PRELIMINARY REPORT ON THE LOCATION OF PRODUCING LAYERS OF GEOTHERMAL WELL HGP-A, PUNA, HAWAII

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ABSTRACT

Geothermal well HGP-A is located on the active east rift zone of Kilauea Volcano on the island of Hawaii. It is presently the only producing geothermal well in the islands, and numerous tests have been performed on the well in an effort to obtain a better understanding of Hawaiian geothermal systems.

This paper considers various data gathered from these tests in an effort to determine the possible location of producing layers of HGP-A. Temperature recovery profiles, drilling mud losses, flow meter tests, and pressure profiles from HGP-A are analyzed. And since these data on HGP-A are limited, research done on other geothermal wells around the world displaying similar characteristics as HGP-A have been used to interpret some of the data but only to describe the general characteristics of a geothermal well.

All data, examined first by type and then collectively, indicate the following about the location of the producing zones of HGP-A and the permeabilities associated with these regions:

- strata between 4300 - 4500 feet and 6000 feet to bottomhole appear to be major producing layers;
- secondary production appears to occur between 4600 - 5900 feet, an area of alternating permeable and impermeable layers.

In other words, the region about 4500 feet seems to mark the upper boundary of an active hydrothermal convection system, and permeable zones below 4500 feet may be producing regions.

DATA EVALUATION

TEMPERATURE RECOVERY PROFILES AFTER A FLASH

Figure 1 represents the temperature recovery profiles taken after a 2-week flash at HGP-A. Profiles 2 and 3 taken shortly after shut-in are still controlled by saturation conditions. Profile 4 taken five days after shut-in begins to approach pre-flash temperatures (profile 1) and shows two areas of sharp temperature increase (about 45°C in five days). The first increase occurs at 4300 feet and the other at 6250 feet. The zone between 5300-5900 feet displays a slower temperature recovery.

Similar temperature recovery profiles were observed at the Cerro Prieto geothermal well in Mexico (J. Septien, 1970) and at the Travale geothermal field in Italy (R. Cataldi, 1970) (Figures 2 and 3). In both fields, areas which displayed rapid temperature recovery after testing and temperature maximums corresponded to permeable regions from which hot water recharge into the well occurred.

Applying this information to HGP-A, temperature increases at two points a few days after shut-in can be attributed to the flow of hot reservoir fluid into the well. These points become prime suspects for zones of production. The regions between 5300-5900 feet exhibit a slower temperature recovery and probably represent an area of low permeability. The hot reservoir fluid is unable to circulate through this stratum; consequently it does not heat up as readily explaining the slower temperature recovery observed at that section.

TEMPERATURE RECOVERY AFTER PUMPDOWN TEST

In this particular test about 72,000 gallons of fresh water or roughly 4.5 times the volume of the well was pumped down HGP-A. It was assumed that during pumping, this water, initially at ambient temperature, would be forced into the more permeable regions of the formation and would cool them down. Once the pumpdown stopped, several downhole temperature measurements were taken to observe the temperature recovery of the well water at various depths. We are interested in locating regions of rapid temperature recovery once pumping had been completed since these regions indicate the flow of hot reservoir fluid into the well from the formation.

