set BX casing to −227 ft, cemented top and bottom after setting; drilled out to −210 ft at 1730.
7/5	0805	207.6	159.9 160.6	(160.2)	9 14		(9 to 14)	On cemented bottom to check possible reversal of July 2; not conclusive.
	0820	(177.2)	156.3 157.1	(156.7)	9 14		(13 to 17)	30 ft off cemented bottom to check 7/1 temperature; not conclusive.
	0850	207.5	(154.4) (152.0)				(14 to 20)	Thermistor check; temperature decreasing with leakage (⅛ gpm) as pressure increasing; boiling from bottom in cemented hole. Then drilled to −293 ft at 1600.
	1630	207½	(158.4)		14	(+60)	**25**	Water pressure (minimum).
7/6	0735	**292.8**	183.4 183.6	**183.5**	9 14		34 to 37	Then drilled to −347 ft at 1550.
7/7	0823	346.3	190.9 190.9	**190.9**	9 14	(+79)	35 to 33	Water pressure 33 psi?
7/8	0740	346.3	190.8 190.8	**190.8**	9 14	(+91)	40 to 41 38 to 40	Then drilled to −378 ft at 1445.
	1555	378					42 to 64	Erupted through side pipe 30 min to determine pressure changes.
	1625					(+77)	64 to 32	Pressure changes during 3 hr after closing valve.
7/9	0748	**378.2**	193.7 194.0	**193.8**	9 14	(+89)	37 to 52 52 to 44	Water pressure 37 psi? After decreasing leakage. Then drilled to −407 ft at 1520.
7/10	0740	**408.8**	197.3 197.7	**197.5**	9 14	(+96)	40 to 44	Water pressure 40 psi? Then drilled to −440 ft at 1605.
7/11	0740	**438.7**	200.3 200.1	**200.2**	9 14	(+122)	51 to 54	Water pressure 51 psi? Then drilled to −465½ ft at 1450 with increasing problems from pressure.
	1630	465				(+216)	90	Pressure 1½ hr after circulation ceased; may be best indication of natural bottom-hole overpressure.
	1900	465					102	Pressure increased with slight leakage to 1900.
7/12	0700	465					118 to 120	Temperature not obtainable because main valve leaking. Decided to terminate drilling. Tried to change valves but packer not working. Pumped 1 sack cement into hole.
7/13	1400	464.8 } **465.0**	203.7	**203.4**	13		122 to 127	1 hr after valve changed and circulation ceased, but no circulation to bottom of hole since 7/11?
	1530	465.3	203.3 203.3		9 14		125 to 130	Temp. reference curve relationships demand at least 126 ft of water or ~53 psi overpressure at bottom.
7/15	0830	464.8	**200.6**		13		180 to 104	Initially all gas, then to all water.
7/16	0900						104 to 105	Thermistor series (curve C, fig. 23).
7/17	1150	**465.3**	**197.1**		14		178 to 102	Leakage all gas, changing to water; maximum thermometer series, not graphed.
7/18		460					131 to 100	In-hole pressures; bottom pressure 226 psia, overpressure 34 psi? Bottom hole pressure 206 psia.
9/15/69		462				(+197)	163 to 82	Pressure change as gas bled off.
10/4/69	0940					(+199)	165 to 83	Maximum-thermometer series (fig. 23, curve D).
	1200	464	198.0 198.4 198.9	**198.4**	12 N–3 N–5	(+180)	75 to 85	
5/27/70		464				(+175)	154 to 73	In-hole pressure series (fig. 24, curves E and F). Bottom hole pressure 206 psia.
5/29/70		455.7	**197.4**		13	(+173)	153	Maximum thermometer series (fig. 24, curve H).
9/25/71		464	**198.5**				148 to 72	In-hole pressure series (fig. 24, curve D) and maximum thermometer series (fig. 24, curve G). Bottom pressure 208 psia.
9/24/73		464.5 463.9	**197.8** 198.0		12		>87 to 70 to 72	Bottom-hole maximum thermometer. Thermistor series (fig. 24, curve I).

[1]Data in boldface considered most reliable; data in parentheses, least reliable.
[2]Relative to ground surface; positive levels in parentheses calculated from wellhead pressures considered to be least affected by vapor.

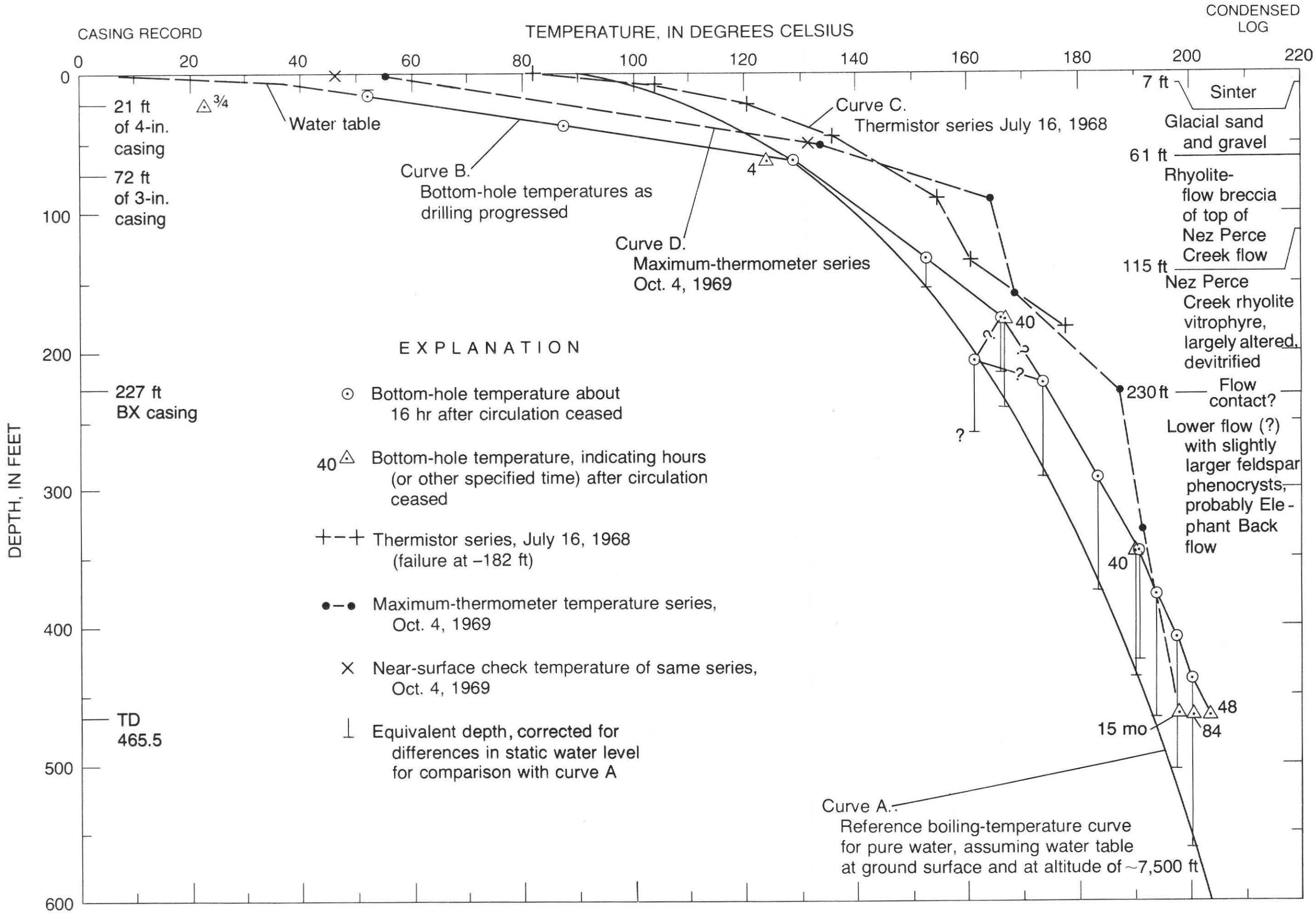

FIGURE 23.—Temperatures and other data, Y–13 (Porcupine Hills) drill hole, Lower Basin.

superheated pool to the northeast). The straight-line temperature gradient from near the water table to the base of the sediments near −61 ft seems to be a purely conductive gradient uncomplicated by convective disturbances. At greater depths temperatures increased rather regularly, generally plotting above the boiling-temperature curve (A of fig. 23). The only exception was near −207 ft where a temperature reversal may have occurred, possibly related to penetration of a cooler tongue of water into the system. Several efforts to substantiate the suggested reversal were inconclusive (table 11, 7/2, 7/5).

An increase in fluid pressures first became evident near −62 ft and wellhead pressures increased regularly thereafter to about −180 ft. Below the zone of uncertain physical characteristics near −207 ft noted above, pressures again increased rather regularly to about 40 psig at −409 ft. At −465 ft a wellhead pressure of ~90 psig was measured (7/11/68) when the drill rods were withdrawn from the bottom of the hole only 1½ hr after circulation ceased; only liquid water was discharging at the top of the hole. This very high wellhead water pressure made it extremely difficult to control the hole while going in and out with the drill rods, so drilling was terminated.

SUMMARY OF DRILLING PROBLEMS

We avoided the mistake made at Y–3 where drilling progressed too rapidly through shallow, easily drilled ground of high eruption potential. Thus, our 3-in. casing was set only to −72 ft—intentionally the shallowest of any of our holes. Perhaps we should have set casing at an even shallower depth, but we strongly desired a good anchor, and rhyolite was not penetrated until −61 ft. Our slight calculated risk fortunately paid off.

Positive wellhead water pressures, as mentioned, first became evident at −62 ft and then increased rapidly with depth and rose higher above the reference pressure curve than in any other Yellowstone drill hole (table 3). In addition, the temperature of 203.4°C measured at −465 ft was higher than temperatures recorded in all drill holes with the single exception of Y–12 at depths below 700 ft, with 237.5°C at −1,088 ft. Nevertheless, drilling progressed in Y–13 with no unsolved problems until very high fluid pressures were encountered near −465 ft, which caused us to stop drilling. On the morning of July 12, 1968, the wellhead pressure was 118 to 120 psig, with a mixture of water and steam leaking from the main valve. An effort was made to insert the packer for changing valves. For the first time, the packer failed to seal off the flow of hot fluids after its forced insertion through the main valve. Later inspection showed that the neoprene expanding unit was damaged, either from BX casing extending up too high within the NX casing, or because of the combined effects of high pressure and temperature. The drillers then pumped one sack of cement into the top of the hole so the valves could be changed. The change was successfully accomplished the following day after the cement had set. However, when the cement was drilled out, we found only one foot of solid cement below the new valve. A serious problem had been narrowly averted! The explanation for the inadequate quantity of cement is not known.

POSTDRILLING MEASUREMENTS AND INTERPRETATION

Bottom-hole temperatures at approximately −465 ft were measured with a maximum-recording thermometer at times of about 48, 88, and 130 hr after the completion of Y–13 (table 11). On July 16, 1968, a thermistor series was run from the surface to −182 ft (C, fig 23), where the equipment failed. In the absence of reliable thermistor gear, temperature profiles were laboriously made with a maximum-recording thermometer on October 4, 1969 (D, fig. 23), May 29, 1970 (H, fig. 24), and September 25, 1971 (G, fig. 24). The first satisfactory thermistor temperature series was obtained on September 24, 1973 (table 11 and curve I, fig. 24).

In-hole pressure measurements were made at the hole bottom on July 18, 1968, and on September 15, 1969. In-hole pressure measurements at various depths were made on May 27, 1970, and on September 25, 1971 (F, E, and D, fig. 24).

All the in-hole pressure profiles show linear pressure-depth gradients at shallow depths. These gradients are parallel to the reference boiling-pressure

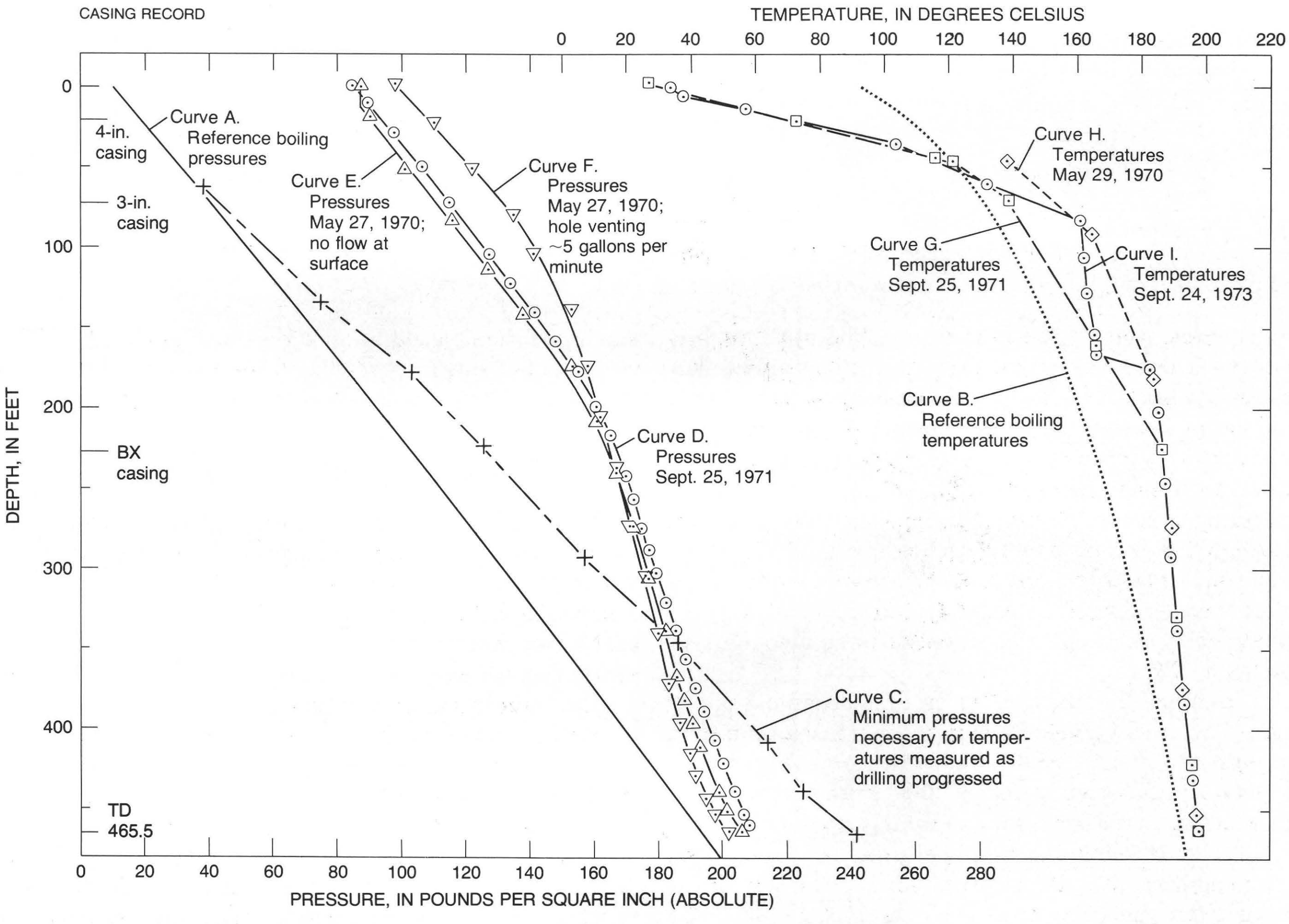

FIGURE 24.—In-hole temperatures and pressures of Y–13 drill hole compared with reference curves.

curve, but are displaced to the right because of water overpressure. At greater depths, the pressure-depth gradients are much too low for liquid water, indicating coexisting liquid and vapor. Boiling water and steam from a zone near the bottom of the hole apparently flow up and out into a relatively permeable zone of lower pressure at the contact of two lava flows and near the bottom of the BX casing at −227 ft. The pressure-depth gradients suggest slight but significant boiling in the aquifer adjacent to the hole bottom, and such boiling was more extensive in 1970 than in 1971. In both years, the extent of boiling increased upward from about −400 to −250 ft. Most of the resulting vapor evidently flows out into the permeable zone at −227 ft, along with the water. A little vapor rises into the water within the BX casing and gradually dissolves upward as temperatures decrease. Consequently, the pressure-depth curves do not display sharp inflections at −227 ft but instead change smoothly into the linear pressure-depth gradients that characterize shallow depths.

The near-surface discrepancy between curves E and D on the one hand and curve F on the other is due to the differing amounts of water allowed to escape from the surface apparatus during the measurements. Curves D and E were obtained with almost no leakage of fluids at the surface but some gas had accumulated in the upper 40 ft of the casing during curve E measurements. Curve F, in contrast, was obtained while water and steam were discharging from the surface apparatus at an estimated rate of 5 gpm. This discharge resulted in decreasing pressures by 4 to 5 psi near the bottom of the hole, which in turn decreased temperatures and increased the rate of boiling as heat was transferred from the rocks to the fluids. Rock permeabilities in the lower 200 ft of the hole are evidently low, thus accounting for the significant change in bottom-hole pressure in response to the estimated discharge of only 5 gpm.

The maximum bottom-hole temperature measured in Y–13 was determined on July 13, 1968, only 48 hours after drilling ceased. Bottom-hole temperatures then declined to 200.6°C after 88 hours, and 197.1°C after 130 hours. In other drill holes (e.g., Y–3), low postdrilling temperatures could be explained by circulation from a shallow cool zone at relatively high pressure as compared to a deep hot zone with lower overpressure. Such an explanation is not possible for the Y–13 data, because water overpressures increase rapidly downward. An alternative explanation is provided by the in-hole pressure data, discussed above, which require that heat be extracted from the rock bordering the drill hole, or from inflowing liquid if pressures are not high enough to maintain a single liquid phase.

Original bottom-hole rock temperatures in Y–13 may have been significantly higher than the maximum measured temperature of 203.4°C, with the higher temperatures being obscured by immediate postdrilling boiling and flow of water and steam up the hole. If the 90 psig wellhead pressure measured on July 11, 1968 approximates the original water overpressure at −465.5 feet, the original rock temperature at this depth could have been as high as 211.5°C. If so, much heat had already been lost by boiling before the temperature of 203.4°C was measured on July 13.

The first satisfactory thermistor temperature profile in Y–13 was obtained on September 24, 1973 (table 11 and fig. 24, curve I). All temperatures obtained during and after October 1969 are in satisfactory agreement at depths below the BX casing at −227 ft, but puzzling disagreement had been found at higher levels. Differing rates of upward leakage of fluids from the surface gear had been considered as the major variable, but a comparison of curves G, H, and I of figure 24 demonstrates that data points of the earlier maximum-thermometer profiles were too widely spaced; the data points of curves G and H, seemingly in major disagreement at depths of about −50 to −175 ft, actually agree closely with those of curve I but the latter defined major changes in gradient near −80 and −165 ft. (These breaks in gradient were actually suggested in curves C and D of figure 16 but were not considered significant.)