FIGURE 1 TEMPERATURE RECOVERY PROFILES AFTER DECEMBER 1979/JANUARY 1980 FLASH

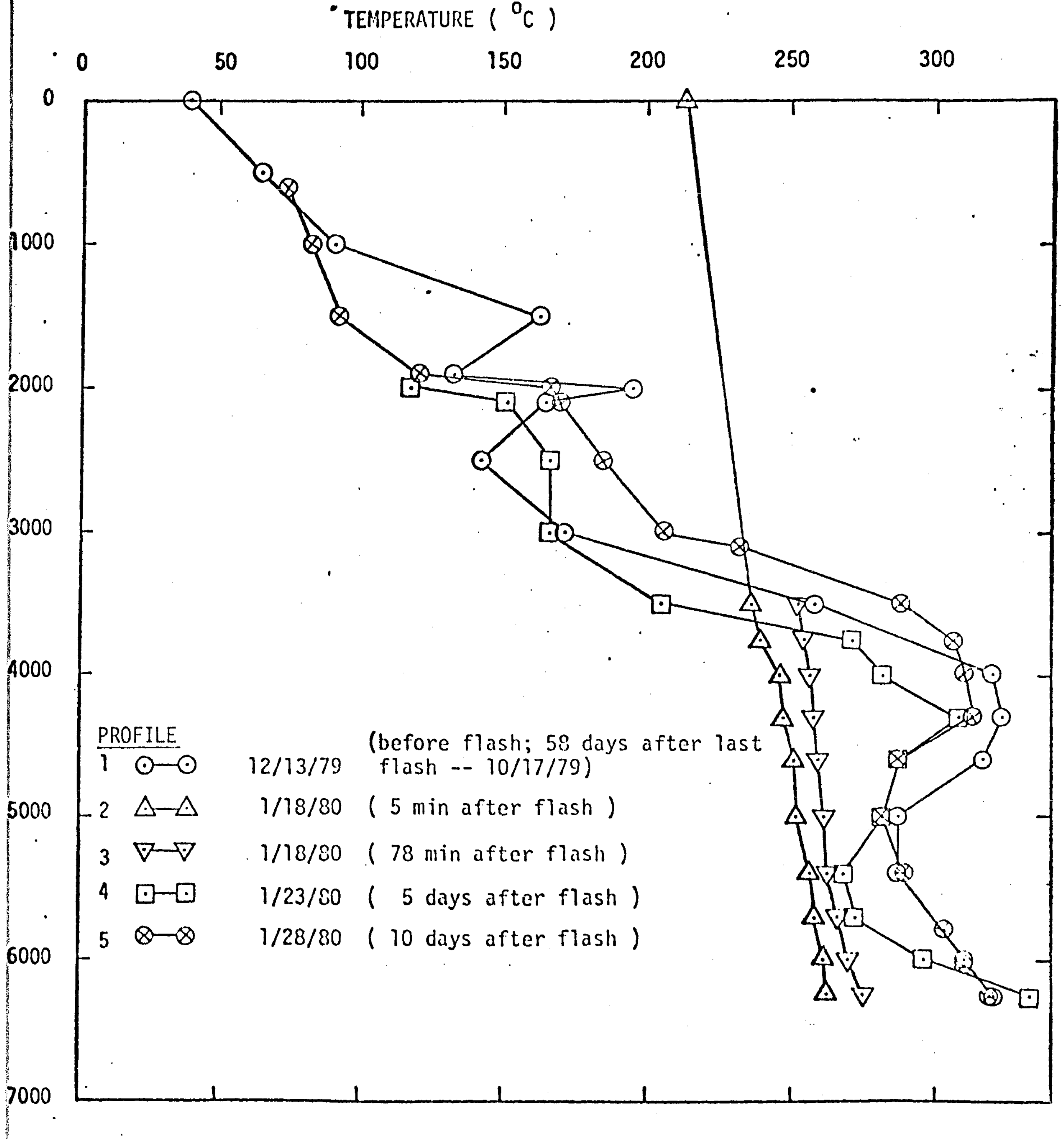


FIGURE 2 TEMPERATURE PROFILE