All postdrilling temperatures indicate that a linear temperature gradient extends from the bottom of the hole to about −175 ft, or 50 ft above the bottom of the BX casing. This gradient, as we have seen, results from upflow of coexisting liquid and vapor, with vapor increasing upward as pressure decreases. Upflow outside an imperfectly cemented BX casing but within the drilled hole could explain the temperatures of curve I, except for the abrupt decrease in temperature upward between −176 and −165 ft, which is unlikely to have been blocked by cement if the casing at greater depth is imperfectly cemented. Instead, hot fluids are probably flowing upward through adjacent permeable rocks to about −176 ft; some fluid leaks through less permeable rocks from −176 to −165 ft, where resistance to flow again decreases, but temperatures are lower. Within this zone, however, the upflow could be largely within the drilled hole but outside the BX casing. The next higher break in thermal gradient is suspiciously close to the bottom of the 3-in. casing at −72 ft, where good cementing would divert any upflowing fluid out into surrounding rocks.

CORRELATION OF DATA FROM Y–4 AND Y–13 DRILL HOLES

Y–13 was very satisfactory in providing data from near the center of an upflowing hydrothermal system. Although this system is now relatively inconspicuous and low in total discharge, geologic evidence implies that it was large in the past—large enough to cement and hydrothermally alter great volumes of glacial deposits. The indicated decrease in discharge of this system over recent tens of thousands of years must be related, in major part, to self-sealing by hydrothermal minerals.

Y–4 is about 2,200 ft northeast of and about 15 ft below Y–13 and is on the northern margin of the same general upflow system; temperatures are consistently much below boiling and in the upper 250 ft are controlled entirely by conductive heat flow. Relatively minor convective disturbances are evident in deeper parts of the hole, accounting for changes in thermal gradient near −250 and −450 ft. A deep fracture zone containing water under high pressure (~76 psi above the reference pressure curve) had little effect on the thermal gradient, suggesting that this zone, if it was ever connected with the surface, has since been isolated by hydrothermal self-sealing.

Y–4 and Y–13 drill holes thus provide a good opportunity for evaluating horizontal variations in physical characteristics between the center and margin of a convection system. The pertinent data are shown in figure 25, greatly generalized between the two holes where subsurface data are lacking.

The western ring-fracture zone of the Yellowstone caldera (Christiansen and Blank, 1973) probably occurs at depth under the section of figure 25 (but not shown), and this fracture zone has probably influenced all post-caldera structures and the distribution of lava flows. In the immediate area the lava flows are identified by Christiansen and Blank as the Nez Perce Creek flow, probably overlying the Elephant Back flow in Y–13 drill hole. The flow contact in figure 25 is hypothesized on this basis, with depths to the bottoms of the flows and identity of underlying rocks completely unknown.

Figure 25 also shows our best estimates of original wellhead water pressures in the two holes, with 6 psi added to the data of Y–13 to compensate for its higher ground level of ~15 ft. Temperatures increase rather steadily in both holes. The temperature contours between the two holes of figure 25 are assumed to be generally convex upward because of convective upflow and discharge from the springs north and northeast of Y–13.

The sands and gravels of the upper 60 ft of Y–13 initially must have had very high permeabilities that have since decreased greatly because of deposition of hydrothermal minerals. The initial permeabilities of the underlying fractured rhyolite flows and flow breccias are less certain but were probably moderately high.

Temperature differences between Y–13 and Y–4 are about 90°C at −100 ft (below ground surface, rather than strictly horizontal), 64°C at −200 ft, 56°C at −300 ft, 41°C at −400 ft, and 36°C at −500 ft (projected under Y–13). The average horizontal temperature gradients at corresponding depths, assuming 2,200 ft between holes, are 4.1°, 2.9°, 2.5°, 1.9°, and 1.6°C per 100 ft. This regular pattern of decreasing gradients suggests that the gradient becomes slight at depths below 1,000 ft.

Large horizontal contrasts in pressure also exist between the two holes. The shallow and intermediate depths provide no evidence of permeability high enough for any significant fluid communication. The massive, dense Nez Perce Creek lava flow, judging from cores and loss of drill water, had some initial fracture permeability, but the fractures have been effectively sealed from the deep high pressures by deposition of hydrothermal minerals. The highest measured horizontal pressure gradient between the two holes is at ~6,755 ft in altitude (the bottom of Y–13). Including the altitude correction of 6 psi, the pressure difference is 105 psi in a horizontal distance of 2,200 ft, or ~4.8 psi/100 ft. The equivalent hydraulic gradient is approximately 11½ ft per 100 ft (0.115).

The temperature curves of Y–13 and Y–4 as drilling progressed are generally similar except that the Y–4 curve is systematically offset to lower temperatures, the amount of offset ranging from 90°C at −100 ft to 36°C at −500 ft. Is this similarity in curvature largely coincidental?

Except at depths of less than 60 ft, the curve of Y–13 is controlled mainly by boiling, with excess heat of the rising water being utilized to form vapor. Control of temperature by vapor formation probably continues downward considerably below the drilled depth of Y–13; the silica content of its water (as much as 390 ppm) suggests a reservoir temperature possibly as high as 229°C. A downward continuation of the deep thermal gradient of Y–13 to this temperature, assuming no additional increase in water overpressure, indicates that boiling may first start at a depth of about 700 ft.

In contrast, boiling can play no direct part in controlling the temperatures of Y–4; the measured temperatures (curve B of fig. 21) are at least 10°C too low at all drilled depths to permit any vapor to form, and are probably at least 20°C too low at −690 ft, considering the effect of overpressure. The major controls over temperature in the two holes therefore cannot be identical. Thus, subsurface boiling provides a major control on temperatures in Y–13, but conductive heat loss must become an increasingly important control as Y–4 is approached.

Three lines of evidence suggest that the waters of the two drill holes are related and that a horizontal northward component of flow of water occurs deep in the system in the general area from Y–13 to Y–4. The

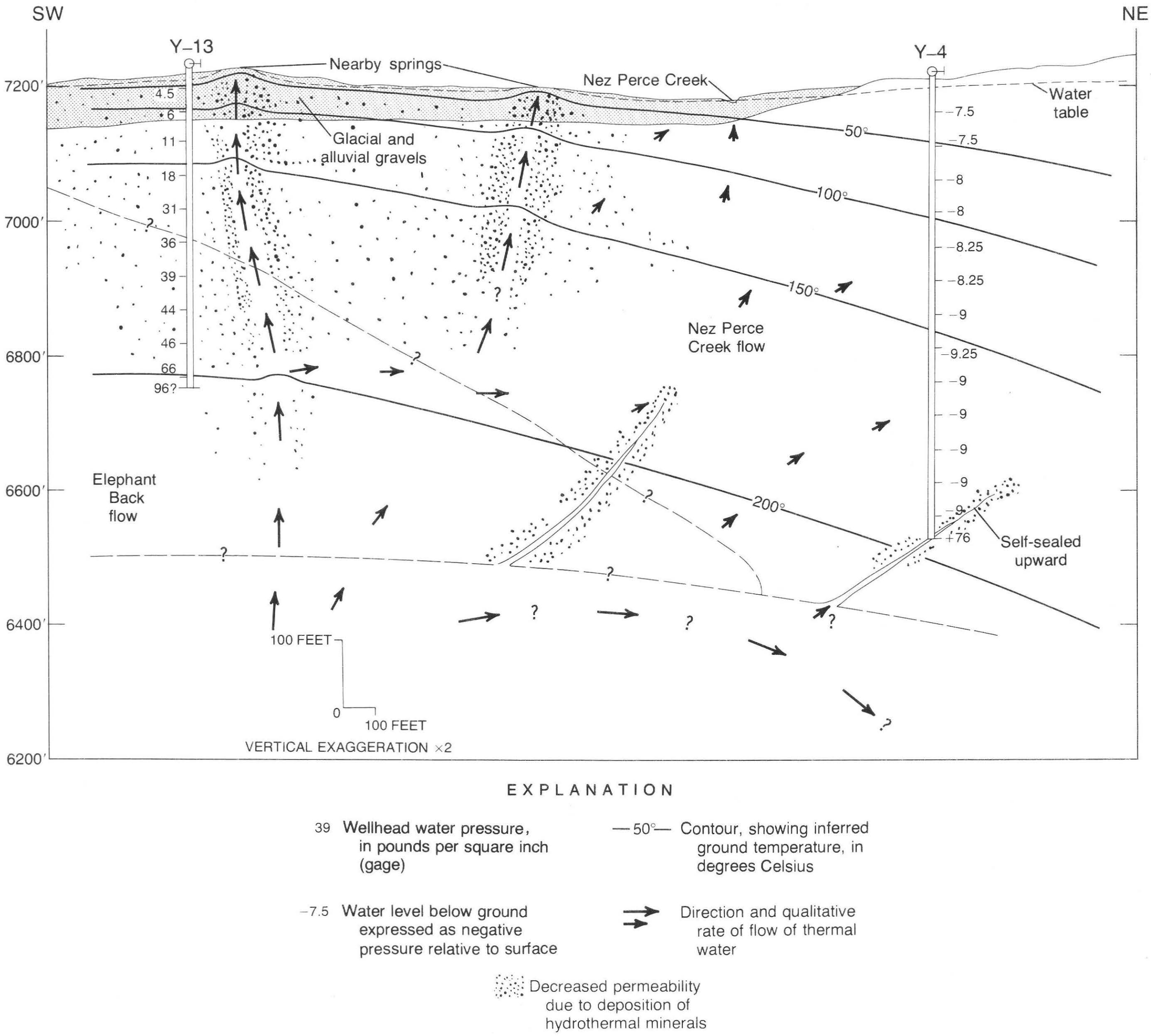

FIGURE 25.—Section through Y–13 and Y–4 drill holes, Lower Basin, showing initial temperature contours, wellhead water pressures (in psig, with water levels below surface as negative pressures) and some hypothesized relationships (6 psi added to original data from Y–13 to compensate for differences in ground level).

chloride contents of waters from the two holes are almost identical (close to 260 ppm), and all analyzed springs in or near the intervening area have relatively uniform concentrations, ranging from 288 to 363 ppm. The spring waters of highest chloride content are in environments suggesting residual concentration by subsurface boiling or surface evaporation from large pools of low discharge. Thus all the waters of the area seem to be relatively homogeneous in chloride and from a common source.

Mazor and Fournier (1973) have shown that the water from Y–4 is unusual among sampled Yellowstone waters in its high retention of the noble gases; about 65 to 85 percent of argon, neon, krypton and xenon are retained, assuming a common source of these gases from the atmosphere, equilibrating at low temperature in meteoric water recharging the hydrothermal system. Other sampled spring and drill-hole waters contained much less noble gases, probably because of loss to vapor that formed as water rose and pressure decreased in the central part of each high-temperature system. The water of Y–4 could have lost only a little gas by deep boiling—but not directly below Y–4 because temperatures are too low for vapor to form, and no nearby discharge of gases is evident. In contrast, some loss deep under the area of Y–13 seems more likely, followed by convective diversion (or flow with a horizontal component) to the northeast. Y–4's observed contents may be a little below those expected of atmospheric equilibration because some gas is lost by separation of vapor within the drill hole, or during or after the sample is collected.

Another alternative is that meteoric recharge of these systems is largely from soil waters high in partial pressure of carbon dioxide and therefore relatively low in other atmospheric gases by about 20 percent.

A final indication of a deep horizontal flow involves the pressure gradients between the two holes. At the altitude of the bottom of Y–13, as we have seen, the pressure gradient toward Y–4 is ~4.8 psi per 100 ft or a hydraulic gradient of 0.115. Gradients at greater depths are less certain, but at the altitude of the bottom of Y–4 (6,514 ft), the water overpressure in Y–13 is probably at least 20 psi above that of Y–4, indicating a gradient of 0.9 psi per 100 ft. If the high rate of increase in water overpressure continues with depth in Y–13, the pressure gradient to the northeast must be even greater.

Thus, temperatures in Y–4 seem to be influenced to a major extent by conductive heat loss. To the northeast, probably within or near the base of the Nez Perce Creek flow, the somewhat cooled, relatively dense water may circulate downward as part of a large convection cell that, in turn, is part of a more complex system.

Y–5 (RABBIT CREEK) DRILL HOLE

SITE SELECTION

Y–5 was selected to provide data on subsurface conditions in the Midway (southern) part of Lower Geyser Basin. Grand Prismatic Pool (4,800 ft to the northwest), is the largest thermal pool in the Park, and Excelsior Geyser (700 ft northeast of Grand Prismatic) has the highest discharge of any single hot spring in the Park (about 3,000 gpm according to Allen and Day, 1935, p. 268). The selected site is on the west edge of the now-abandoned Rabbit Creek garbage dump on a former service road with locked gate, isolating the site suitably from midsummer tourist traffic and tourist-related hazards (but not from grizzly bears!).

All previous drill holes had encountered high wellhead water pressures that prevented deep penetration with our drilling equipment. We hoped that the large natural discharge from Excelsior and other nearby springs would have resulted in lower fluid pressures than in other systems of more restricted discharge, but this hope was not realized. This hole was especially valuable stratigraphically because it penetrated the only known occurrence of the Lava Creek Tuff within the western segment of the Yellowstone caldera. Lava Creek Tuff first occurs at the surprisingly shallow depth of 32 ft in Y–5. Careful search of Rabbit Creek and nearby areas failed to locate any outcrops of the tuff.

PHYSICAL MEASUREMENTS AS DRILLING PROGRESSED

Physical data from the hole are shown in table 12 and figure 26. Temperatures increased rapidly to about −100 ft and then less rapidly to about −250 ft where the maximum temperature of the hole, about 170°C, was measured. With deeper drilling, temperatures declined slightly to about 165°C at the total drilled depth of −538 ft.

Static water levels above ground surface first became evident at −66 ft; wellhead water pressures increased to about 11½ psig at −211 ft and then abruptly to ~39 psig at −248 ft. At greater depths, wellhead pressures seem to have decreased slightly (table 12) to 37 or 38 psig.

The major hazard in the drilling of Y–5 was the grizzly bears feeding at the Rabbit Creek garbage dump 300 ft to the east. The only actual damage was done by bears that chewed the plastic hoses carrying drill water from the creek. This problem was easily solved by moving the hose to a route less attractive to the bears.

POSTDRILLING MEASUREMENTS

A series of thermistor temperatures was obtained in the hole about 10 months after completion (fig. 25, curve C), showing a maximum of 167.8°C at −232 ft and confirming a slight temperature reversal downward to the bottom of the hole. Near-maximum temperatures also persisted upward to −160 ft and temperatures then declined abruptly to the surface; boiling from about −120 to −140 ft (curves C and D) is indicated.

The first reliable in-hole pressures were measured on October 22, 1967 (table 12). Other in-hole pressure measurements were made in July 1969, September 1969, May 1970, and September 1971. The results (not illustrated) were all nearly identical and show a uniform increase in pressure with depth. An in-hole pressure at −240 ft was 150 psia, which is 41.5 psi greater than the pressure curve calculated for water at original ground temperatures and extending just to the ground surface. The pressure at −528.5 ft was 260 psia, or 39.5 psi greater than the reference curve for original ground temperature.

A major aquifer containing water flowing at ~170°C and with an overpressure close to 39 psig evidently exists near −240 ft, which is about 200 ft below the top of the Lava Creek Tuff. Movement of water may be mainly horizontal rather than vertical, and this aquifer appears to be nearly isolated from shallower levels, probably because of hydrothermal self-sealing.

Curve C of figure 26 confirmed the temperature reversal at depth, but near-surface temperatures seem likely to be too high because of inadequate equilibration after bleeding off its gas cap. A series of maximum-

TABLE 12.—*Temperatures, pressures, and other observations from Y–5 (Rabbit Creek) drill hole, Midway-Lower Basin*

Date and time 1967	Observation depth, ft[1]	Temp. °C[1]	Thermometer No.	Static water level, ft[1 2]	Wellhead pressure, psig[1]	Comments
7/26 1350		(37)		−5.3		After drilling to −19 ft at 1350; caving. Montmorillonite then added, drilled to −20½ ft at 1645.
7/27 0800	**13.0**	**38**		(−3.1)		Water level not reliable; caved to −13 ft. Then drilled to −32 ft at 1640; set 4-in. casing to −32 ft and cemented.
7/28 1210	(34.4)	(44)		(−8.4)		After drilling to −35 ft. Then drilled to −49 ft at 1300.
1337	(49)	(84)		**−8.1**		½ hr after circulation; best shallow water level; then drilled to −67 ft at 1450.
7/30 1923	**66.3**	**116.6**	4	**+3.9**		~50 hr after circulation; gas-rich water; slight wellhead water pressure first evident.
7/31 0755	**66.3**	**116.8**	4	**+4.2**		~64 hr after circulation. Then drilled to −103 ft at 1230; set and cemented 3-in. casing to −103 ft; good cement job, top and bottom.
8/1 0742						Drilled out cement to −103 ft.
8/2	103.4 } **103.3**	147.3 } **147.3**	4	(+17)	**7** to 7¾	All wellhead water pressure ~7 psig.
	103.3	147.3	8		8	Then drilled to −173 ft at 1510.
8/3 ~0730	173.1 } **173.1**	161.1 } **161.1**	4		14 to 18	Water, some gas.
~0745	173.1	161.1	8		19½ to 20	Then drilled to −211½ ft at 1535.
8/4 0730	211.2 } **211.2**	164.4 } **164.5**	4	(+28)	13 to **11½**	Wellhead water pressure ~11½ psi?
	211.3	164.6	8		13 to 14½	Then drilled to −248½ ft at 1445.
1530				(+86)	**36**	¾ hr after circulation; all water pressure.
8/5 0745	248.2 } **248.2**	169.3 } **169.5**	4	(+93)	**39**	Then drilled to −278 ft at 1620; increasing problems with high wellhead pressures.
	248.2	169.6	8		39¼ to 39½	
8/6 0930	277.9 } **277.9**	168.4 } **168.7**	4	(+93)	**39** to 39½	Wellhead water pressure close to 39 psig.
	277.9	168.9	8		40	
8/7 0720	277.9 } **277.9**	168.9 } **169.3**	4		39½ to 40	39 hr after circulation.
	277.9	169.7	8		40¼	Then drilled to −328 ft at 1605.
8/8 0745	327.8 } **327.8**	168.0 } **168.2**	4	(+91)	**38** to 38½	Temperature reversal? Thermometers not insulated.
	327.7	168.4	8		38¼ to 38½	Then drilled to −378 ft at 1605.
8/9 0730	377.9 } **377.8**	(167.6)	4	(+91)	**38** to 38¼	Thermometer not insulated.
	377.7	(167.8)	8		38¼ to 38½	Thermometer not insulated.
		165.6	4		39	Insulated; reversal confirmed. Then drilled to −418 ft at 1615.
8/10 0733	417.8	(167.7)	8	(+92)	**38¼** to 38½	Not insulated.
0806	**417.7**	**165.6**	4		38¼ to 38½	Insulated. Then drilled to −468 ft at 1640.
8/11 0740	467.8 } **467.8**	(166.8)	4	(+90)	**37¾** to 48	Not insulated.
	467.7	**165.6**	8		38 to 38¾	Insulated; then drilled to −498 ft at 1550.
8/12 0747	**497.7**	**165.7**	8	(+89)	**37¼** to 38¼	Insulated.
0815	(245.7)	(168.6)			38¼	Uninsulated to test previous maximum temperature (169.5°C). Then drilled to −538 ft at 1515, total depth.
8/13 1137	**537.6**	**164.2**	8	(+88)	**36¾** to 39	Insulated.
8/14 0736	**537.8**	**165.4**	8	(+91)	**37¾** to 38½	Insulated. ~40 hr after circulation.
10/19 1013	**533.5**	(170.2)	11		72 to 45	Not insulated so not reliable.
1053		**170.1**(?)	11		45½	Insulated, but not adequate?
1105	(249)	(170.4)	11		46 to 46½	To previous maximum.
10/22					83 to 48	Pressure at −267 ft, 148±1 psig, or 41.5 psi above reference pressure curve.
6/13/68	510	165.8			84 to 46	Thermistor series; figure 26, curve C.
	231.5	167.8 (max.)				
9/20/69	530					
5/26/70	529				90 to 52	Bottom pressure 248 psig.
9/28/71	529				84 to 43	Bottom pressure 251 psig.
	172.0	169.0	13 & 14		42	Bottom pressure 248 psig.
	199.5	169.0	13 & 14			Checking temperatures through maximum.

[1]Data in boldface considered most reliable; data in parentheses, least reliable.
[2]Relative to ground surface; positive levels in parentheses, calculated from wellhead pressures considered to be least affected by vapor.

thermometer temperatures were obtained on September 27, 1971 (shown as +'s on fig. 26), ~2 hr after bleeding off the gas cap, and minimizing leakage during the measurements. These suggest that predrilling and postdrilling temperatures differ only slightly near the surface and at depths below about 240 ft, but that major changes resulted from flow of hot water from −240 ft up to aquifers of lower initial pressures and temperatures near the bottom of the casing, perhaps along a porous zone noted in the core near −110 ft.

NORRIS BASIN

Y–9 (NORRIS I) DRILL HOLE

SITE SELECTION

Norris Basin is perhaps Yellowstone's most fascinating thermal area because of its highly varied activity (Allen and Day, 1935), its great contrasts in chemical composition of fluids, and its major-rank geyser (Steamboat, by far the most spectacular geyser in the Park from 1961 through 1970, when major eruptions, at least temporarily, ceased). In addition, the highest temperature previously measured in the Park was in Carnegie II at Norris—205°C at −246 ft (Fenner, 1936). The chemical geothermometers, silica content, sodium/potassium ratio, and Na-K-Ca relationships (Fournier and Truesdell, 1970, 1973; White, 1970), suggest temperatures at depth of at least 250°C.

High temperatures and pressures, potentially as much as 575 psia at a saturation temperature of 250°C, were a recognized hazard, especially in view of Fenner's (1936) graphic description of the drilling problems he encountered in 1930. We wanted to obtain data on this high-temperature environment, but we also needed sufficient altitude at the wellhead for the hydrostatic pressure of expected liquid water to counterbalance most of the vapor pressure of steam at high temperatures. The cooler borders of the Norris system were therefore favored on the assumption that the borders expand downward and that very hot internal parts could be pentrated at relatively greater depth by a vertical drill hole. The new Norris Basin bypass road, constructed in 1966–67, provided access to a pine-covered ridge just east of the Norris Museum that seemed to

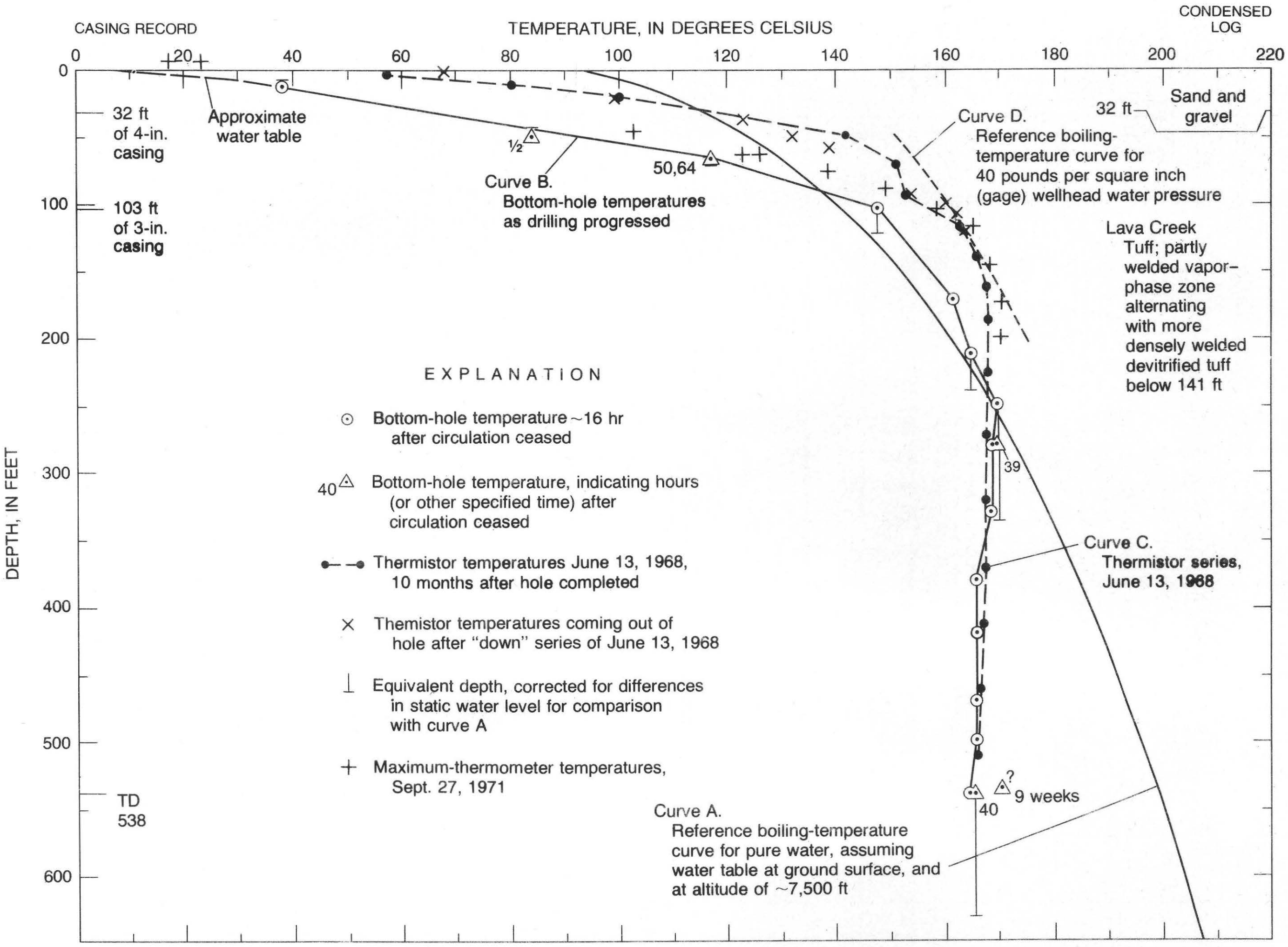

FIGURE 26.—Temperatures and other data, Y-5 (Rabbit Creek) drill hole, Midway-Lower Basin.

have the desired characteristics. Fenner's drill hole, here called Carnegie II, and the varied thermal activity near Congress Pool were only 300 to 400 ft to the north, and other intense thermal activity that included Steamboat Geyser was 600 to 1,200 ft to the southwest. By late September of 1967 nearly all tourists had left the Park, and drilling could be conducted on the north edge of the new Norris parking area with little danger to the public.

PHYSICAL MEASUREMENTS AS DRILLING PROGRESSED

Physical data are shown in table 13 and figure 27. Near-surface temperatures increased with depth on a nearly constant gradient to about −160 ft (curve B); a reliable water level (water table?) was first identified at −28.8 ft when the drilled depth was 61 ft. The first changes in fluid circulation and static water level probably occurred with penetration of a relatively permeable contact at about −125 ft between members B and A of the Lava Creek Tuff (dashed segment of curve B).

The basal 3 ft of the upper member B from −125 to −128 ft consists of crystal-rich air-fall tuff. At or near this depth the static water level rose about 10 ft in the hole, indicating a higher fluid pressure. A slightly lower temperature gradient occurs below −125 ft, probably extending down to about −216 ft (another dashed segment of curve B), where a slight reversal in temperature occurred along with another increase in fluid pressure. At the next deeper data point, −232 ft, water rose in the hole to ground level. The reversal probably terminated near −280 ft, with temperatures thereafter increasing at a nearly constant rate of ~1°C/16.7 ft (nearly 10 times the worldwide "normal" conductive gradient).

Wellhead pressures increased irregularly below −300 ft and became troublesome at depths below −550 ft. An apparent wellhead water pressure of 42 psig was noted when the drilled depth was 502 ft, but at greater depths water pressures could not be distinguished with

TABLE 13.—*Temperatures, pressures, and other observations from Y-9 (Norris I) drill hole, Norris Basin*

Date and time 1967		Observation depth, ft[1]	Temp. °C[1]	Thermometer No.	Static water level, ft[1 2]	Wellhead pressure, psig[1]	Comments
9/27	1545	(11)			(−3.8)		Set up and drilled to −11 ft at 1535; lost circulation at about −10 ft.
9/28	0818	**8.8**	**21.0**		(−6.3 ?)		Temperature at fill, −8.8 ft. Perched water table?
		9.2	**21.5**				Temperature 0.4 ft into mud and sand.
	1055	(16)			(−10.2)		Drilled to −16 ft; 15 min after circulation.
	1205	(17.7)	(16.5)		(−9.4)		5 min after drilling to −21 ft at 1145.
	1310	(19.7)	(20)		(−11.0)		1 hr after circulation; set and cemented 21 ft of 4-in. casing.
9/29	1000	**10.0**	**24.5**				On cement; then drilled to −50 ft at 1325.
	1325	50.1	(25.0)		(−3.1)		3 min after circulation.
	1337	50.1	(30.0)		(−4.7)		15 min after circulation.
	1357	50.1	(37.0)		(−8.5)		35 min after circulation; then drilled to −61 ft at 1435.
	1450	60.8	(39)		(−12.8)		15 min after circulation.
	1535	60.8	(50)		(−22.4)		1 hr after circulation.
9/30	0805	**60.8**	**69.0**		**−28.8**		Then drilled to −100 ft at 1100.
	1215	100			**−24.8**		1 hr after circulation; water level steady. Then set 100 ft of 3-in. casing, cemented.
10/1	0945	**88.7**	**94.5**				On cement.
10/2	0820	**88.7**	96.4 } **96.1**	?			On cement. Then drilled to −152 ft at 1325.
	0833	88.7	95.9	8			
10/3	0810	**152.0**	137.2 } **137.4**	4	**−18.5**		Then drilled to −202 ft at 1200.
			137.6	8			
10/4	0800	**202**	158.8 } **158.9**	4	**−15.2**		Then drilled to −232 ft at 1550.
			159.0	8			
10/5	0810	**232.4**	164.4 } **164.3**	8	**+0.4**		First water level above ground. Then drilled to −282 ft at 1410.
			164.3	8			
10/6	0806	**282.1**	163.9	4			No insulated.
			163.7	8			Not insulated.
			163.3	8	**+1.8**		Insulated (down 20 min). Then drilled to −343 ft at 1545.
10/7	0845	343 } **342.8**	166.6 } **167.0**	8		0	Insulated; water level not measured.
	0900	342.3	167.3	4			Not insulated; then drilled to −403 ft at 1440.
10/8	1100	**402.6**	171.7 } **171.5**	4		8 to 0	Pressure decreased as gas bled off.
	1125		171.4		−8.1	− to +	Water level below ground but then surged up to discharge—gas effect.
10/9	0820	402.3 } **402.3**	171.7 } **172.0**	4	(+17 ?)	**7** to 9	Water, some gas; then drilled to −452 ft at 1500, slight positive pressure between runs.
	0833	402.3	172.2	8			
	1500				+3.1		Immediately after circulation ceased.
10/10	0820	452.1 } **452.1**	173.3 } **173.6**	4		18½	All water?
	0833	452.2	173.8	8	(+38 ?)	**16** to 19½	Water pressure ~16 psi? Then drilled to −502 ft at 1445.
10/11	0845	502.2 } **502.3**	175.6 } **176.1**	4	(+100 ?)	**42** to 49	All water at 42 psig?
		502.4	176.6	8			Gas increased with increasing pressure; then drilled to −552 ft at 1610; intermittently erupting between runs.
10/12	0855	~552	180.0 } **180.0**	4		95 to 60	Pumping of cold water fails to decrease pressure; 63 psig with rods full of water. Then drilled to −593 ft at 1620; water level intermittently below ground between runs.
	0910		180.1	8		75 to 56	
10/13	0855	593.0 } 592.9	181.2 } **181.5**	4	(+172 ?)	110 to **72**	Water pressure 72 psi? Superheated steam at 150°C, 68 psig from side valve; after closure pressure rose to 102 psig. Then drilled to −642 ft at 1630.
		592.9	181.8				
	~1800				(+216 ?)	**90**	Leakage all water.
10/14	0856	~642	185.3 } **185.5**	4	(+187 ?)	105 to **78**	Water pressure 78 psi? Then drilled to −663 ft at 1245. Now normally erupting water from rods with core barrel down and latched, prior to core retrieval or pulling rods.
	0914		185.7	8			
10/15	0955	**663.2**	**185.9**	8	(+134 ?)	78 to **56**	Water pressure 56 psi?
10/16	0953	663.4 } **663.2**	186.2 } **186.5**	4		85 to 88	Pressure nearly constant.
	1006	663.1	186.9	8			
10/17	0852	**663.0**				87 to 99	Broke thermometers 4 and 8; then drilled to −692 ft at 1650.
10/18	0831	692.4 } **692.4**	188.3 } **188.1**	11		101 to 71	Becoming increasingly difficult to reenter hole after changing bits; drilled to −723 ft at 1550.
	0851	692.4	187.9	9			
10/19	0834	723.0 } **723.0**	189.6 } **189.6**	11	(+154 ?)	104 to **64**	Then drilled to −773 ft at 1620; each eruption from rods prior to core retrieval is similar to geyser eruption with duration ~6½ min with initial "bursting" phase and ending in steam phase.
	0852	723.0	189.7	9			
10/20	0850	**772.9**	193.0 } **192.9**	11	(+175 ?)	92 to **73**	Then drilled to −813 ft at 1715.
	0904		192.9	9			
10/21	0902	813.0 } **812.8**	195.4 } **195.7**	9	(+177 ?)	85 to **74** to 94	Decided to terminate drilling; pulled rods and changed valves.
	0936	812.6	195.9	9			
10/23	0854	**813.0**	195.4 } 195.7	11		129 to 140	
	0910	813.0	195.9	9			
10/29		725				136	In-hole pressure 281 ± 3 psig at −725 ft.
6/10/68		**807.8**	**195.2**			138	Thermistor series, figure 27; pressure constant; indicated water level in hole −210 ft.
						132	
9/13/69		796					In-hole pressure series, pressure constant (132 psig all vapor) to 202-ft depth; 357 psi at bottom, calculated water overpressure 49 psi; curve C, figure 28.
9/24/69							25 sacks cement pumped in hole, pressured to 200 psi.

[1]Data in boldface considered most reliable; data in parenthese, least reliable.
[2]Relative to ground surface; positive levels in parentheses calculated from wellhead pressures considered to be least affected by vapor—but all may be so affected.

confidence from total wellhead fluid pressure, which was clearly affected by gas.

SUMMARY OF DRILLING PROBLEMS

No serious problems were encountered in the hole. The crew was experienced, and equipment and techniques were then available for controlling high temperatures and wellhead pressures. Bottom-hole temperatures were generally much below the reference boiling-temperature curve. As we had hoped, no high wellhead pressures were encountered until the hole was about 400 ft deep. Below −500 ft, however, observed wellhead fluid pressures increased notably and ranged from about 60 to 140 psig at all depths below −550 ft. The hole nearly always erupted when fittings were disconnected and drill rods or core barrel were withdrawn (fig. 4C), but the crew became skilled in controlling these eruptions; also, each was limited by low permeability of the rocks and the small amount of available water in the hole. We had hoped (and also feared) to penetrate the base of the thick lower unit of the Lava Creek Tuff, where high permeability and extreme fluid pressures were likely to occur. We drilled through 685 ft of homogeneous tuff of the lower unit to a total depth of

813 ft, with no evidence that more than half of the unit had been penetrated.

POSTDRILLING MEASUREMENTS AND INTERPRETATION

A temperature profile made June 10, 1968, nearly 8 months after completion, is shown in figure 27. At depths below 400 ft the temperatures agree remarkably well with bottom-hole temperatures measured as drilling progressed (curve B); this indicates that predrilling ground temperatures can recover from disturbances from drilling and that this gradient of ~1°C/16.7 ft produces no obvious convection in the hole. Temperatures of curve C are slightly above curve B from −400 ft up to about −240 ft, and the contrast then increases spectacularly upward, where 180.3°C was measured at −210 ft; the same temperature prevailed nearly to the top of the hole. The wellhead pressure of 138 psig (149 psia) is close to the vapor pressure of water at 180.3°C (146.5 psia), and the difference may be explained by partial pressures of other gases.