RECOVERY OF A GEOTHERMAL WELL IN THE CERRO PRIETO GEOTHERMAL FIELD, MEXICO

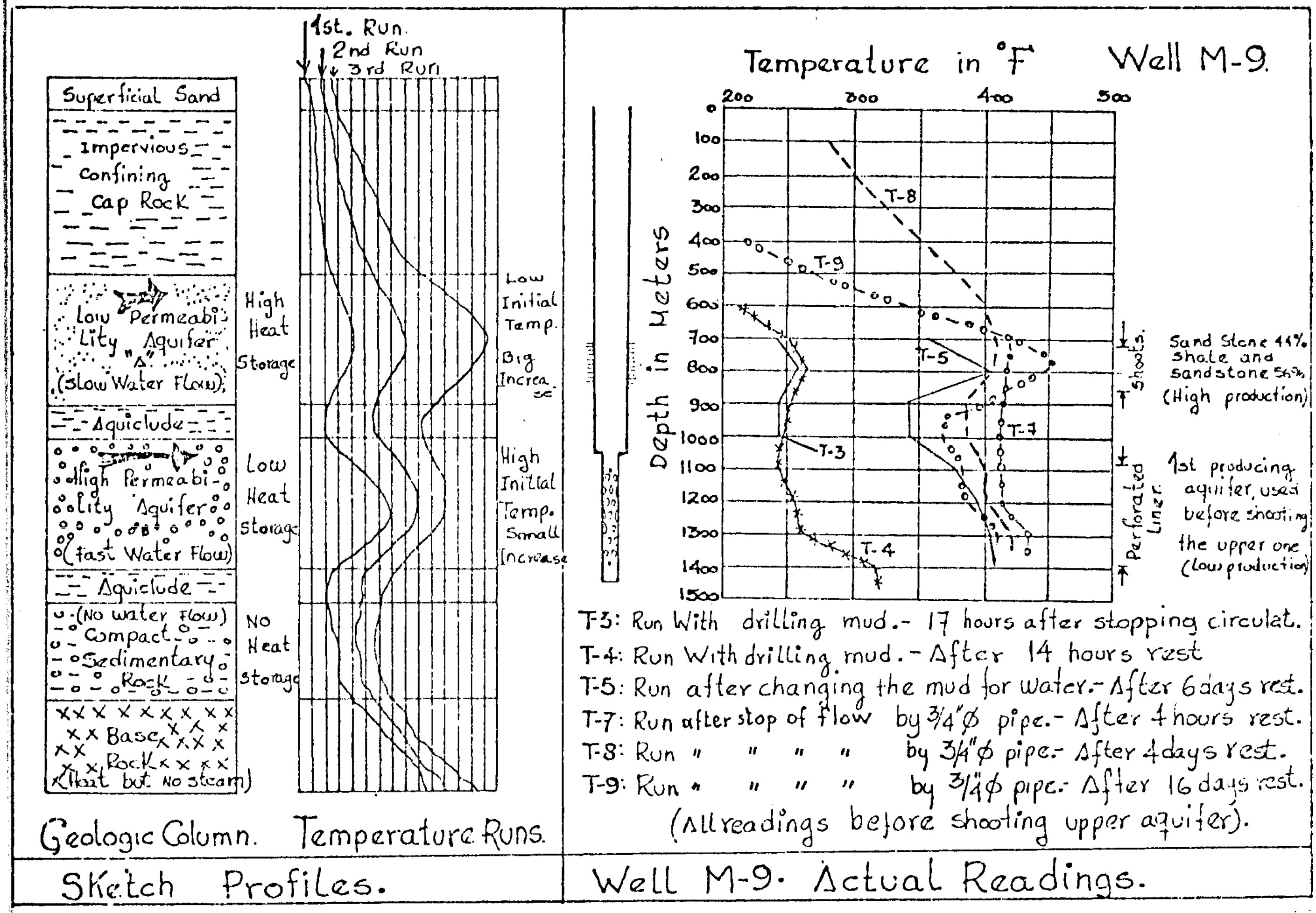
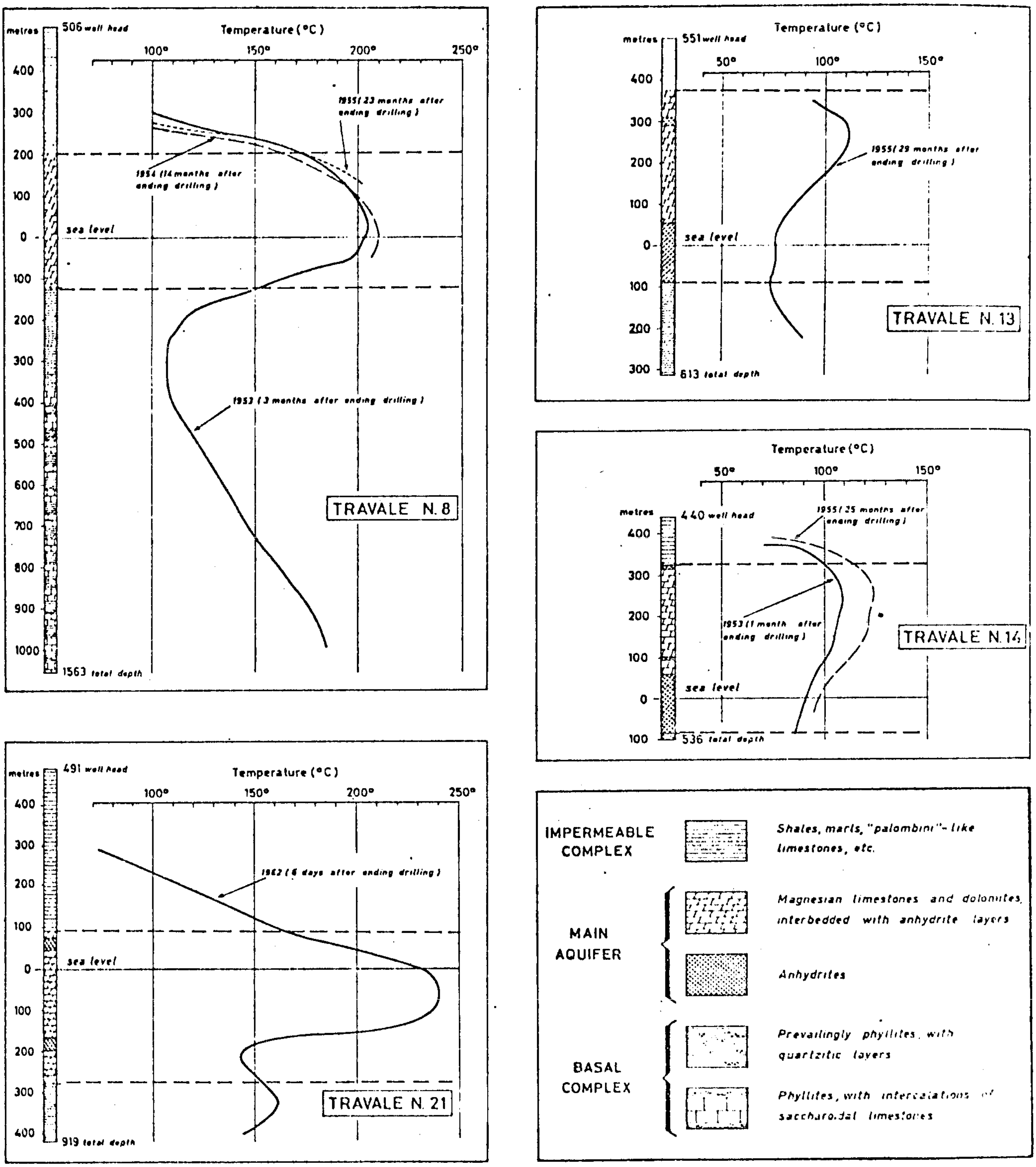