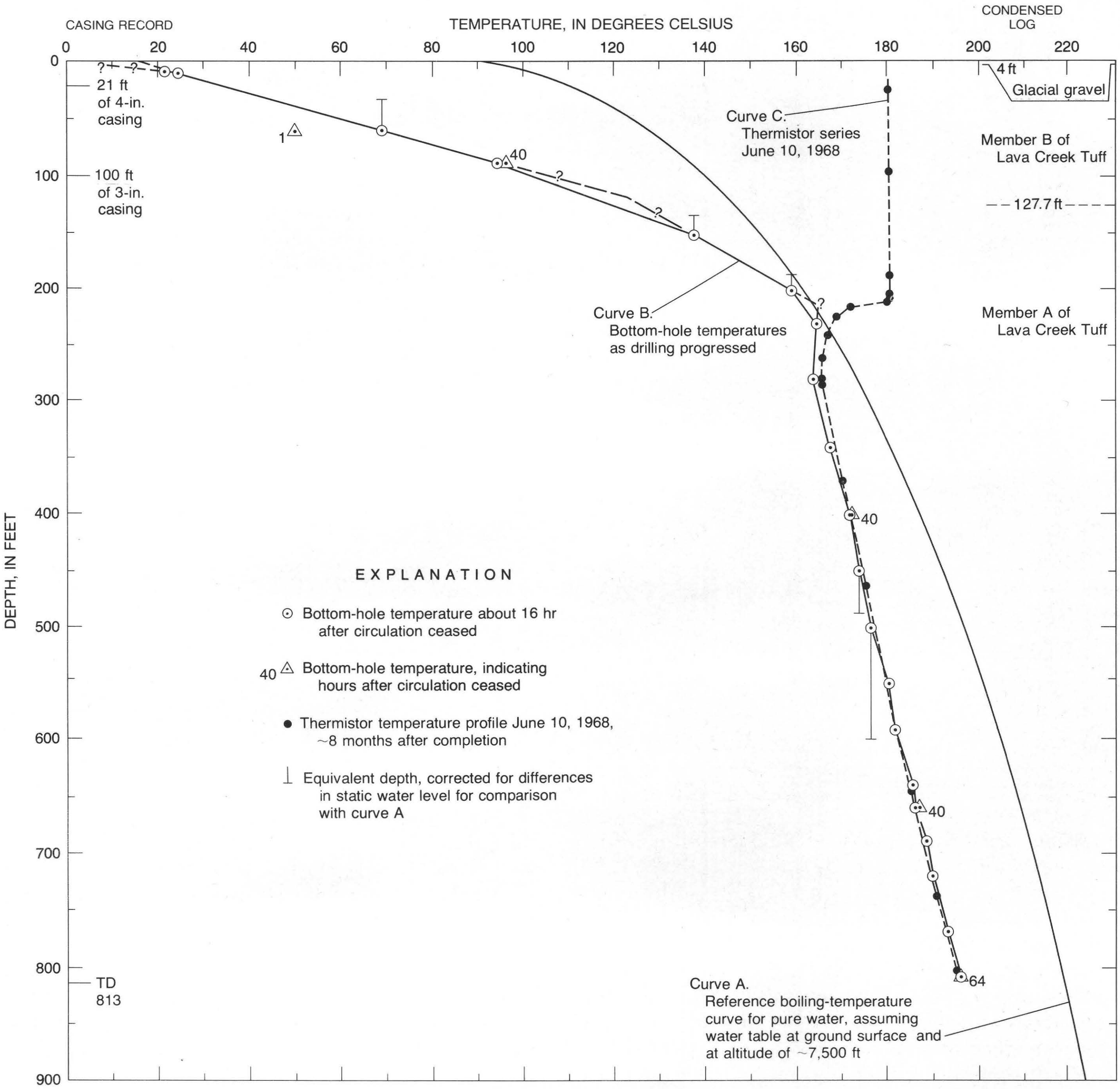

FIGURE 27.—Temperatures and other data, Y–9 (Norris I) drill hole, Norris Basin.

In-hole pressures measured 15 months later (fig. 28, curve C) were constant at 132 psig from the surface to −202 ft. As we had suspected, vapor evidently filled the top of the hole. The observed gage pressure of 132 psig (143 psia) is that of saturated steam at 179.3°C. During the 15-month interval between the thermistor and the pressure measurements, the wellhead pressure had declined about 6 psi and the indicated level of water in the hole rose about 8 ft. Of much greater significance, however, were the major changes that must have occurred during or soon after drilling. The change was probably localized by a prominent, nearly vertical, kaolinite-filled fracture identified in the drill core from −212 to −216 ft. A little hot water probably flowed in this aquifer prior to drilling, thus accounting for the break in temperature at this depth in curve B of figure 27 (shown by dashed-line extensions of nearby gradients). The initial aquifer temperature prior to drilling

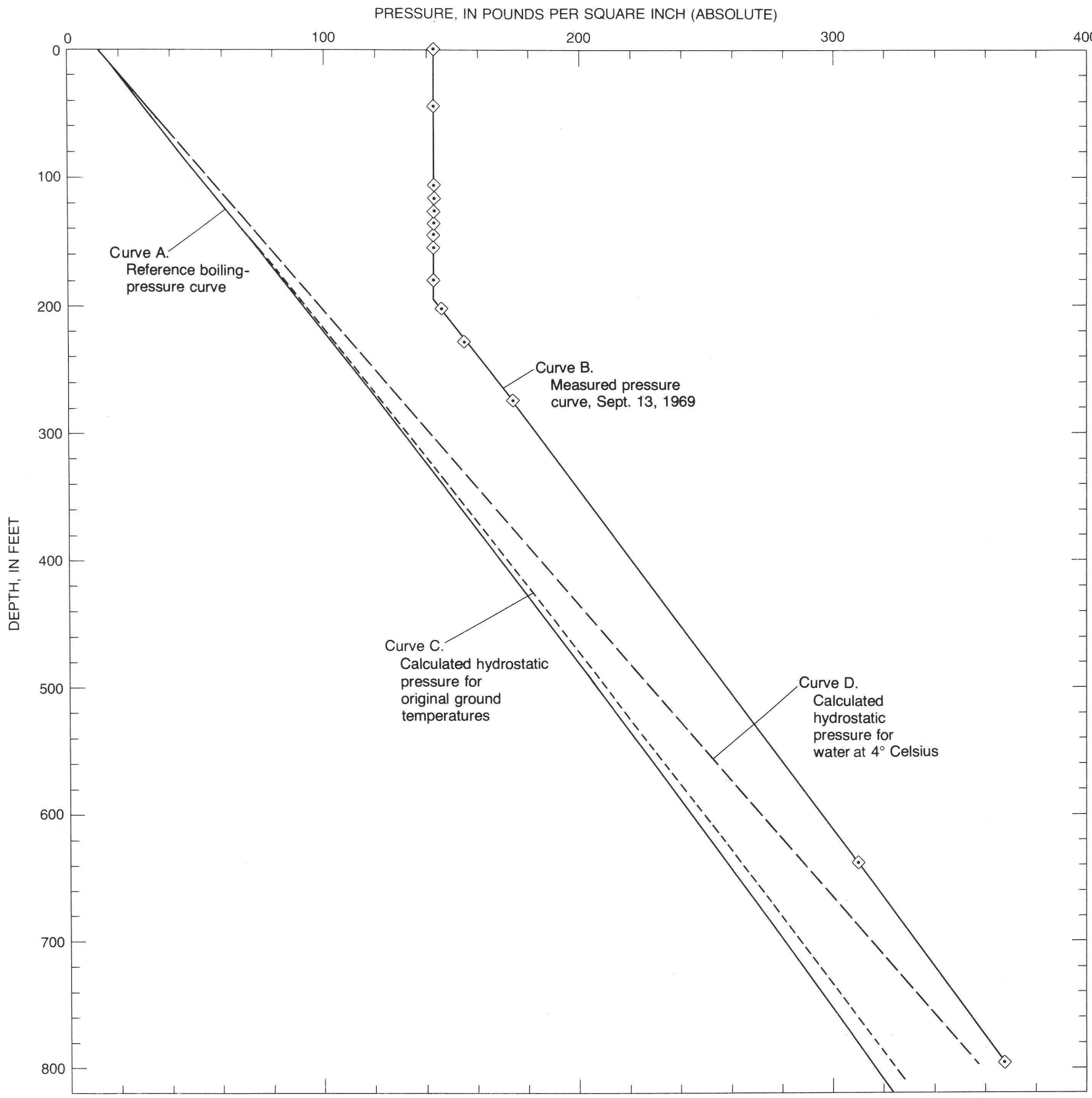

FIGURE 28.—In-hole pressures of Y–9 drill hole compared with other reference curves.

the hole could not have been much above 164°C since high wellhead fluid pressures were absent. A major change in local regime evidently was induced by the drill hole, resulting in a decrease in resistance to flow in this aquifer. The exact nature of the change is not known, but presumably the short circuit provided by the drill hole permitted flow to increase as the clay plug was eroded. The increased rate of flow then permitted access of water of much higher temperature than had formerly existed at this depth. Temperatures increased over previous ground temperatures by about 15°C at −212 ft and by about 160°C at −10 ft (because of high-pressure steam).

This change clearly did not occur immediately upon penetrating the −212-ft level, but developed gradually over the following week. Puzzling variations in gage pressure (see column 5 of table 13, which converts the most reliable pressure data to equivalent static water levels) and increasing proportions of gas in the discharged fluids became especially evident during drilling below −450 ft. The changes near −212 ft probably were delayed by the circulation of cold drill water. The rate of hot inflow probably also increased as the kaolinite filling of the fracture was flushed out. The close agreement between the deep parts of curves B and C of figure 27 provides strong, even conclusive evidence that the zone below −300 ft could not have been involved in the change. The data suggest instead that hot fluids, initially near 165°C but increasing to 180°C, flow into the hole near −212 ft. Vapor evidently separates from water at this level, with some steam flowing upward and condensing in the casing. Water, perhaps with some vapor, may flow out of the hole into the extension of the same permeable fracture at about the depth of separation, −212 ft. However, some water flowed up the hole to about −202 ft during the measurements of September 13, 1969, accounting for the observed pressures and calculated temperature of that date. The nature of some of the changes that occurred in Y–9 is still not clearly understood, especially why the same narrow depth zone (same fracture?) seems to control both entry and exit of the thermal fluids. We speculate here that discharge and eruption from Y–9 cleared the entry channel, and that the resulting increase in pressure and the intermittent eruptions from the hole also cleared the exit channel to establish communication with other permeable fractures.

The water column from −212 to about −280 ft (curve C, fig. 27) is gravitationally stable, with no significant motion either upward or downward but heated a little by conduction from the overlying water.

Other aspects of our data from Y–9 are considered in a later section that considers all Norris drill holes.

Y–12 (NORRIS II) DRILL HOLE

SITE SELECTION

Y–12 was sited on the edge of Porcelain Terrace in the northeastern part of Norris Basin. Access was by an abandoned road that extended through the basin from its northern junction with the new Norris bypass road. The surface of the old road had been torn up and partly restored to natural conditions, but the Park Service granted us temporary access. The drill hole was collared in the old roadbed about 200 ft east of Opal Spring on the crest of Porcelain Terrace; the collar is about 9 ft above the terrace and 42 ft below the collar of Y–9 (table 3). The precise location of Y–12 was a compromise between a border position of relative safety and a position near Porcelain Terrace, where geochemical data provided evidence for subsurface temperatures at least as high as 250°C (Fournier and Truesdell, 1970). The selected site is near mature trees and is 75 ft on the cool side of the present limit of the area where temperatures and heat flow are too high for trees to grow. Ground to the north is still cooler, as judged by the presence of trees and the absence of hydrothermal activity, but a small "hot spot" called the Annex area lies about 300 ft east-southeast of the site. The drill hole is actually within a zone of stunted trees that connects the hotter areas. Measurement by snowfall calorimetry (White, 1969) have since indicated for these areas of stunted trees in Norris Basin a total heat flow of about 500 heat-flow units, or ~350 times the world "normal" conductive heat flow. These facts, along with proximity to Porcelain Terrace on the west, provided nearly a certain guarantee of very high subsurface temperatures.

PHYSICAL MEASUREMENTS AS DRILLING PROGRESSED

Physical data are shown in table 14 and figure 29. The water table was first identified at about −18 feet and about 7 ft below the water levels in Porcelain Terrace. Static water levels at drilled depths of 180 to 460 ft, in contrast, were very close to or slightly above the top of Porcelain Terrace, where springs had discharged prior to the 1959 Hebgen Lake earthquake. Static water levels above ground surface and moderately high wellhead pressures characterized all drilled depths below about 500 ft.

Near-surface temperatures increased rapidly to about −74 ft, perhaps along a straight-line conductive gradient. Bottom-hole temperatures at greater depth generally are remarkably close to the reference boiling-temperature curve A of figure 29. This drill hole provides another example of our conclusion that, if a reference boiling-temperature curve had not been available prior to our Yellowstone drilling, we should

TABLE 14.—*Temperatures, pressures, and other observations from Y–12 (Norris II) drill hole, Porcelain Terrace, Norris Basin*

Date and time 1968		Observation depth, ft[1]	Temp. °C[1]	Thermometer No.	Static water level, ft[1, 2]	Wellhead pressure, psig[1]	Comments
5/27	1300						Started drilling; to −21 ft at ~1600 where 20 ft of 4-in. casing was set and cemented.
5/28	0830	17.2 } **17.2**	54.0 } **54.2**				On cement; then drilled to −62 ft at 1305.
	0835	17.2	54.5				
5/29	0805	62.0 } **62.0**	90.0 } **90.8**		**−17.9**		Then drilled to −111 ft at 1510.
	0815	62.0	91.6				
	1700	111.0	135.3	11			1½ hr after circulation.
5/30	0800	**110.3**	**137.9**		?	0	Water level below ground; before it could be measured, water surged up and erupted; 3-in. casing to −110 ft; cemented top and bottom.
5/31	0800	**74.3**	**125.7**	11 (?)			On cement. Near original ground temperature, or modified? Then drilled to −180 ft at 1445.
	1535	~180	(122.3?)	6	−12.6		½ hr after circulation; thermometer snagged.
6/1	0750	180.4 } **180.0**	(150.6?)	6	**−10.0**		Mercury dropped in thermometer?
	0800	179.7	**155.7**	11			Then drilled to −250 ft at 1345.
	1500	250.3 } **250.3**	156.7 } 157.8	5	−11.4		1 hr after circulation.
	1515	250.3	158.9	9	−11.3		1¼ hr after circulation.
6/2	1140	**250.3**	167.6 } **167.6**	11	(~−10)		Measuring tape greasy.
			167.7	9			
6/3	0830	**250.3**	167.9 } **167.5**	11	**−8.6**		
	0840		167.0	9			Then drilled to −320 ft at 1420.
	1615	~320	162.2 } **162.7**	5	−10.1		2 hr after circulation.
			163.1	11			
6/4	0730	320.2 } **320.1**	176.9 } **177.0**	5			
	0742	320.1	177.2	11	**−7.9**		
	0755	320.1	176.8	1 H.T.			All H.T. thermometers range from 93° to 260°C and require pressure corrections that have been applied. Drilled on to −390 ft at 1305.
	1520	**390.4**	176.1	5			2 hr after circulation.
6/5	0800	**390.3**	184.2 } **184.6**	9	**−7.3**		
			184.9	11			Then drilled to −460 ft at 1210.
	1645	**460.4**	**185.8**	5	**−7.4**		4½ hr after circulation.
6/6	0740	460.1 } **460.3**	189.8 } **189.0**	11	**−7.3**		Then drilled to −532 ft at ~1230; slight positive pressure below −507 ft.
	0755	464.4	188.7	1 H.T.			
6/7	0806	531.3 } **531.5**	192.9 } **193.4**				Then set 530 ft BX casing, cementing top and bottom.
	0815	531.5	194.2	9	[2]**+1.2**		
	0840	531.7	193.1	11			
6/8							Drilled out cement, then on to −569 ft at 1620.
6/9	1150	**569.2**	**194.7**	5	(+38?)	32 to 16	16 psig wellhead water pressure? Low permeability below casing.
6/10	0745	**567.4**	**195.3**	11	(+41?)	**17** to 8	All water at 17 psig, bled down to 8 psig; then drilled to −637 ft at 1300.
6/11	0750	637.4 } **637.2**	198.0 } **198.6**	9		32 to 7½	All water at ~20 psig.
	0810	637.0	199.2	11	(+36?)	**15** to 7	Permeability still very low. Drilled to −707½ ft at 1335.
	1345				(+36)	**15**	~10 min after circulation—all water.
	1645				(+70)	**29**	3 hr after circulation—all water pressure.
6/12	0743	**707.2**	203.0 } **203.8**	1 H.T.	(+86?)	**36** to 21	All water out of 36 psig bleeding down to 21 psig because of low permeability? Drilled to −757 ft at 1510.
	0805		204.6	11			
6/13	0753	756.4 } **756.5**	206.7 } **207.4**	1 H.T.	?	~14 to ~0 to 9½	
	0808	756.7	208.0	11		8½	
	0815				?	~10 to 21½	Pressure increased to 21½ psig in 10 min, then constant; drilled to −792 ft at 1530.
6/14	0750	**789.9**	209.2	1 H.T.	(+58?)	**24** to 16	All water pressure, bleeding down; drilled to −867 ft at 1540.
6/15	0753	**866.9**	217.5	1 H.T.	?	7 to 18, to 8½	Drilled to −937 ft at 1510.
6/16	0915	936.0 } **937.4**	225.2 } **225.3**	1 H.T.	(+67?)	**28** to 15	All water discharged; 28 psig pressure bleeding down; permeability still low.
	0935	936.7	225.4	2 H.T.		15 to 16	
6/17	0754	**936.5**	225.2 } **225.2**	1 H.T.	(+95?)	**39½** to 25	All water discharged at first, then bled down, water and gas.
			225.1	2 H.T.		23	Drilled to −994 ft at 1540 but 10-ft core on bottom.
6/18	0752	**983.2**	230.3 } **230.3**	1 H.T.	(+86?)	**36** to 9	All water, 36 psig, bleeding down to 9 psig, water and gas.
			230.3	2 H.T.			
6/19	0755	**983.4**	230.3 } **230.3**	1 H.T.	(+72?)	**30** to 4	All water at 30 psig, then bleeding down; drilled to −1,035½ ft at 1530.
			230.3	2 H.T.		15 to 5	
	1554					4	24 min after circulation stopped.
	1658					24	1½ hr after circulation stopped.
	2120				(+75)	31½	All water pressure.
6/20	0730	**1,035.5**	234.6 } **234.4**	1 H.T.	(+83)	**34½** to 13½	All water pressure, bleeding down; drilled to −1,088 ft at 1458.
			234.3	2 H.T.			
	1520				(+70)	**29**	20 min after circulation; pressure gradually increasing.
	1550				(+91?)	**38**	50 min after circulation.
	1705				(+79)	**33**	2 hr after circulation; reason for pressure decrease not clear.
6/21	0745	**1,087.8**	237.5 } **237.5**	1 H.T.	(+77)	**32** to 14	All water pressure, 32 psig, bleeding down. Hole erupted; decided to terminate drilling at −1,088 ft; changed valves with packer.
			237.5	2 H.T.			
9/13/69		**1,079**			(+120?)	**50** to 33	Wellhead water pressure 50 psig? Bottom-hole pressure 425 psia, calculated water overpressure.
6/2/71		**1,078.5**				33 to 72	The initial bottom-hole pressure was 433.3 psig with a steady wellhead pressure of 33. Water was then vented from the top at 4 gpm for 37 min. At the end of that time the wellhead pressure had increased to 72 psig and the bottom pressure had declined to 341.4 psig.
9/21/72		**1,081.0**				43½ to 46½	Bottom-hole pressure 446.4 psig.

[1]Data in boldface considered most reliable; data in parentheses, least reliable.
[2]Relative to ground surface; positive levels in parentheses calculated from wellhead pressures considered to be least affected by vapor.

have invented one! Corrections for existing static water levels and wellhead water pressures (fig. 29) indicate that equivalent depths plot nearly on this reference curve at all depths from −160 to −400 ft. Equivalent depths plot below curve A at greater depths down to −900 ft but are again nearly on curve A from −983 ft to the bottom of the hole.

Temperatures as originally measured and associated pressures at first seemed anomalous at and below −983 ft; pressure-corrected depths ("equivalent" depths) consistently plotted above our reference curve A, which seemed to have no logical explanation in a system of coexisting water and vapor. The anomaly was resolved when calibration of the high-temperature thermometers (200°–500°F, equivalent to 93.3° to 260.0°C) used at depths below 700 ft showed them to have much larger pressure corrections than our other thermometers, for which pressure corrections were within the errors of measurement.

SUMMARY OF DRILLING PROBLEMS

Temperatures, as we had hoped, attained by far the

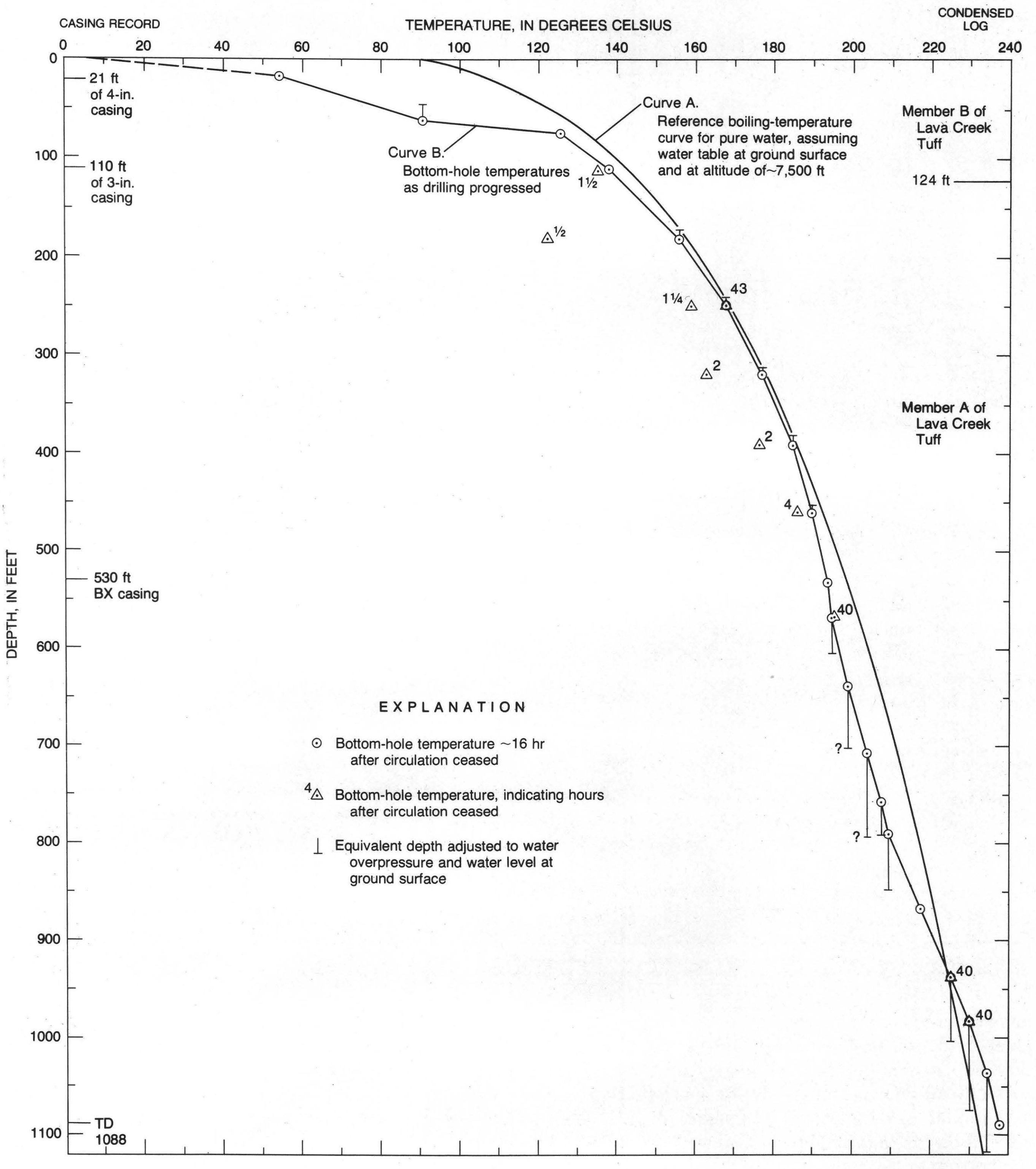

FIGURE 29.—Temperatures and other data, Y–12 (Norris II) drill hole, Norris Basin.

highest levels yet measured in Yellowstone Park (237½°C) but pressures were never very troublesome, in part because permeabilities of the rocks were very low. In addition to our usual two shallow strings of casing, a BX string was set at −530 ft to insure control of the hole if extreme pressures were encountered at greater depths, but such pressures were not found.

Excessive wear of the thin BX wire-line drill rods caused considerable delay and became a serious hazard near and below −900 ft; an increasing number of rods were being rejected because of excessive wear. At −1,088 ft our supply of additional usable BX drill rods was exhausted, and all those in use were so worn that a new set was necessary to continue drilling. By then, 964 ft of the lower unit of the Lava Creek Tuff had been penetrated with no evidence of nearing the basal contact. We had hoped to reach this contact, but if highly permeable ground had been suddenly penetrated, perhaps along with extreme water pressures and total fluid pressure of 575 psia or more, our light equipment was likely to be inadequate. So, regretfully, we decided to quit while we were still ahead!

POSTDRILLING MEASUREMENT

We obtained no reliable postdrilling temperature profiles in Y–12. Our thermistor cable was only 1,000 ft long and its lack of consistent reliability at temperatures near 200°C discouraged its use in Y–12. A maximum-thermometer profile was not considered worth the effort because the hole was too impermeable to sustain in-hole pressures, as discussed below.

In order to clarify interpretation of the wellhead pressure data determined as drilling progressed, the in-hole pressure data of curve C of figure 30 were obtained on September 21, 1971, with water filling the hole and with leakage almost completely eliminated. As expected, curve C is remarkably similar to reference pressure curve A, but with an indicated wellhead water pressure of ~48 psi above the reference curve A and a bottom-hole water pressure of 40 psi above the same curve.

Curve D was measured on July 2, 1972, after venting the hole for 20 minutes at an estimated rate of 4 gpm. This curve is on and below the reference pressure curve at all depths below −175 ft, and the bottom-hole pressure is more than 110 psi below curve C. Only near the surface were pressures relatively high because the high temperatures of the previously discharged fluid had heated the near-surface rocks; after the hole was shut in, steam pressures corresponding to these temperatures at saturation were maintained until the rocks could cool.

We conclude that permeabilities are so low in the open hole below the BX casing that any leakage is only slowly replaced by inflow. When leakage is greater than inflow, pressures decrease, boiling occurs throughout the hole, and heat flows by conduction from surrounding rocks to vaporize part of the available water, thereby decreasing temperatures.

CARNEGIE II (NORRIS) DRILL HOLE

SITE SELECTION

Allen, Day, and Fenner desired a "typical acid area" for the second Carnegie hole drilled in 1929 and 1930 and here called Carnegie II. According to Allen and Day (1935, p. 473–475), the selected site was on the border of Norris Basin in a small muddy flat "dotted with many small shallow hot springs of acid or mixed (acid-chloride-sulfate) type, and one large spring, Congress Pool, of mixed water * * * A rather thorough study of thermal activity at Norris Basin had led to the conviction that underground conditions more intense than those at Old Faithful would be encountered here. Superheated steam was confidently predicted." Allen and Day had concluded from their Yellowstone work and earlier studies at Mt. Lassen (Day and Allen, 1925) and The Geysers (1927) that superheated magmatic steam is a fundamental cause of hydrothermal activity, mixing near the surface with ground water. The alkaline geyser areas were thought to be characterized by relatively deep penetration of ground water, while the areas of acid or "mixed" waters were thought to be related to shallow penetration of ground water. They viewed as highly significant the relatively rare superheated fumaroles where surface temperatures exceeded that of boiling water at existing atmospheric pressure (Allen and Day, 1935, p. 32, 35–39). At that time four superheated-steam vents occurred in Norris Basin within 300 yards of the Carnegie II drill site, with temperatures ranging from 112° to 139°C. Allen and Day (1935, p. 39) also stated emphatically that "steam superheated at the surface must have remained superheated throughout its passage from the magma." The evidence seems clear from the above quotations that the major objective of Carnegie II was to drill through a near-surface water-saturated zone into a zone of superheated magmatic steam, and that such a zone was assumed to underlie Norris Basin at a depth of only a few hundred feet.

We prefer alternate explanations for all of these concepts. For example, superheated steam is commonly derived from liquid water in environments where the supply of liquid is limited and the stored heat of solid phases is vaporizing all available water (White and others, 1971; this report, table 13, 10/13/67). Even the Carnegie II drill hole vented dry steam (transparent and almost certainly slightly superheated) from a

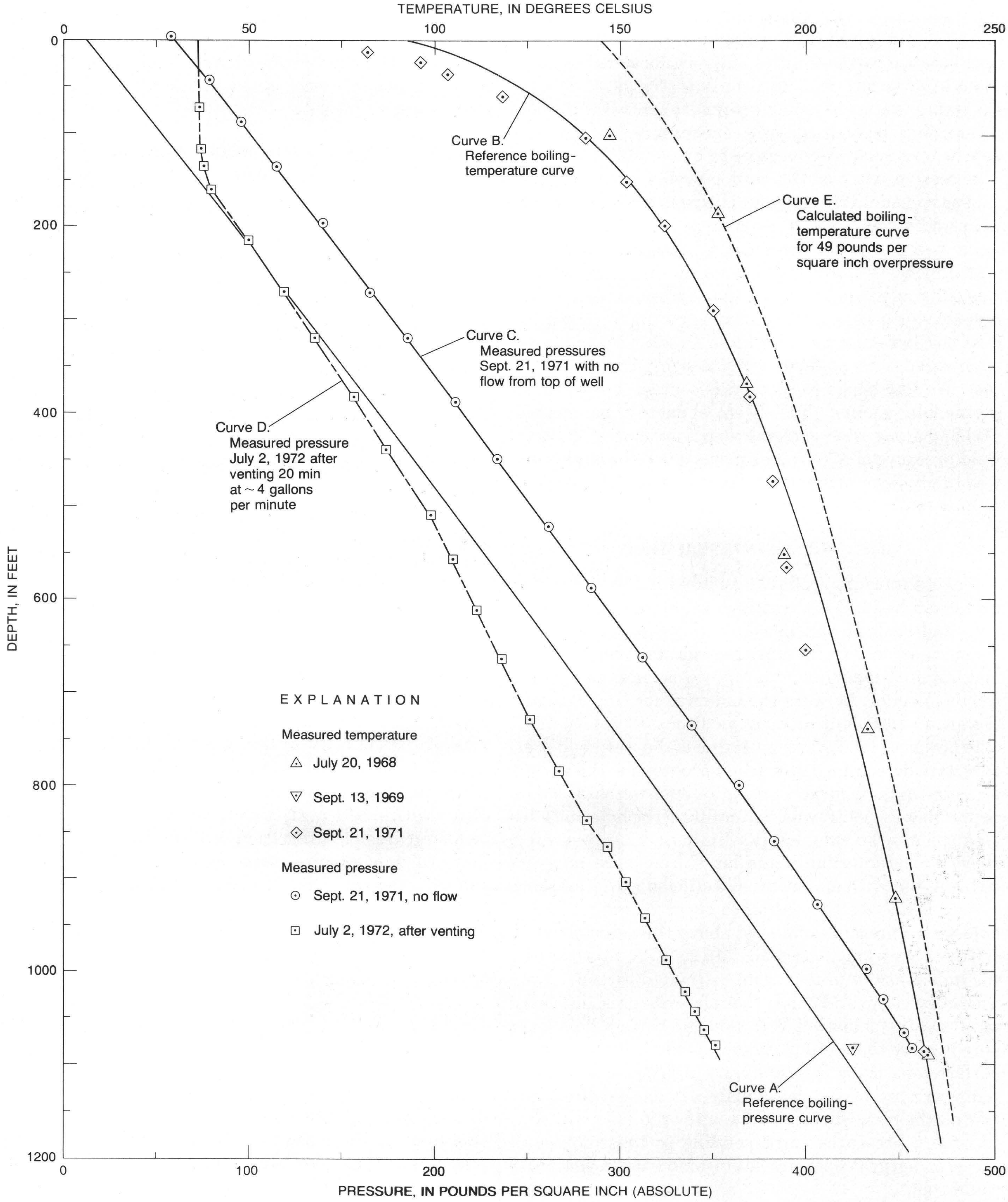

FIGURE 30.—In-hole temperatures and pressures of Y–12 drill hole after completion, compared with other data.

water-saturated environment (Fenner, 1930, figs. 11 and 12; table 16, 9/9/30), although Fenner, Allen, and Day were evidently not aware of this fact; Allen and Day state (1935, p. 475) that "steam issuing from this test hole was not itself superheated." Because of the thermodynamic characteristics of H_2O, saturated steam separated from liquid water at temperatures up to 236°C (and pressures up to 452 psig) and permitted to decompress at constant enthalpy will become superheated—that is, the steam is too hot to coexist with liquid water (White and others, 1971, fig. 2). In light of our present experience, we consider Fenner's figures 11 and 12 as clear evidence for superheated steam because the steam is transparent (and therefore lacks dispersed water droplets) for about 6 in. beyond the end of the discharge pipe. This difference in appearance consistently distinguishes vapor-dominated (dry steam) and hot-water geothermal fluids.

We now have the benefit of much drilling and other experience in geothermal areas that was not available to the Carnegie scientists in their pioneering efforts. The abundance of thermal emissions, intense acid alteration, and absence of pine trees at the Carnegie II site guarantees the existence of convective upflow of fluids, with total heat flow in excess of 1,000 heat-flow units, over 700 times the world average conductive heat flow. We can now predict most of the problems that Fenner actually encountered, and such dangerous sites were consciously avoided.

PHYSICAL MEASUREMENTS

The physical data recorded by Fenner are shown in table 15 and figure 31. Most of these data are included in his published account, but the record is supplemented from his unpublished notes.

Because of drilling problems, caving ground, and frequent eruptions, relatively few temperature measurements were made in Carnegie II. These temperatures increased irregularly but consistently plotted below our reference curve A, except near the bottom of the hole. Startling temperature and pressure changes occurred between September 10, 1930 (159°C at 243.6 ft, with wellhead pressure of 97 to 88 psig) and September 16 when the drilled depth was only 3 feet greater (246.5 ft); the temperature had then increased to 205°C and observed pressures ranged from 225 to 297½ psig.

TABLE 15.—*Temperatures, pressures, and other data from Carnegie II drill hole, Norris Basin*

[From Fenner (1936) and unpublished notes]

Date	Observation depth, ft[1]	Temperature °C[1]	Wellhead pressure, psig	Comments
10/15/29	12			Setting up drill rig on "hot ground," south side of Nuphar Lake; "no steam vents in immediate vicinity."
10/18/29	12			"A little steam coming out"; no data on water levels.
10/19/29	(~20)			Terminated drilling for season. Unpublished notes indicate depth may be ~26 ft(?).
1930				
8/12	(~20)	95		Drilled to −20 ft, fall 1929; boiling at bottom (below water table).
8/15				Started drilling again. First hard rock 28 ft below ground; disintegrates to "sand" at shallower depths; hole filled(?) with cement.
8/17				Drilled out cement to 31 ft; new hole to −34 ft.
8/18				Drilled out to −65 ft.
8/19	56	115	?	After "blowing," perhaps a consequence of static water level above ground surface; drilled depth −71 ft but thermometer only to −56 ft.
8/21				Drilled to −107 ft; leaking outside casing (3-in. casing to about −40 ft(?).
8/23	72	121	15	Drilled to −129 ft but caved; measurements 1 hr after "blowing."
8/24				Drilled to −134 ft, caving.
8/25				Drilled to −159 ft, caving.
8/26				Drilled to −175 ft, caving.
8/27				Drilled to −186½ ft; rods stuck.
8/30				Recovered drill rods; 2½-in. casing installed, depths not stated, inside 3-in. casing, but notes imply to −80 ft; evidently hung in hole, not cemented.
9/1	202.8		46	
9/3	200	141		Drilled depth −215 ft; casing problems.
9/4	213	135	35	Drilled depth −220½ ft; temperature soon after circulation, but not erupted; pressure after "blowing." Lost circulation into permeable zone near 220-ft depth.
9/5	(107)	(144)	55	Drilled to −230 ft; high temperature from upflow; pressure without blowing.
9/6			48 to 112	Drilled to −242 ft.
9/7			130	Drilled to −243 ft 7 in.; pressure with valve partly open.
9/8			132	Large block of cement around casing at surface. Thermometer wedged.
9/9			181 to 170	Depth still −243 ft 7 in.
9/10	243.6	159	97 to 88	Thermometer recovered but jarred (146°C), 2d measurement.
9/11			89	Depth −244.8 ft.
			225	Depth −246.5 ft; pressure suddenly increased.
9/12			250	Same depth, after closing valve "for a moment"; Fenner's photographs (1936, p. 286, 287) indicate flow of superheated steam, no liquid water. Leakage starting around concrete.
9/16			297½ to 265	More concrete at surface reinforced with iron bars (297½ psig or ~309 psia requires subsurface temperature of at least 215°C).
	246.5	205	?	Thermometer lowered on drill tools, valve at side wide open; hole diameter reduced.
9/17			250	Valve open all night, closed before measurement.
9/18			250 to 277½	Valve open; pressure increased after closing valve.
9/20			250	Depth −248.9 ft.
			250 to 265	After drilling to −254.8 ft, with valves closed 1 hr.
9/22			265	Depth −263.3 ft.
9/23			252½	Depth −264.8 ft; lost rod with thermometer.
9/24			145 to 113	Casing ruptured at −36 ft; blowouts appearing in ground to south and west, then north.
10/2				Abandoned attempts to continue.
10/5				Pumped in 100 sacks cement (100 lb each); new blowout ~75 ft northwest of drill hole.
10/7				New steam vent ~50 ft west of drill hole; other vents to south and west diminishing.

[1]Data in parentheses considered less reliable.

These data are not directly comparable to ours for reasons specified in our discussion of Carnegie I in Upper Basin. As compared to our temperatures, most of Fenner's probably were much below predrilling ground temperatures, but his wellhead pressures were probably somewhat higher because liquid water was generally not permitted to accumulate in the hole to offset in part the vapor pressures related to temperature.

Wellhead water pressures were not identified by Fenner as such; the data suggest that static water levels above ground surface may have been first encountered from −65 to −71 ft (table 15). At all greater depths, observed wellhead pressures are probably combinations of high water pressure and gas accumulation in unknown proportions.

The water table also was not specifically identified by Fenner but was probably slightly less than −12 ft (ground level at the drill site is ~12 ft above the surface of Nuphar Lake, which is assumed to establish the base level for the local water table).