FIGURE 3 TEMPERATURE PROFILES OF WELLS IN THE TRAVALE GEOTHERMAL FIELD, ITALY



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boundary between main aquifer

Comparison of the temperature profiles taken before and directly after the pumpdown test shows that the water temperature in the well had obviously cooled down (Figure 4). The profile taken 2.25 hours after the completion of the test shows a rapid temperature recovery at around 4300 feet and at the bottom of the well (6400 feet) indicating the most probable regions into which reservoir fluid is entering the well from the formation.

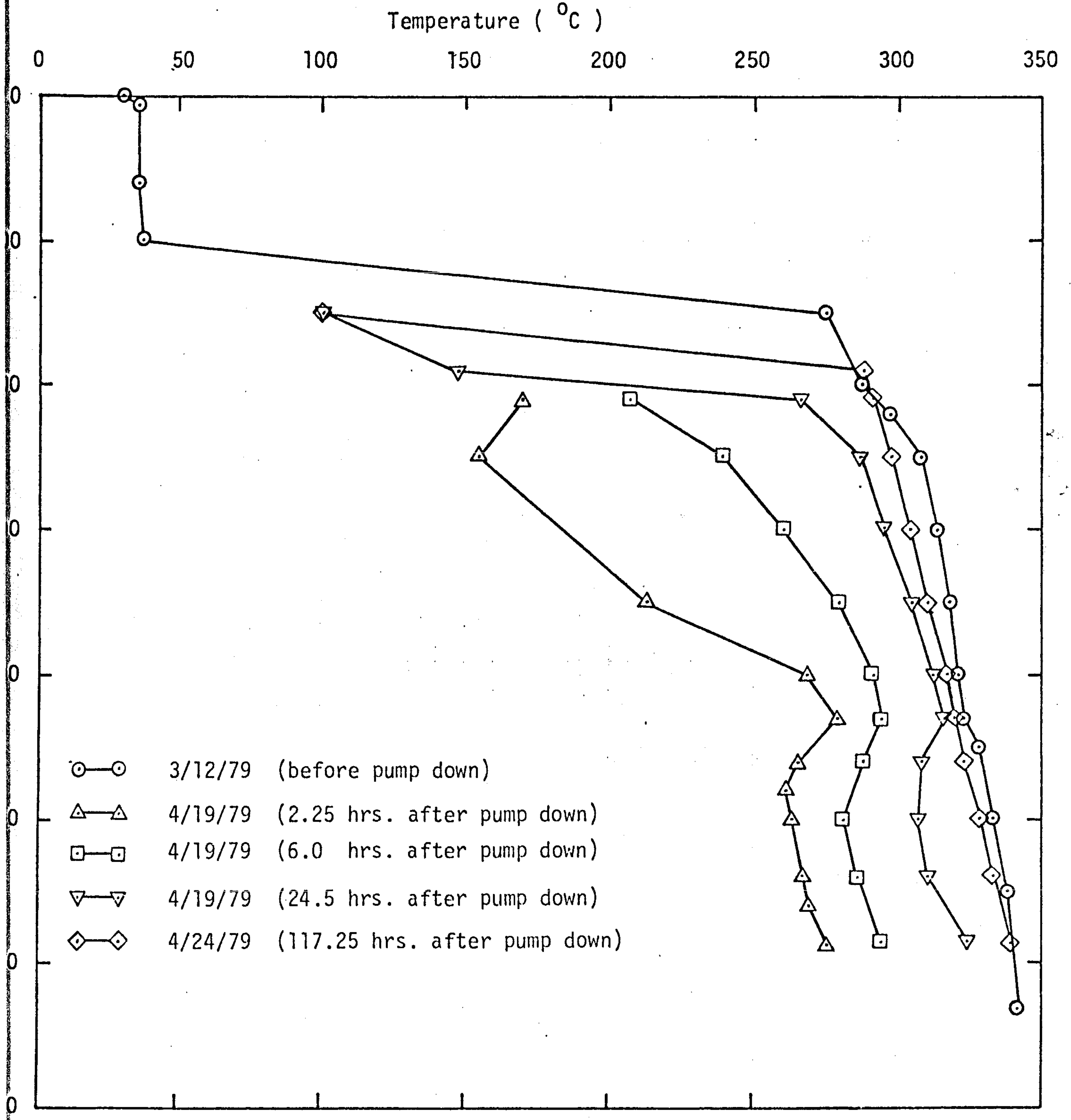
The area between 2200-4300 feet shows the greatest overall temperature decrease. This is probably a region of fairly high permeability into which most of the cold water penetrated. Successive temperature profiles taken after the pumping stopped indicate that this region experienced a fairly rapid temperature recovery but the thermal gradient seen between 2000-4300 feet (Figure 1, Profile 4) seems to suggest that this part of the well was probably heated by the convecting hot reservoir fluid rising from below 4300 feet. The ability of this hot water to circulate readily throughout the permeable formation above 4300 feet could explain the rapid temperature recovery exhibited by this region.

The region between 4300-6000 feet did not experience as great a temperature drop as did the zone above 4300 feet. This section of the well is hotter than the region above 4300 feet, and thermal equilibrium between the cold descending water and the hot well water occurred at a much higher temperature. It is also believed that only a small portion of the pumped down water penetrated below 4300 feet.

The temperature profiles after pumpdown reveal that the region between 4300 feet and bottomhole did not heat up as quickly as the section above 4300 feet. If this region is assumed to be fairly impermeable, the colder water sitting in the well would be heated by the convecting hot reservoir fluid entering from bottomhole. Since there can be no lateral movement of hot water through formation into the well in this section, the heating process could take longer since convective heating would occur only within the wellbore itself and explain the slower temperature recovery observed in this region.

The temperature profiles after pumpdown seem to suggest that two production zones exist, the first one located at 4300 feet and the second one near the bottom of the hole. The region above 4300 feet is permeable but nonproducing; a region of low permeability may exist between 4300 feet and bottomhole.

IGURE 4 TEMPERATURE RECOVERY PROFILES AFTER APRIL 1979 PUMP DOWN TEST



MUD LOSS DATA

MUD LOSS DURING DRILLING

Loss of mud circulation is a good indicator of areas of relatively high permeability because as drilling mud is pumped down into the well, it will penetrate and fill fractures and vesicles in the surrounding formation if they are there.

Table 1 condenses data from the drilling records kept by the drill crew and shows regions of mud loss during the drilling of HGP-A. Clearly, circulation loss occurred at several places. But of interest are mud losses below 3000 feet since this is the depth at which the solid casing ends and the slotted liner begins. Mud loss below 3000 feet occurred only during the drilling of the 8 1/2 inch diameter hole. At 5900 feet, 25 percent of the mud circulation was lost for about 4 hours, after which 95 percent returned. This continued until 6029 feet when 100 percent mud return occurred. Then between 6060-6170 feet, there was a 5 percent loss in circulation for about 4 hours which was followed by 100 percent resumption of circulation. There was no loss in circulation below 6170 feet.

It would appear from the mud loss record that two regions of high permeability exist below 5900 feet, one at 5900-6029 feet and the other between 6060-6170 feet.

MUD LOSS AFTER INITIAL COMPLETION OF THE WELL

After drilling of the well was completed, mud was pumped into the well bore to a predetermined height each morning of 19 days and allowed to sit overnight. The drop in mud level was measured the following morning. During this period, several temperature profiles were also taken. On each day, the temperature probe could not be lowered past a certain, changing depth. Table 2 shows the mud loss record and the maximum depth to which the temperature probe was lowered on a particular day.

Two reasons could explain why the temperature probe could not be lowered past a certain depth:

- mud caking in the well bore due to high temperatures in the formation;
- filling of the fractures and open pores in the formation with mud.

TABLE 1 DRILLING MUD CIRCULATION LOSS RECORD

Mud Circulation Loss Record

depth (ft)	drill bit diameter (in)	mud loss
34	9 7/8	lost circulation for 15 min. regained after 30 min.
42		lost circulation
207		pumped in 2000 gals of mud no loss
218		90% return
248		1500 gals
278		1000 gals
307		1000 gals
330		1000 gals
351-396		80-90 % return
27-32	15 1/2	return of circulation
38		lost circulation
38-175		drilling blind**
175-197		mud standing 35' below rotary table
206-290		drilling blind
300		mud level about 60 ft below rotary table
356-361		drilling blind
28-326	20	drilling blind
326-351		mud level at ground level but later dropped out of sight
359-400		drilling blind
0-41	26	drilling blind
41-48		1000 gals/hr for 4 hours after which 100% return occurred
68		lost circulation, about 4000 gals
77-227		drilling blind
1354	12 1/4	lost 9000 gals/hr for 3.33 hrs (?) lost 3000 gals/hr for 1 hr lost 450 gals/hr for 7 hrs. (?)
1403		750 gals/hr for 6.25 hrs (?)
1450-1850		100% returns
2324-5900	8 1/4	100% returns
5900		75% returns, about 100 bbls lost for 4 hours after which 95% return occurred
5968-6029		95% return for 6.5 hrs, then 100% return of circulation
6091-6170		lost 20 bbls/hr, about 95% return, for 8 hours
6330-6444		100% return

note: The question marks indicate that it was not recorded whether or not the loss in circulation occurred over the entire time period.

** Drilling blind indicates that the drilling was done without mud circulation. It is not possible to determine if these zones are permeable or impermeable.

TABLE 2 MUD LOSS UPON COMPLETION OF WELL DRILLING

Date	Mud Loss Down Well** (ft/day)	Change in Mud Loss (ft/day)	Temperature Probe Maximum Depth (ft)
4/30/76	300		--
5/01/76	286	- 14	5350
5/02/76	184	-102	5170
5/03/76	186	+ 2	--
5/04/76	174	- 12	4660
5/05/76	170	- 4	--
5/06/76	146	- 24	4650
5/07/76	107	- 39	--
5/08/76	84	- 23	--
5/09/76	67	- 17	--
5/10/76	61	- 6	--
5/11/76	55	- 6	4305
5/12/76	49	- 6	--
5/13/76	49	0	--
5/14/76	39	- 10	--
5/15/76	37	- 2	--
5/16/76	38	+ 1	--
5/17/76	30	- 8	--
5/18/76	30	0	--

**Mud was added each morning to bring the mud height in the well to approximately the same level.

--No temperature profile taken

NOTE: The above information was abstracted from the drilling logs kept by the crew at HGP-A well site.

It is probably a combination of both processes and from the data shown, it is not possible to determine which of the two dominates. Regions displaying an appreciable decrease in the amount of mud loss per day could, however, be indicating that possible permeable strata are filling up with mud.

Regions displaying this characteristic are between 5350-5170 feet, 4660-4650 feet, and 4650-4305 feet (Table 2). The strata below 5170 feet and around 4650 feet seemed to display the greatest amount of mud loss in feet/day. Below 5170 feet, mud loss fell from 300 feet/day to 184 feet/day within a two day period with the greatest decrease in loss between 5170-5350 feet. Between 4560-4660 feet, the mud loss dropped from 170 feet/day to 146 feet/day within a single day. Then between 4305-4650 feet, probably closer to 4650 feet, the mud loss dropped from 146 to 107 feet/day and from 107 to 84 feet/day within a three day period.