Fenner's skeleton collection of drill cores from Carnegie II was made available to us for restudy (White, 1955). R. L. Christiansen's intimate knowledge of the detailed stratigraphy of ash-flow tuffs of the Yellowstone Group permitted him to recognize the contact between the two members of the Lava Creek Tuff at a depth of about −78 ft in Carnegie II.

SUMMARY OF DRILLING PROBLEMS

Temperatures and pressures encountered in Carnegie II drill hole were extremely high, as indicated by Fenner's (1936) account, the cited quotations from Allen and Day (1935), and the data of table 15. Their driller, Vance Butler, was the most highly qualified man of his time, having drilled the early exploratory holes at The Geysers (Allen and Day, 1927).

Shortly after drilling began, a strong flow of steam developed (Allen and Day, 1935, p. 475); temperatures and pressures increased rapidly until, at a depth of −246 ft, 205°C and 297½ psig were measured. These are records for such a shallow depth, not yet (1974) surpassed in geothermal drilling. Considerable difficulty was experienced in controlling the steam, which from time to time burst through the surrounding ground in new

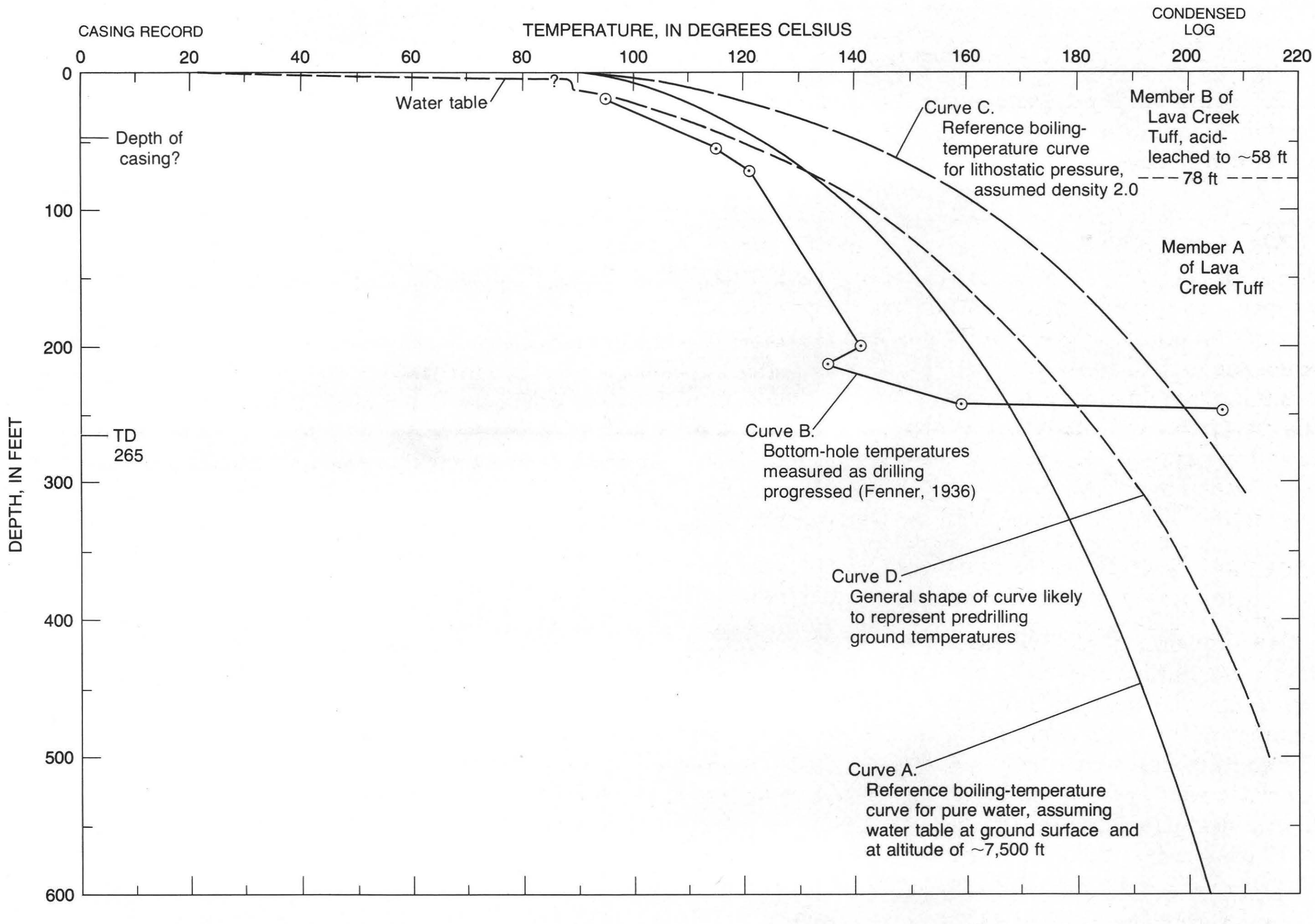

FIGURE 31.—Temperatures and other data, Carnegie II drill hole, Norris Basin (from Fenner, 1936).

jets. These signs of danger increased so rapidly that at a depth of 265 ft the work was stopped. According to Fenner's unpublished notes, "Butler * * * seems somewhat apprehensive that the situation may get out of hand if there are further large increases in pressure; a crater might be formed by forcing out the not-too-strong roof rock * * * Butler says that such a great volume of steam combined with such high pressure is outside his experience." Five tons of cement were then pumped into the hole.

Fenner's maximum temperature of 205°C (with corresponding vapor pressure of about 250 psia or ~239 psig) is not consistent with his maximum recorded wellhead pressure of 297 ½ psig, which requires a subsurface temperature of at least 215°C (neglecting water in the hole, and partial pressures of other gases). We have no convincing explanation for this anomaly; two possibilities are that removal of the thermometer from the violently discharging hole resulted in loss of mercury from above the maximum-recording restriction, or his gage was indicating pressures that were too high.

Additional problems not specifically described or defined were caused by porous acid-leached rhyolite tuff in the upper 25 ft or more in the drill hole and the lack of securely anchored casing in hard rocks at depths below 80 ft. Casing depths and cementing procedures were not described, either in Fenner's published account or in his unpublished notes.

INTERPRETATION OF DATA

We are convinced that most of Fenner's measured temperatures were significantly below original ground temperatures; a notable exception was the spectacular increase in temperature of 46°C over a period of 6 days when the drilled depth increased only from 243.6 ft to 246.5 ft. This change was almost certainly induced by the drill hole, and the temperatures surely do not represent original ground temperatures. Our reasons are based in part on integrated evidence from all three Norris drill holes, as discussed in the following section.

SUMMARY OF SUBSURFACE RELATIONS, NORRIS BASIN, AND CHANGES INDUCED BY THE DRILL HOLES

Generalized subsurface geologic and temperature data from all three Norris Basin drillholes are shown in figure 32. The near-surface rocks consist of the upper member of the Lava Creek Tuff. Diagnostic rocks near the contact between the two units of this formation (Christiansen and Blank, 1972, p. B8–B9) were positively identified near −128 and −124 ft in Y–9 and Y–12, respectively. The same contact zone is partly displayed in the drill core from Carnegie II near −78 ft (R. L. Christiansen, written commun., 1968). The contact (plotted in fig. 32) dips 2° northeast, with no evidence for warping or faulting along the line of the holes.

Temperature contours are also shown in figure 32. Temperatures measured in Y–9 (fig. 27, curve B) and Y–12 (fig. 29, curve B) as drilling progressed are probably within 2° or 3°C of predrilling ground temperatures.

Fenner's data cannot be treated in the same way because, as we have seen, most of his measured temperatures were probably considerably below original ground temperatures. This of course cannot be known with certainty but note, for example, that all of his temperatures (except for 205°C) plot well below the reference boiling temperature curve. This is in spite of the fact that the hole was sited in an area of considerable upflow of thermal fluids and much heat. Predrilling relations in this area (Allen and Day, 1935, p. 473, 474) and photographs of trees near the drill site (Fenner, 1936, fig. 9) suggest that total heat flow at the drill site was then considerably more than 1,000 heat-flow units (White and others, 1971, p. 84–88; White, 1969), or over 700 times the worldwide average for conductive heat flow. Such large heat flows and the existing hot springs demand much convective upflow of water and heat and a corresponding change in temperature contours. But Fenner's measured temperatures, as shown in figure 32, permit no rise of temperature contours near Carnegie II and, in fact, temperatures are lower than for similar altitudes in Y–9 and Y–12 where immediate upflow is absent. For these reasons the inferred temperature contours near Carnegie II in figure 32 are based on curve D of figure 31, which we offer here as our best estimate of the ground temperatures likely to have existed before the hole was drilled. For simplicity, the fractures likely to have controlled the upflowing fluids near Carnegie II are omitted from figure 32.

A more serious problem is to explain the marked increases in temperature with time in Y–9 near −212 ft and in Carnegie II near −246 ft. Figure 32, with its inferred temperature contours, provides a plausible model for reaching higher temperatures by rapid upflow from greater depths as a result of the drilling of the holes. Figure 32 assumes the existence of very hot fluids at depth within the plane of this section. We do know that temperatures as high as 237½°C exist in Y–12 and that geochemical data, cited previously, indicate temperatures at least as high as 250°C in the Norris system. Upflow with a horizontal component from north and west of Carnegie II and Y–9, rather than upflow in the plane of this section, is an alternate possibility.

The temperatures near Y–12 (fig. 29) are generally close to the reference boiling-temperature curve and do not require high wellhead water pressures. According to our deduced temperature contours for Carnegie II, however, wellhead water pressures were high at all depths below about −70 ft. In view of our findings that high water pressures characterize all other drilled geyser basins of Yellowstone, the assumption of high pressures in the centers of major upflow at Norris is very reasonable. For example, if water at 210°C exists under Carnegie II at an altitude of 7,050 ft (as in fig. 32), a high wellhead water pressure is a necessary consequence, probably on the order of 70 psig.

According to interpretations shown in figure 32, the 180°C eventually measured in Y–9 near −210 ft and the 205°C measured in Carnegie II at −246½ ft did not occur in the original natural system nearer than about 200 ft below the points of measurement. Self-sealing of natural channels by silica and other minerals presumably has greatly inhibited discharge from this system and has also caused high water pressures. High pressures, in turn, permitted temperatures to be much above boiling in an unconfined hydrostatic environment. The drilling of a hole upsets the natural regime and short-circuits aquifers of differing static fluid pressures. The kaolinite-filled fracture described from Y–9 at −212 to −216 ft evidently was cleared of its kaolinite filling, short-circuiting other channels of the whole system. With slow natural flow, the tongue of moderately hot liquid (~165°C) was losing most of its excess heat by conduction to cooler walls. With more upflow of water at 190°C or hotter, the excess heat first heated the channel walls and then, more and more, boiled the water to steam. The fluid pressure at −210 ft increased from an estimated predrilling level of 95 psia to ~145 psia (fig. 28). This increase of 50 psi could have been important in increasing the flow of fluid from the drill hole through the fracture on the outflow side.

A similar response best explains the great increase in temperature in Carnegie II at about −245 ft. Fenner's graphic descriptions of increasing steam flow from newly activated nearby vents indicates that the drill hole was short-circuiting natural channels between the deep high-temperature environment and the surface. The sudden increase in pressure noted at 246½ ft (table 15) presumably signifies the penetration of an aquifer

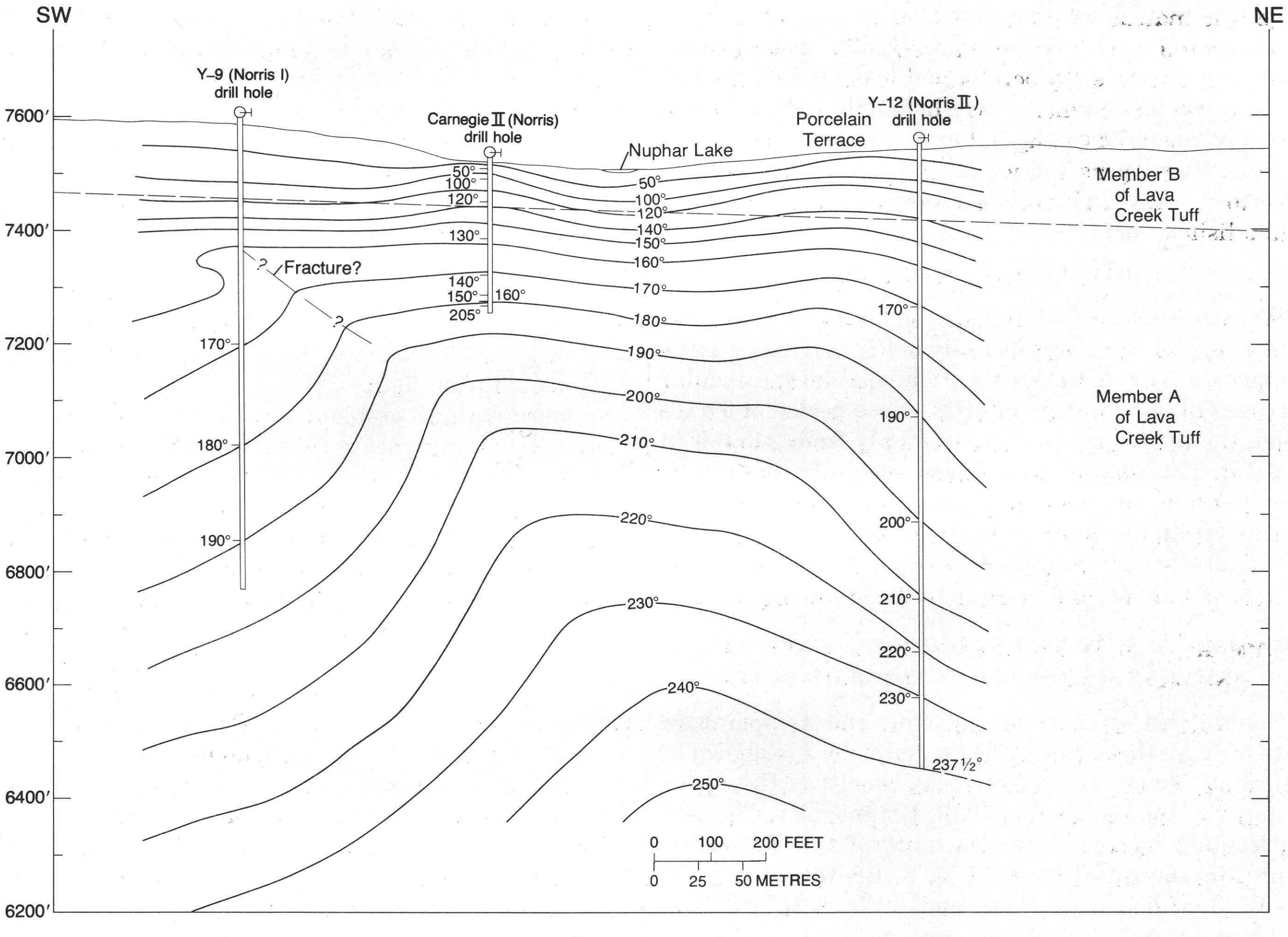

FIGURE 32.—Vertical section through Norris Basin drill holes Y–9, Carnegie II, and Y–12, showing bedrock, measured bottom-hole temperatures, and inferred temperature contours. Note contrast between measured and inferred temperatures in Carnegie II drill hole. The inferred fracture near Y–9 presumably connects with others (not shown) that account for the activity near Carnegie II and Congress Pool.

TABLE 16.—*Temperatures, pressures, and other observations from Y–10 (Mammoth Terrace) drill hole*

Date and time 1967		Observation depth, ft[1]	Temp. °C[1]	Static water level, ft[1 2]	Wellhead pressure, psig[1]	Comments
10/25						Drilled to −22 ft at 1340; set 21 ft of 4-in. casing and cemented.
10/26	0915	**20.5**	**57**	−11.8		Most of cement evidently washed; temperature and water level probably good.
	1055	(36)		−15.1		Water level when drilled depth 36 ft; drilled on to −86 ft at 1400, with first eruption; first gas (H_2S and CO_2?) at −70 ft. Set and cemented 86 ft of 3-in casing.
10/27	0835	47.7 } **47.7**	71.3 } **71.3**			On cement; then drilled to −153 ft at 1640 with pressure increasing.
	0845	47.7	71.4			
10/28	0905	153.2 } **153.3**	73.2 } **73.1**	(+14)	**6**	Wellhead water pressure (evidently not gas accumulation because constant). Then drilled to −243 ft at ~1615.
	0915	153.4	73.0			
10/29	1116	242.4 } **242.3**	73.0 } **72.4**	(+29)	**12¼**	Water pressure, steady.
	1121	242.3	72.0			Different thermometer, not insulated.
	1205	242.3	72.2			Same as above, insulated.
10/30	0840	**242.1**	**72.4**	(+30)	**12½** to 13	Water pressure; drilled to −333 ft at 1600; 2-ft cavities near −262 ft and −322 ft.
	~1630	333		(+98)	**41**	Pressure increased near −333 ft.
10/31	0839	**331.3**	72.5 } **73.0**	(+96)	**40** to 40¾	Insulated thermometer.
			73.6			Different thermometer, not insulated, no significant difference. Drilled to −370 ft at 1215. Terminated drilling, changed valve.
11/1	~1000	199		?	34	Top of caving ground in hole; collected fluid samples.
6/22/68		192		?	37 to 37½	Total pressure at −192 ft, 125 psia; calculated water overpressure ~39 psi; much above pressure measured 10/29 and 10/30 so probably influenced by upflow.
6/24/68						Replaced leaking 3-in. valve and adaptor.
9/20/69		184		?	78 to 41	Total pressure at −184 ft, 121 psia; calculated overpressure ~38 psi.

[1]Data in boldface considered most reliable; data in parentheses least reliable.
[2]Relative to ground surface; positive levels in parentheses, calculated from wellhead pressures considered least affected by vapor; assumed factor of 2.4 is somewhat high.

(vertical fracture?) not shown in figure 32, but assumed to be permeable and communicating with much higher temperatures at depth. Tongues of rapidly moving hot fluids cooled, first by loss of heat to channel walls, then by increased boiling. The high-pressure fluids flowed up the hole and out into fractured and hydrothermally altered wall rocks, thus accounting for the spectacular increase in flow of steam at the surface that Fenner noted. The 210°C and deeper contours of figure 32 consequently were distorted upward.

MAMMOTH HOT SPRINGS

Y–10 (MAMMOTH TERRACE) DRILL HOLE

SITE SELECTION

Y–10 was drilled to obtain data on the thickness, history, and subsurface conditions of Mammoth Terrace, which is the largest hot-spring deposit in Yellowstone National Park and one of the most impressive travertine ($CaCO_3$) deposits in the world.

The selected site is about 60 ft east-northeast of Bath Lake near the southwest limit of present surface activity, and is adjacent to Upper Terrace Drive. Surface altitude is 6,742 ft, which is 4 ft above the level of warm, nondischarging Bath Lake. For comparison, the altitude of Hot River 2 miles to the northeast, which probably represents the subsurface discharge of most of the Mammoth system, is about 5,650 ft. The highest recognized postglacial travertine of the Mammoth system is near 7,150 ft in altitude thus indicating that wellhead pressures that might be obtained in a deep drill hole at the site could be as much as 150 psig, equivalent to 400 ft of water.