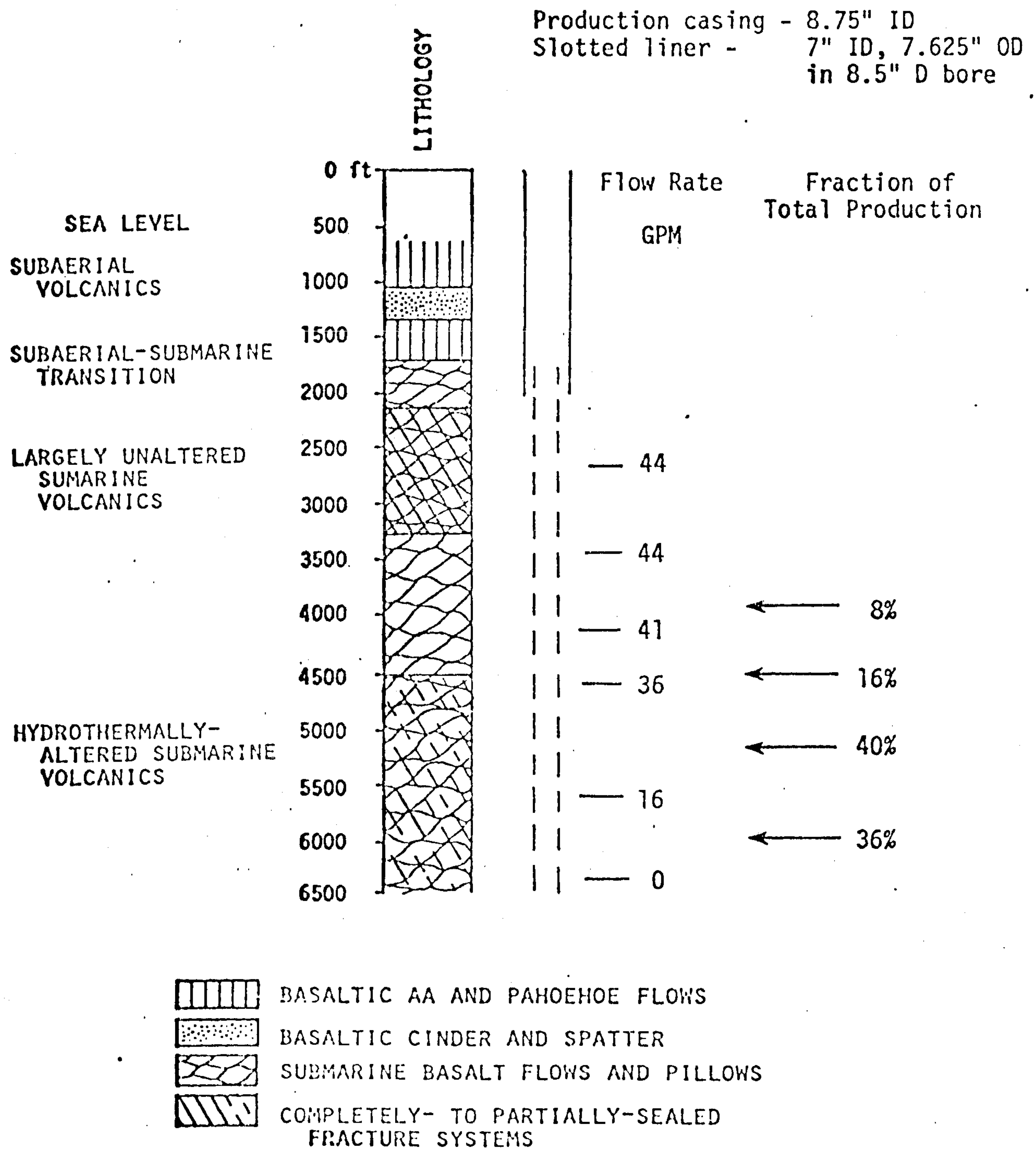
The results from this set of data are questionable since it is not known for certain whether mud is actually entering the formation or caking up in the well bore. But if we assume that a notable decrease in mud loss in a short time indicates that mud is filling the surrounding formation, it then seems likely that a permeable region may exist below 5170 feet, more likely between 5170-5350 feet and the another one around 4650 feet.

FLOW METER DATA

Several flow meter tests were run at HGP-A to determine producing layers of the well. In this test, the well was throttled to keep well fluid in an entirely liquid condition. A volumetric flow meter was sent down to measure the flow rate of the reservoir fluid into the well from the formation at various depths. Because of the many mechanical problems encountered, mainly silica precipitates clogging the impeller, only relative numbers obtained from the test can be used with a fair degree of confidence.

Figure 5 shows that most of the production (75 percent) occurred below 4500 feet. Because only 3 points were measured below that depth, it is not possible to determine exactly where the production regions are located or how many regions exist. It can only be established that at least one producing zone exists below 4500 feet.

FIGURE 5 FLOW METER TEST RESULTS



PRESSURE PROFILES DURING FLASHING

Figure 6 indicates pressure versus depth curves measured at HGP-A during flashing. Slight pivots in the direction of the pressure gradient (slope of the pressure versus depth profile) can be observed, the first shift occuring roughly around 2200 feet and the second one, between 4000-4500 feet. These shifts in pressure gradient are due to variations in the physical parameters which govern pressure losses experienced by fluid flowing upward in a vertical pipe. According to O. Rumi (1970), this pressure loss can be expressed by the following general relationship:

$$\frac{\Delta P}{\Delta L} \propto \left(f,\ Q^2,\ \frac{1}{D^5},\ \frac{1}{\rho m}\right) \qquad (1)$$

where:

$\frac{\Delta P}{\Delta L}$ = slope of the pressure versus depth curve or the pressure gradient

f = frictional coefficient

Q = total mass flow rate

D = inside diameter of the well bore

ρm = mean density of the well bore fluid

Are changes in the direction of pressure gradient during flashing due to the flow of reservoir fluid (i.e. variation in the mass flow rate, Q) into the well from the formation? As seen in Equation 1, the pressure gradient, $\Delta P/\Delta L$, is not only a function of the mass flow rate but also dependent upon the diameter of the well bore, the density of the well fluid, and the fractional coefficient. Thus, although we are mainly seeking the effect of the mass flow rate on the pressure gradient, the influence of the other variables must also be taken into consideration.

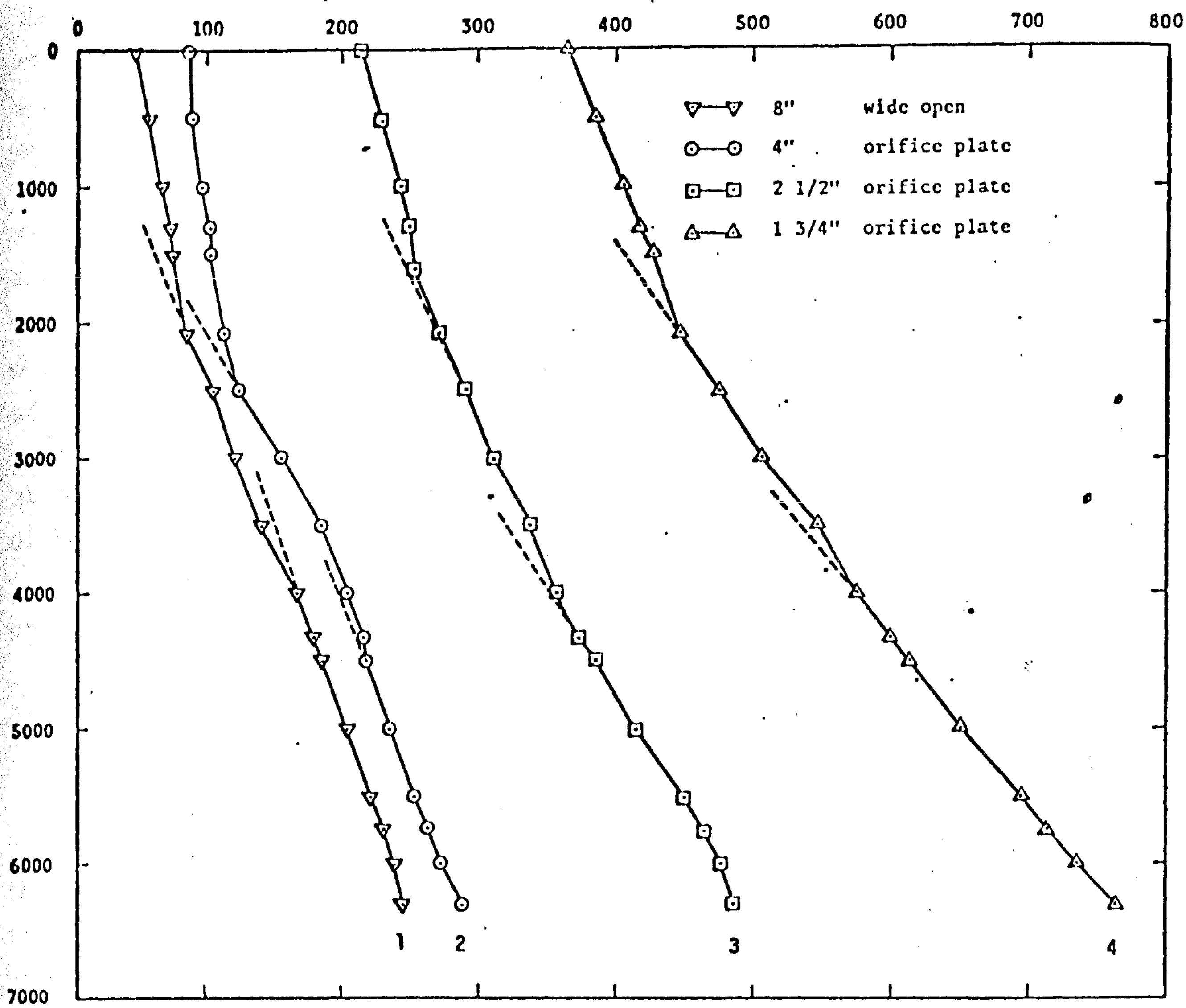
A few general assumptions were made in order to simplify the analysis and must be clarified before applying Equation 1 to the HGP-A pressure curves.

Assumption 1: Only the variables having first-order effects, or gross changes in the pressure versus depth curve, will be considered.

Assumption 2: Fluids which fill the entire well bore at HGP-A are a mixture of steam and water during flashing.

As a well undergoes flashing, fluid in the well experiences a change in phase from hot water into steam, much as a boiling pot of water on a stove.

FIGURE 6 PRESSURE PROFILES DURING FLASHING AT HGP-A
(JAN/FEB 1977 FLOW TEST)



THROTTLED FLOW DATA

ORIFICE SIZE (inches)	TOTAL MASS FLOW RATE (Klb/hr)	STEAM FLOW RATE (Klb/hr)	STEAM QUALITY (%)
8	101	64	64
4	93	57	64
2 1/2	84	48	57
1 3/4	76	39	52

The boundary between the steam and water is referred to as the depth of boiling. That is, below this depth the well is composed of hot water and above this depth the well consists of steam or in the case of HGP-A, a mixture of steam and water. At the depth of boiling, an abrupt shift in the slope of the pressure versus depth profile can be observed because the density of the well fluid decreases suddenly as it flashes from hot water to steam; if there are no changes in the flow rate or the diameter of the well, the pressure becomes a direct measure of the fluid density.

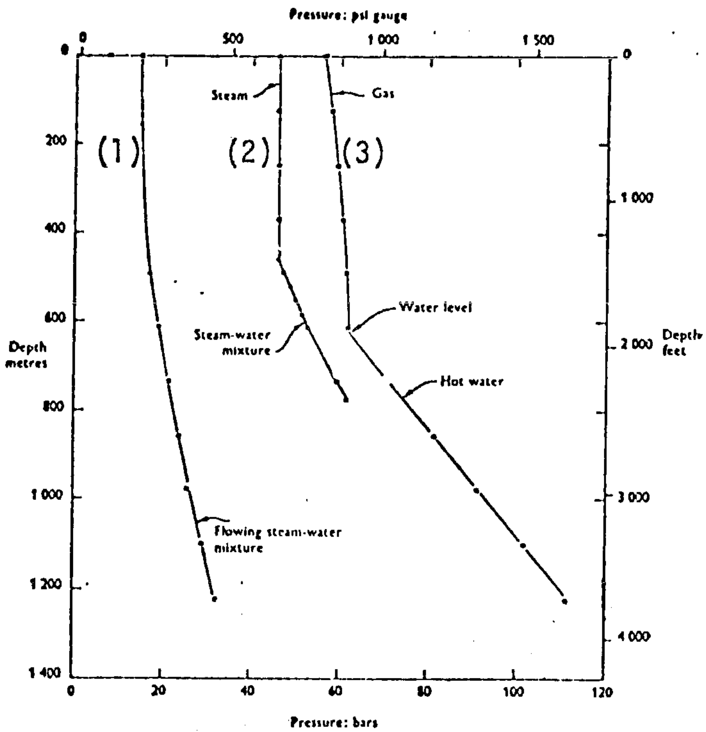
Figure 7 compares typical pressure versus depth profiles obtained during flashing. Curve (1) represents the profile of a flowing mixture of steam and water. Curves (2) and (3) represent profiles in which a change in phase of the well fluid occurs in the well bore. In both Curves (2) and (3) the depth of boiling is quite evident, and in comparing these two curves to the pressure profiles measured at HGP-A (Figure 6) this sharp shift in the pressure gradient is not apparent. Curve (1) displays a profile resembling those seen at HGP-A; therefore it is more likely that the entire well at HGP-A is composed of steam and water during flashing,and the changes seen in the direction of the pressure gradient observed at HGP-A are not due to a change in the phase of the well fluid.