PHYSICAL MEASUREMENTS

Data are shown in table 16 and figure 33. The water table was first identified at −11.8 ft, about 8 ft below the surface of Bath Lake. Such a relationship is not surprising in Mammoth Terrace, where former vents and cracks are frequently dry down to levels considerably below nearby discharging springs.

Near-surface temperatures increased rapidly to about −40 ft and then leveled off, with little or no significant change below −50 ft. A maximum temperature of 73.1°C, measured at −153 ft, persisted, perhaps with a very slight reversal, to the bottom of the hole (table 16). A high wellhead pressure was first suspected at −70 ft and was clearly evident at −153 ft; a major increase in wellhead water pressure (to ~40 psig) occurred near −330 ft. Later in-hole pressure measurements (table 16) indicate wellhead water pressures of 34 to 41 psig, but these occurred after some caving in the hole and probably reflect the water pressures of deeper levels. When the hole was permitted to stand for nearly 10 months, wellhead fluid pressures as high as 78 psig were observed. Such pressures were obviously related to accumulation of gas, which forced the water level downward.

High subsurface temperatures had not been expected in Y–10, for travertine-depositing waters nearly always have lower subsurface temperatures than sinter-depositing waters (White, 1970). Temperatures slightly above 70°C have commonly been observed in surface springs of Mammoth; the highest ever recorded (Allen and Day, 1935, p. 371, 372) was 74.5°C. Fournier and Truesdell (1970) predicted a subsurface temperature of 72°C for the Mammoth system, based on a silica content of 55 ppm in typical spring water and assuming subsurface equilibration with chalcedony (rather than quartz). A few analyses report somewhat higher silica contents (72 ppm, Allen and Day, 1935, p. 373; 60 ppm, White

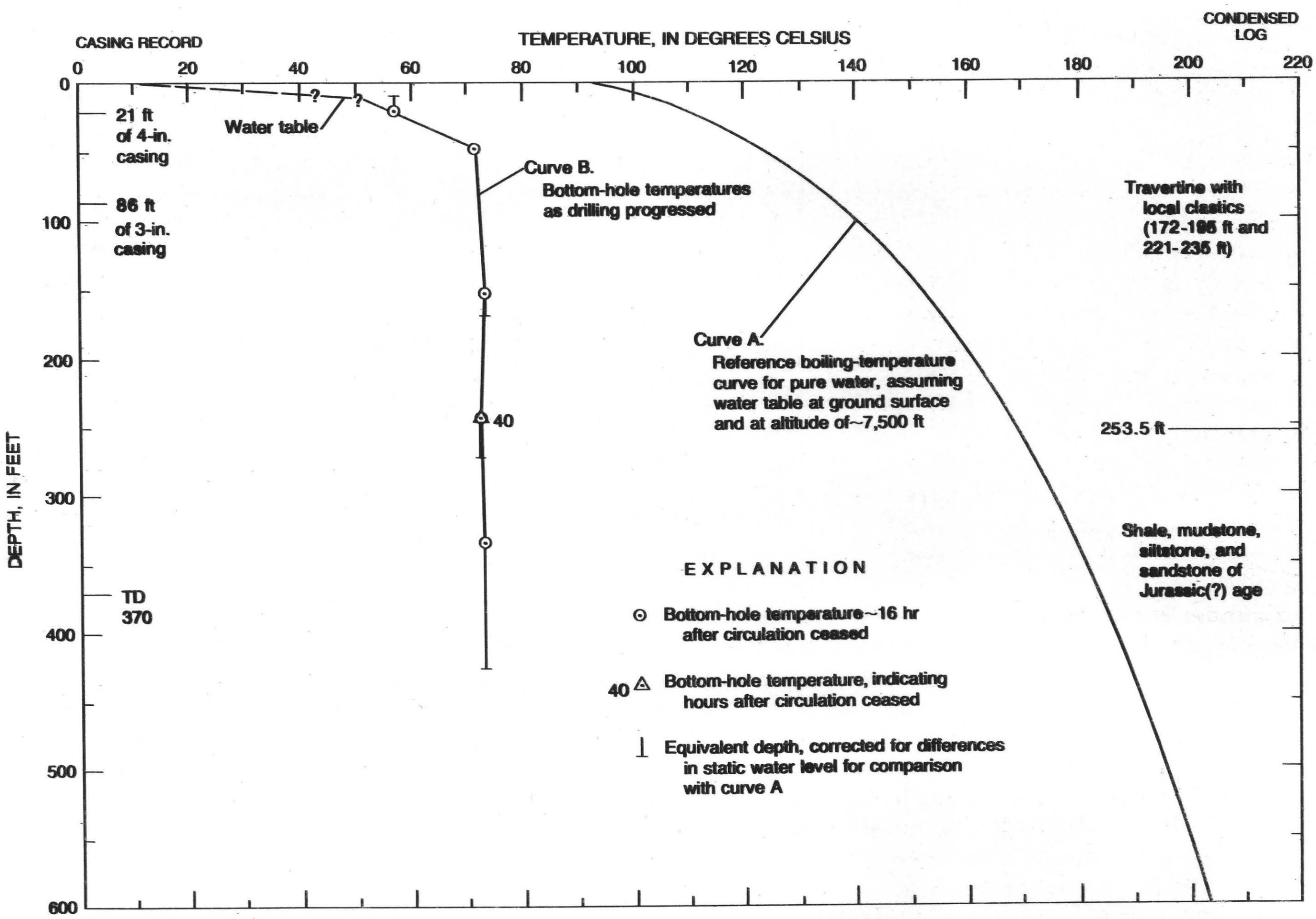

FIGURE 33.—Temperatures and other data, Y-10 (Mammoth Terrace) drill hole.

and others, 1963, p. F54). A content of 72 ppm indicates subsurface temperatures as high as 119°C if in equilibrium with quartz, but only 88°C if chalcedony is the controlling phase.

SUMMARY OF DRILLING PROBLEMS

Y-10 was a relatively easy hole to drill because of its low temperatures (table 16). The principal problems, routine by this time, involved the moderately high wellhead water pressures and unusually high content of dissolved gases. Because of this gas content, the hole actually had eruption tendencies that were similar to those drilled in the geyser basins, where water vaporized rapidly when discharged to atmospheric pressure. Even though the temperature of the fluids discharged from Y-10 was relatively low and not very hazardous to the drill crew, condensing water vapor greatly decreased visibility and hampered operations during eruptions in the cold fall atmosphere.

Caving ground was encountered at depths below the 3-inch casing at −86 ft and was especially troublesome below −190 ft. Cavernous ground (or soft uncemented sediments) was noted in Jurassic(?) rocks near −262 and −322 ft. We could have cased off these zones and drilled to greater depths but our major objectives had been attained so drilling was terminated at −370 ft.

INTERPRETATION OF DATA

The Mammoth travertine terraces are the near-surface expression of a huge convection system that is everywhere at relatively low temperature. The drill hole shows remarkably constant temperatures that were close to 73°C at all depths below 50 ft and almost identical with the maximum observed in surface springs. Evidently all of the water of the system is heated to this temperature or only a little higher, and it rises as liquid water and dissolved gases with no significant change until total vapor pressure has decreased to a few atmospheres. The partial pressure of dissolved gases is then high enough for a carbon-dioxide-rich phase to form; no true boiling of water occurs.

The minimum partial pressures of dissolved gases may be calculated from the data of table 16. A wellhead pressure of 78 psig (89.5 psia) was measured September 20, 1969, a year after leakage of gas through the main valve was eliminated. This high pressure resulted from exsolution of gas, depressing the water level in the hole to the bottom of the casing at −86 ft. The ground temperature at that depth is close to 73°C and the corresponding vapor pressure of water is 5.1 psia. Therefore the partial pressure of gases, other than water vapor, at the gas-water interface was at least 84.4 psia (5.8 atmospheres, more than 16 times the vapor pressure of water!); this is the highest pressure of gases other than water vapor yet observed for Yellowstone fluids.

Allen and Day (1935, p. 86) found that carbon dioxide ranges from 97.1 to 99.5 volume percent of total gases at Mammoth; our best samples from Y–10 contained 96 to 97 percent CO_2. Thus the partial pressure of carbon dioxide must be at least 5.5. atmospheres. This is a minimum partial pressure because gas is presumably escaping from the hole into the country rock below the casing; with a deeper casing, presumably the water level would be depressed even more and the measured wellhead pressure would exceed 89½ psia.

These data suggest that water and dissolved gases rise until hydrostatic pressure has decreased to a value somewhere above 90 psia, where the gases start to exsolve. Because of high wellhead water pressures, the depth of first exsolution may be as low as 170 ft.

Subsurface pH's are below 6.5 and are controlled by the partial pressure of carbon dioxide. Because the solubility of calcite is directly proportional to carbon dioxide concentration, calcite precipitates as carbon dioxide exsolves from the rising water.

Travertine deposited near the surface is porous and, in places, may even be cavernous. Our drill cores show that, with burial, old travertine becomes more dense because of subsurface deposition of calcite in pore spaces. At depths below 170 ft or so, where all carbon dioxide is in solution, the rising water may be unsaturated with respect to calcite and dissolution could be occurring. The principal cavities noted in drilling, however, were in Cretaceous rocks below the oldest travertine.

MUD VOLCANO AREA

Y–11 (SULPHUR CAULDRON) DRILL HOLE

SITE SELECTION

The Mud Volcano area was selected for drilling to test geochemical evidence that pointed to this area as a vapor-dominated system (White and others, 1971). The thermal springs of the area are characterized by acid-sulfate and nearly neutral bicarbonate-sulfate waters that contain very little chloride, and rates of discharge are consistently low. Similar springs occur even near the Yellowstone River, which cuts across the spring group and is the local base level for the water table. Vigorous streams of gas bubbles are discharged from the river bottom with little or no associated temperature anomaly, indicating the absence of associated hot water. In contrast, the major geyser basins are characterized by water relatively rich in chloride and by rates of individual spring discharge that can be exceedingly high.

The significance of chloride in distinguishing between vapor-dominated and water-dominated geothermal systems seems to have been first emphasized by White (1957) in explaining why some systems produce only dry steam with minor associated gases (CO_2, H_2S, H_3BO_3) from deep wells, and other geothermal systems (including all drilled areas with true geysers) yield hot chloride water accompanied by some steam. The common chlorides of sodium, potassium, calcium, and magnesium are all highly soluble in water and are selectively leached from rocks in contact with hot water. In contrast, these chlorides have low volatilities at temperatures below about 400°C. These facts explain why springs in water-producing areas are moderate to high in chloride content, but springs in areas producing dry steam are low in chloride. For example, the Geysers geothermal area discharges superheated steam from producing wells, and the natural springs of the area have less than about 15 ppm chloride (White, 1957; White and others, 1971).

We looked for low chloride levels to tentatively identify and then to confirm by drilling a vapor-dominated system in Yellowstone Park. The whole Mud Volcano group has the desired characteristics; a specific site near Sulphur Cauldron was selected because of its access by road to a picnic ground (since abandoned) and its proximity to Yellowstone River for a supply of drill water.

The selected drill site is just inside the border of an oval-shaped treeless area of high total heat flow. The heat-flow contours shown in figure 4 of White, Muffler, and Truesdell (1971, p. 85) were mapped by snowfall calorimetry (White, 1969) while Y–11 was being drilled. The location of the drill hole relative to the 900 heat-flow unit contour and the tree line indicates that total heat flow at the site is about 800 heat-flow units (more than 500 times the average worldwide conductive heat flow).

PHYSICAL MEASUREMENTS AS DRILLING PROGRESSED

The data are shown in table 17 and figure 34. These data have been described previously (White and others, 1971) but are included here to provide a complete record of our research drilling in Yellowstone Park. The measured bottom-hole temperatures in Y–11 are generally

TABLE 17.—*Temperatures, pressures, and other observations from Y–11 (Sulphur Cauldron) drill hole, Mud Volcano Group*

Date and time 1968		Observation depth, ft[1]	Average	Temp. °C[1]	Average	Thermometer No.	Static water level, ft[1]	Wellhead pressure, psig	Comments
5/14									Drilled to −20 ft at 1425; set 4-in. casing, and cemented.
5/15	0835	**6.7**		**43.0**					On cement at −6.7 ft; temperature probably minimum.
	1210	(27.1)		(36.0)			**−7.6**		80 min after circulation ceased; good water level. Then drilled to −60 ft at 1430; pressure all gas.
	1525	**59.4**		**87.0**				~1	
5/16	0815	56.8	**56.9**	104.4	**105.4**	9		5½ to 0	Gas escaping; 91°C at water level. Then drilled to −91 ft at 1215.
	0823	57.0		106.4		11	**−7.5**		
	1325	**91**		**123.3**				18	70 min since circulation; could have erupted; much H_2S; set 90 ft of 3-in. casing and cemented; excellent cement job.
5/17	0800	**44.9**		**73.0**					On cement; temperature probably minimum? Then drilled to −137 ft at ~1600; lost circulation from −122 to −137 ft.
	1645	(137.0)		116.1		9	−17.0		
5/18	0750	135.8	**135.8**	137.0	**137.1**	9	−16.1	11¼	Gas pressure outside rods, water level inside rods; temperature 73°C. at water level.
	0808	135.8		137.2		9			
	1300	187		(120.3)		9	−15.5		1½ hr after drilling to −187 ft at 1135; lost circulation from −137 to −187 ft.
5/19	1040	186.8	**186.8**	152.4	**151.9**	11	**−15.2**		~23 hr after circulation.
	1100	186.8		151.4		9			
5/20	0754	187.0	**187.0**	151.4	**151.9**	9			~45 hr after circulation.
	0805	186.9		153.4		11			
	0812			150.9		9			
	0822			151.9		1	½ to −3		Water level fluctuating, gassy; then drilled to −237 ft at 1100.
	1400	**237**		**154.5**		11		0 to 1	3 hr after circulation, pressure fluctuating; water discharging outside of rods. Temperature more valid than on 5/21.
5/21	0745	236.9	**236.9**	151.1	**151.6**	9	?	39 to 40½	Gas at top; no H_2S noted; note temperature decrease since 5/20. Then drilled to −307 ft at 1200; erupted after pulling core; nearly all steam after initial water.
	0757	236.9		152.0		11		40	
	1220	306.6	**306.6**	**174.3**		11	?	72 to 47	Temperature 40 min after eruption; some water with steam at 47 psig.
	1545	306.6		**174.7**		11		100 to 73	Leaking steam at 100 psig, decreasing to 73 psig, some water. Side valve pressure outside drill rods, 52 psig.
5/22	0800	306.1	**306.6**	175.7	**175.9**	9	?	132 to 99	Leaking vapor only. Then drilled on, increasingly difficult below −330 ft. Violent eruption at −347 ft, 1530, initially much water (drill water?), then mostly steam.
	0812	307.0		176.1		11			
5/23	0815			191.6	**191.4**	11	?	170 to 148	Leaking vapor only. Drill rods in hole a few feet off bottom; exact depth not noted. Decided to terminate drilling.
	0830	**346.8**		191.1		9			
	~1100						?	60	Rods pulled, pumping cold water down outside rods throughout; pressure with open hole below −90 ft. Hang up at about −110 ft erupted to clear hole; powerful steam eruption with little water.
5/27	not noted	~346		161.1	**161.3**	11	?	64	Note major permanent changes in temperature and pressure after rods out of hole.
				161.4		9		66	
6/10	1000	~345		**158.6**			?	64½ to 67	Thermistor temperature series plotted on fig 34. Temperatures generally steady and reproducible down to −276 ft, fluctuating somewhat at greater depths, up to ±4°C at bottom.
7/10	~1300	315.9					?	60	Attempted to sample water but hole filled with vapor to existing bottom.
7/28		128					?	54	Blocked; no access to greater depths; no water below −128 ft.
9/21/69		91.9		**131.7**			?	34 to 39	Attempted thermistor series; initial temperature at top 75°C, increasing to 107°C with leakage of gas. Hole full of gas to cave at −92 ft, just below casing; thermistor wedged and lost. Erupted gas, mud, and water, and collected water sample.
9/24									Pumped in 5 sacks of cement.

[1]Data in boldface considered most reliable; data in parentheses, least reliable.

less reliable than in other Yellowstone drill holes because all drill water was lost into permeable ground from −122 ft to −187 ft; at greater depths only about half of the drill water returned to the surface. In spite of excessive loss of drill water, most bottom-hole measurements made 16 hr or more after circulation ceased are probably within a few degrees of original ground temperatures. As with other holes, the setting of two strings of casing (at −20 and −90 ft) interfered with collection of satisfactory near-surface data. The temperature of 123.3°C at −91 ft was obtained only 1¼ hr after circulation ceased and before the second string of casing was set. A flow of steam and water into the bottom of the hole no doubt assisted in rapid approach to the original temperature; a considerably higher temperature at this depth seems unlikely, judging from relations to other nearby measurements (curve B, fig. 34). The temperature of 151.9°C measured at −187 ft seems especially reliable in view of identical averages 23 and 44 hr after circulation. The decrease in temperature from 154.5° to 151.6°C that occurred overnight at −237 ft (table 16, 5/20 to 5/21) is significant, especially in view of the accompanying increase in wellhead pressure. These data are best explained by steam and water flowing into the hole at a temperature of about 152°C (probably from about −190 ft), with the water fraction flowing down the hole and out into adjacent rocks near the bottom with consequent cooling effect, while the steam phase controlled the pressure in the hole. The temperature of 191.4°C measured near −347 ft the morning after completion of drilling is nearly 10°C above reference curve A of figure 34.

On several occasions during the drilling of Y–11 the hole could not be prevented from erupting for short intervals. These eruptions differed notably from those of drill holes in the hot-water systems of the geyser basins. Where permeability and water supply are adequate, liquid water at 160°C, for example, will erupt at constant enthalpy to atmospheric pressure, and 11 percent of the original liquid will be vaporized to steam. The remaining 89 percent remains liquid, producing effects that are similar to many major geyser eruptions. In contrast, during an eruption of Y–11 the local supply of liquid water was soon nearly exhausted and steam became completely dominant, probably with less than 10 mass percent of liquid. Although at no time did the

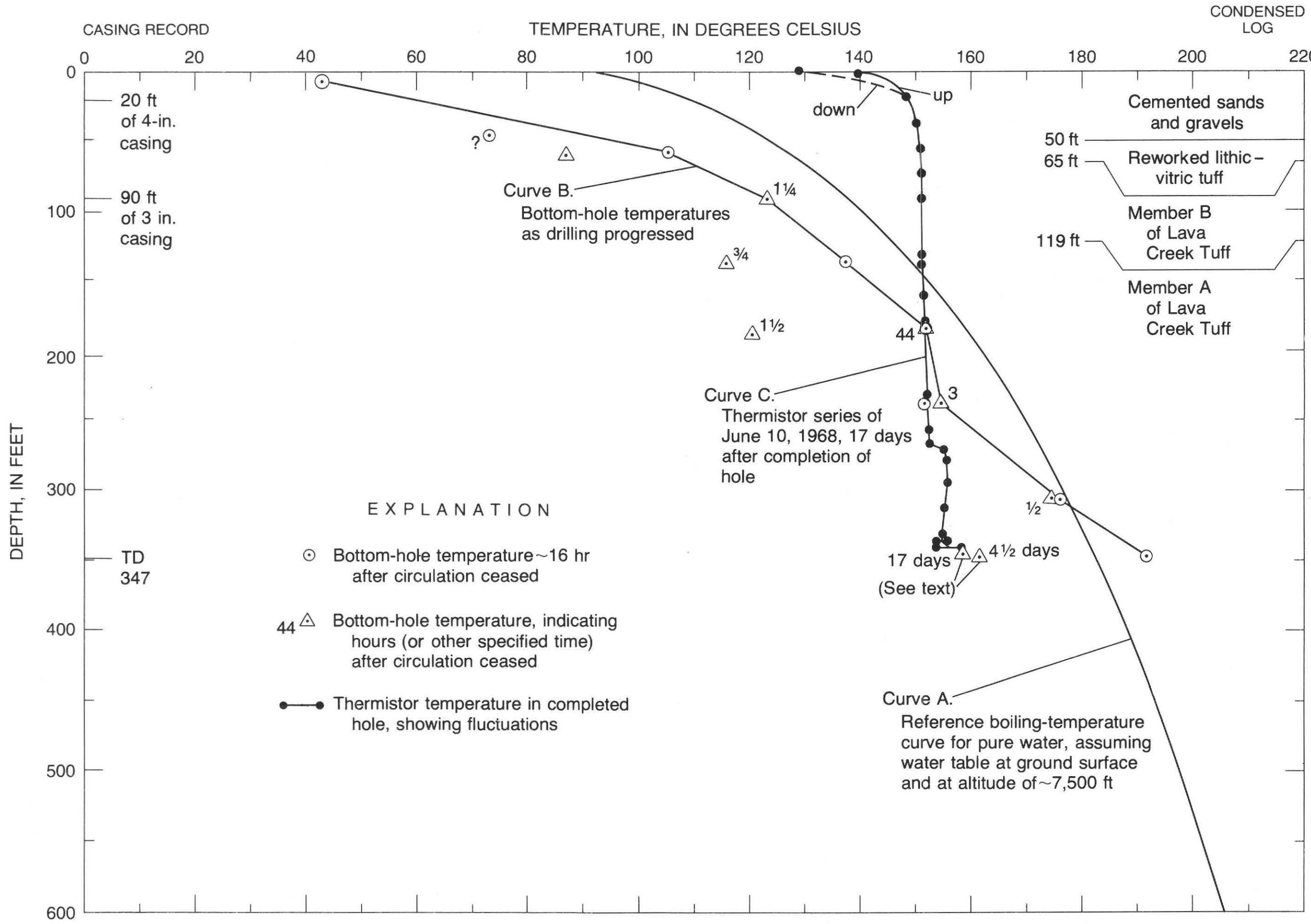

FIGURE 34.—Temperatures and other data, Y–11 (Sulphur Cauldron) drill hole, Mud Volcano area.

full opened hole discharge dry steam without any liquid, we are confident that a dry discharge would have occurred if eruption had continued or if the hole had been cased a little deeper to shut off near-surface water-bearing channels. In other areas, some erupting drill holes in water-saturated rocks of low permeability soon exhaust their local water supply and then discharge dry steam, utilizing the stored heat of rocks to vaporize the available liquid. Y–11's eruptions cannot be explained in this way because the large loss of drill water, noted above, proves adequate permeability below cased parts of the hole. These facts clearly indicate to us that Y–11 did indeed penetrate into a vapor-dominated system that differs greatly from the water-dominated systems of the geyser basins. Further confirmation of the differences is provided by water samples from Y–11 and springs of the Mud Volcano group, compared with water from hot-water systems (White and others, 1971, table 1).

SUMMARY OF DRILLING PROBLEMS

Wellhead pressures increased greatly with depth; at times these pressures were close to the calculated vapor pressures of water at the measured bottom-hole temperatures. This occurs when little or no water is in the hole to offset the pressure of water vapor at existing temperatures. For example, the wellhead pressure of 170 psig (~181 psia) first observed on May 23 is equivalent to the vapor pressure of water at 189.7°C, which in only 0.7°C below the measured temperature. If the partial pressures of other gases are neglected, the calculation indicates that less than 4 percent of the drill hole was filled with liquid water. This lack of counterbalancing water pressure, combined with high permeabilities and high discharge rates of steam, were difficulties that forced us to terminate the hole before we had planned.

POSTDRILLING MEASUREMENTS AND INTERPRETATIONS

A series of thermistor temperature measurements were made in Y–11, 17 days after completion (curve C, fig. 34). Temperatures increased rapidly below the surface to about 151°C at −50 ft and rose to 153°C at −268 ft, and then abruptly to 155°C, which was maintained approximately to the bottom of the hole. Temperatures actually fluctuated slightly at each depth below about −260 ft, and fluctuations ranging from about 1° to 5°C were especially notable near the bottom. These fluctuations were not instrumental errors and were far too large and rapid to be caused by a vapor phase alone. The pressure of saturated steam at 153°C (base of the nearly constant zone) is 74.8 psia, which is nearly identical to the measured wellhead pressures during the series, ranging from ~75½ to 78 psia (table 17). Thus the coexistence of steam and water is indicated at all depths below about −268 ft. We concluded from the drill records that some water entered the hole near −190 ft and flowed down and out into adjacent rocks near the bottom while steam flowed up from near the bottom, largely filling the hole at all depths above −268 ft and thereby controlling pressures above this level. At very shallow depths (above −50 ft), high conductive thermal gradients in rock outside the drill hole permitted condensation of water vapor on the casing, thereby concentrating residual gases and permitting pressure to be constant upward as temperature decreased. This interplay of temperature, pressure, and gas content is discussed in more detail by White, Muffler, and Truesdell (1971, p. 84–88).

In-hole measurements on July 10, 1968, showed constant pressure (~60 psig) to the then-existing bottom of the hole at −316 ft, with no significant difference detected from bottom to top. This indicates the accessible hole was completely filled with vapor. Presumably the liquid water supply available at high levels on June 10 had been largely drained by gravity through the short-circuiting drill hole and was exhausted by July 10. Still later attempts to measure in-hole temperatures and pressures were largely unsuccessful (table 17); the accessible depth decreased with time, indicating that the hole was either collapsing or being filled with clay minerals flowing or being squeezed from adjacent fractures.

For other aspects of our model of vapor-dominated geothermal systems and the possible relationships of Y–11 to the border zone of such a system, the reader is referred to White, Muffler, and Truesdell (1971).

The fact that liquid was only indirectly evident in Y–11 on June 10 and seemed to be absent as an identifiable phase at all later times is another contrast with distribution of fluids in all holes drilled in the geyser basins. In these holes, vapor commonly accumulated in the upper cased parts, depressing the water level down to the base of the cased interval (or to the top of the next lower aquifer). A general saturation of ground with liquid in the hot-water systems, and a dominance of vapor in large pores and fractures of the Mud Volcano system, provide the most satisfactory explanation for all observations.

CONCLUSIONS

1. Drilling a hole into a high-temperature hydrothermal system almost always upsets the local hydrologic regime by short-circuiting aquifers of differing temperatures and pressures. Consequently, the "steady-state" temperatures measured long after completion of a hole may depart greatly from original ground temperatures.
2. Sequential bottom-hole temperatures taken as drilling progresses, with at least 16 hours for recovery without drill fluid circulation prior to each measurement, provide a temperature-depth profile far more representative of original ground temperatures than a profile made in a completed hole.
3. Bottom-hole temperatures measured at the same depth over several days without fluid circulation indicate that almost all recovery of temperature occurs within the first 16 hours after circulation ceases. Thereafter, the bottom-hole temperature may increase as much as a few degrees, or decrease, depending on the hydrologic behavior of the drill hole and intersected aquifers. The 16-hr bottom-hole temperatures are probably within 1° to 2°C of original ground temperatures except where boiling occurs, with resultant loss of heat from the wall rocks, or where water flows downward from a cooler zone into an initially hotter zone.
4. Maximum-recording mercury thermometers are dependable and rapid for determining bottom-hole temperatures in the usual situation where temperatures increase downward. A temperature reversal may be suspected wherever recorded values fail to increase with depth, and an actual reversal may be detected by insulating the maximum thermometer (but the procedure is time consuming). Maximum thermometers are not subject to the chronic failures of insulation, potting compound, and instruments that plague the various electrical temperature-measuring devices, but are less precise and are much less suitable for making temperature profiles in a completed hole.
5. Most Yellowstone drill holes to depths of 100 to 250 ft show a nearly linear near-surface thermal gradient. This zone is bounded upward by the water table or ground surface and downward by the first aquifer in which significant fluid flow occurs. This linear gradient is best explained by conductive heat flow through water-saturated rocks of

nearly constant thermal conductivity; the absence of significant convection is supported by the nearly constant static water levels measured at different drilled depths within the zone.

6. Although most rocks within the near-surface zone of linear gradient were initially porous and permeable, temperature and pressure data combined with petrographic observations indicate "self-sealing" by deposition of hydrothermal minerals. Flow channels are progressively restricted with time, which leads to concentration of flow into a few large channels.
7. Below the zone of nearly constant thermal gradient, many Yellowstone drill holes with static water levels near the ground surface are characterized by temperatures close to the reference boiling-temperature curve. Where static water levels are above ground level because of artesian and thermoartesian pressure, temperatures may, but do not always, plot above the reference boiling-temperature curve by amounts equivalent to the static water level above ground surface.
8. Yellowstone drill holes located near the centers of hot-water upflow (Y–1 and Y–13) had temperatures that plot well above the reference boiling-temperature curve and also exhibited high wellhead water pressures (high static water levels); temperatures were still increasing with depth along the liquid-vapor two-phase boundary, with no indication within drilled depths of attaining the maximum temperature existing in each system (the base-temperature of Bodvarsson, 1964).
9. Yellowstone drill holes located somewhat away from the centers of hot-water upflow (Y–2, Y–3, Y–5, Y–8, Y–11, Y–12, and Y–10) had temperatures nearly on the reference boiling-temperature curve with only slight overpressure, and several of these holes (Y–5, Y–8, Y–10) showed a leveling off or a slight reversal in temperature with depth.
10. Temperature-depth curves of three holes (Y–4, Y–6, and Y–7) plot below but crudely parallel to the reference boiling-temperature curve, with temperatures probably being controlled largely by water circulation and thermal conduction outward from nearby hot-water upflow systems that are boiling.
11. One drill hole, Y–11, penetrated the margins of a vapor-dominated geothermal system that had been tentatively recognized by geochemical criteria prior to drilling. Pores and fractures at depth contained both steam and water, with the steam, being volumetrically dominant, as the hydraulically controlling phase.
12. Maximum measured temperatures in each area (Fournier and Truesdell, 1970, 1973) provided good to strong corroboration for the silica and Na-K-Ca hydrogeothermometers for predicting reservoir temperatures from surface hot springs; the simple sodium/potassium geothermometer is not as reliable in Yellowstone National Park as in most high-temperature hot-water systems.
13. Wellhead fluid pressures may greatly exceed wellhead water pressure, either because gas accumulates in the casing and forces the water level downward, or because water rising from a highly overpressured aquifer to another of lower overpressure exsolves and entrains vapor bubbles, with consequent decrease in density.
14. Each hole showed an irregular rise in static water level with increasing drilled depth. Vertical hydraulic gradients exceeded 0.1 for all holes except Y–7. Maximum hydraulic gradients observed were 0.30 in Y–4, 0.37 in Y–1 and 0.47 in Y–13.
15. In-hole pressures showed that the wellhead water pressure generally is controlled by the aquifer of highest overpressure, except where this aquifer has a permeability that is appreciably less than that of other aquifers intersected by the drill hole.
16. In-hole pressure measurements indicate that both water and vapor can exist in parts of a drill hole while water alone is being discharged at the wellhead. This situation, as in Y–4 and Y–13, results from the flow of water and vapor up the hole, with both phases being diverted into an aquifer.
17. Pressures much in excess of cold hydrostatic are characteristic of the Yellowstone thermal systems and are due to thermoartesian pressure, perhaps supplemented by normal artesian pressure.

REFERENCES CITED

Allen, E. T., and Day, A. L., 1927, Steam wells and other thermal activity at "The Geysers," California: Carnegie Inst. Washington Pub. 378, 106 p.

———1935, The hot springs of the Yellowstone National Park: Carnegie Inst. Washington Pub. 466, 525 p.

Bargar, K. E., Beeson, M. H., Fournier, R. O., and Muffler, L. J. P., 1973, Present-day deposition of lepidolite from thermal waters in Yellowstone National Park: Am. Mineralogist, v. 58, p. 901–904.

Bodvarsson, Gunnar, 1964, Physical characteristics of natural heat resources in Iceland, *in* Geothermal Energy I: United Nations Conf. New Sources Energy, Rome 1961, Proc., v. 2, p. 82–90.

Christiansen, R. L., and Blank, H. R., Jr., 1972, Volcanic stratigraphy of the Quaternary rhyolite plateau in Yellowstone National Park: U.S. Geol. Survey Prof. Paper 729–B, 18 p.

———1975, Quarternary volcanism of Yellowstone Rhyolite Plateau Region of Wyoming, Idaho and Montana: U.S. Geol. Survey Prof. Paper 729–D (in press).

Day, A. L., and Allen, E. T., 1925, The volcanic activity and hot springs of Lassen Peak: Carnegie Inst. Washington Pub. 360, 190 p.

Fenner, C. N., 1936, Bore-hole investigations in the Yellowstone Park: Jour. Geology, v. 44, p. 225–315.

Fournier, R. O., 1973, Silica in thermal waters: laboratory and field investigations: Proc. of Internat. Symposium on Hydrogeochemistry and Biogeochemistry, Tokyo 1970, I. Hydrogeochemistry, p. 122–139, Clark, Washington, D.C.

Fournier, R. O., and Morgenstern, J. C., 1971, A device for collecting down-hole water and gas samples in geothermal wells, *in* Geological Survey research 1971: U.S. Geol. Survey Prof. Paper 750–C, p. C151–C155.

Fournier, R. O., and Rowe, J. J., 1966, Estimation of underground temperatures from the silica content of water from hot springs and wet-steam wells: Am. Jour. Sci., v. 264, p. 685–697.

Fournier, R. O., and Truesdell, A. H., 1970, Chemical indicators of subsurface temperature applied to hot spring waters in Yellowstone National Park, Wyoming, U.S.A.: Geothermics, Special Issue 2, v. 2, pt. 1, p. 529–535.

———1971, A device for measuring downhole pressures and for sampling fluids in geothermal wells, *in* Geological Survey research 1971: U.S. Geol. Survey Prof. Paper 750–C, p. C146–C150.

———1973, An empirical Na-K-Ca geothermometer for natural waters: Geochim. et Cosmochim. Acta, v. 37, p. 1255–1275.

Haas, J. L., Jr., 1971, The effect of salinity on the maximum thermal gradient of a hydrothermal system at hydrostatic pressure: Econ. Geol., v. 66, p. 940–946.

Honda, Sakuro, and Muffler, L. J. P., 1970, Hydrothermal alteration in core from research drill hole Y–1, Upper Geyser Basin, Yellowstone National Park, Wyoming: Am. Mineralogist, v. 55, p. 1714–1737.

Keefer, W. R., 1972, The geologic story of Yellowstone National Park: U.S. Geol. Survey Bull. 1347, 92 p.

Keenan, J. H., Keyes, F. G., Hill, P. G., and Moore, J. G., 1969, Steam tables: thermodynamic properties of water including vapor, liquid and solid phases (International edition—metric units): New York, John Wiley & Sons, Inc., 162 p.

Koenig, J. B., 1970, Geothermal exploration in the western United States: Geothermics, Special Issue 2, v. 2, pt. 1, p. 1–13.

———1973, Worldwide status of geothermal resources development, *in* Kruger, Paul, and Otte, Carel, [eds.], Geothermal Energy: Resources, Production, Stimulation: Stanford, Calif., Stanford University Press, p. 15–58.

Marler, G. D., 1973, Inventory of thermal features of the Firehole River Geyser Basins and other selected areas of Yellowstone National Park: Natl. Tech. Inf. Service Rept. PB–221289, 648 p.

Mazor, E., and Fournier, R. O., 1973, More on noble gases in Yellowstone National Park hot waters: Geochim. et Cosmochim. Acta, v. 37, p. 515–526.

Muffler, L. J. P., White, D. E., and Truesdell, A. H., 1971, Hydrothermal explosion craters in Yellowstone National Park: Geol. Soc. Amer. Bull., v. 82, p. 723–740.

Smedes, H. W. and Prostka, H. J., 1972, Stratigraphic framework of the Absaroka volcanic supergroup in the Yellowstone National Park region: U.S. Geol. Survey Prof. Paper 729–C, p. C1–C33.

Studt, F. E., 1958, The Wairakei hydrothermal field under exploitation: New Zealand Jour. Geol. and Geophys., v. 1, p. 703–723.

U.S. Geol. Survey, 1972a, Geologic map of Yellowstone National Park: U.S. Geol. Survey Misc. Geol. Inv. Map I–711.

———1972b, Surficial geologic map of Yellowstone National Park: U.S. Geol. Survey Misc. Geol. Inv. Map I–710.

White, D. E., 1955, Thermal springs and epithermal ore deposits: Econ. Geology, 50th Anniversary Volume, p. 99–154.

———1957, Thermal waters of volcanic origin: Geol. Soc. America Bull., v. 68, p. 1637–1658.

———1967, Some principles of geyser activity, mainly from Steamboat Springs, Nevada: Am. Jour. Sci., v. 265, p. 641–684.

———1968, Hydrology, activity, and heat flow of the Steamboat Springs thermal system, Washoe County, Nevada: U.S. Geol. Survey Prof. Paper 458–C, 109 p.

———1969, Rapid heat-flow surveying of geothermal areas, utilizing individual snowfalls as calorimeters: Jour. Geophys. Research, v. 74, no. 22, p. 5191–5201.

———1970, Geochemistry applied to the discovery, evaluation, and exploitation of geothermal energy resources: United Nations Symposium, Pisa, Italy.

White, D. E., Brannock, W. W., and Murata, K. J., 1956, Silica in hot-spring waters: Geochim. et Cosmochim. Acta, v. 10, p. 27–59.

White, D. E., Hem, J. D., and Waring, G. A., 1963, Chemical compositions of subsurface waters: U.S. Geol. Survey Prof. Paper 440–F, p. F40.

White, D. E., Muffler, L. J. P., and Truesdell, A. H., 1971, Vapor-dominated hydrothermal systems compared with hot-water systems: Econ. Geology, v. 66, no. 1, p. 75–97.