Assumption 3: The effect of the frictional coefficient will be neglected.

Changes in the frictional coefficient occur when the roughness factor of the pipe alters. Generally in fluid flow, the higher the roughness factor, the larger the frictional coefficient. At HGP-A, changes in the roughness factor occur between the slotted pipes (higher roughness) and the unslotted pipes (lower roughness). Below 4000 feet, slotted pipes are alternated with unslotted pipes about every 40 feet. If the frictional coefficient had a marked control on the pressure gradient, several slope changes would appear between 4000-6300 feet, but there is only one obvious change in the pressure gradient. So it would appear that even though the frictional coefficient does change within the well bore, it does not profoundly affect the pressure gradient.

The above assumptions imply that gross changes in the direction of the pressure gradient are more likely due to variations in mass flow rate and

FIGURE 7 PRESSURE PROFILES OF TYPICAL WELLS



"Well Measurements", N. Dench, Unesco, 1973, Geothermal Energy (Earth Sciences,12) diameter of the well bore. The frictional coefficient and density of the well fluid would produce gradual or minor changes in the slope of the pressure versus depth profiles.

As mentioned at the beginning of this section, two slight pivots in the pressure gradient are observed at HGP-A, one at around 2200 feet and the other at 4300 feet. The boundary between the solid production casing and the slotted liner at the time the pressure measurements were taken was located at 2200 feet. The diameter of the solid casing is slightly larger than that of the slotted liner ($D_{solid\ casing}$ = 8.75 inches, $D_{slotted\ liner}$ = 7.0 inches). Equation 1 states that the pressure gradient is proportional to the square of the mass flow rate and inversely proportional to the fifth power of the diameter of the well bore. This indicates that diameter changes would have a more profound effect on the pressure gradient than changes in the mass flow rate. It is also highly unlikely that a major producing zone would exist at such a shallow depth.

Below 2200 feet the diameter of the slotted liner is constant and deviations in the pressure gradient are controlled by increases and decreases in the mass flow rate and the density of the well fluid. Density variations will not be considered since it was assumed earlier that sharp changes in the pressure versus depth curves can be caused only by a phase change in the well and this phenomenon does not occur at HGP-A. In Figure 6, a shift occurs around 4300 feet and most likely represents a major producing zone. There are no obvious gradient changes below 4300 feet; hence if another major producing zone exists below 4300 feet, it must be located at or very near the bottom of the well.

SUBSURFACE GEOLOGY

The description of the subsurface geology of HGP-A results from summarizing the observations made by

- Dr. Gordon Macdonald, geologist on HGP-A well site who examined cores on the field with a hand magnifier;
- Mr. Daniel Palmiter, head geologist on HGP-A well site who made macroscopic examination of core samples and rock cuttings;
- Ms. Claudia Stone, geologist who made microscopic examinations and x-ray diffraction analyses of the core samples and rock cuttings and whose Master's thesis is on "Chemistry, Petrology, and Hydrothermal Alterations for Hawaii Geothermal Project Well-A, Kilauea, Hawaii."

The rock cuttings and core samples retrieved from the drilling of HGP-A should give a fairly accurate description of the subsurface geology at various depths under and in the immediate vicinity of the well. Ten core samples were taken at 400-900 foot intervals and accounted for less than 2 percent of the total rock penetrated by the well. A total of 780 rock cuttings were collected from the shale shaker during drilling. The cuttings were taken at 10 foot intervals from 680-1420 feet below the ground surface, at 5 foot intervals from 1420-3000 feet, and at 10 foot intervals from 3500-6440 feet. Although the core samples were examined in the laboratory under more precise conditions, emphasis will be placed on the information obtained from the rock cuttings since they were collected more frequently and at more frequent intervals of depth than the core samples and would more readily reveal the overall geologic structure of the subsurface formation.

Figure 8 represents a summary of the geologic data obtained from the rock cuttings and cores. Chart I refers to the type of alteration products and secondary minerals present in the rock samples. Chart II indicates the percent of secondary minerals present in the rock samples with respect to the amount of ground mass. Chart III represents the percent of vesicularity in the rock chips and cores. Chart IV shows the percent of alteration the rock samples have undergone. Table 3 represents the microscopic and x-ray analysis of the cores.

This geologic data can be used to locate areas having relatively high permeability since the producing layers would be found only in areas which allow hot reservoir fluids to pass through them with comparative ease. But before data on the absence/presence of rock alteration, secondary mineralization, and vesicularity are analyzed, their importance in locating areas of permeability will be discussed.

Rock alteration simply means that a change in the rock's mineral composition has occurred. The type of alteration present at HGP-A is due to the passage of groundwater and/or hydrothermal fluids through the formation (C. Stone, 1977). The extent to which a rock hydrothermally altered is highly dependent upon the initial composition of the basaltic rock, the temperature and chemical composition of the circulating reservoir fluids, and the permeability of the rock formation.

The chemical composition of individual lava flows issuing out of Kilauea Volcano has not deviated appreciably with time. In other words, a lava flow that occurred 500 years ago basically had the same chemical composition as a

FIGURE 8   SUMMARY OF GEOLOGICAL DATA FROM THE ROCK CHIPS AND CORE SAMPLES COLLECTED FROM HGP-A

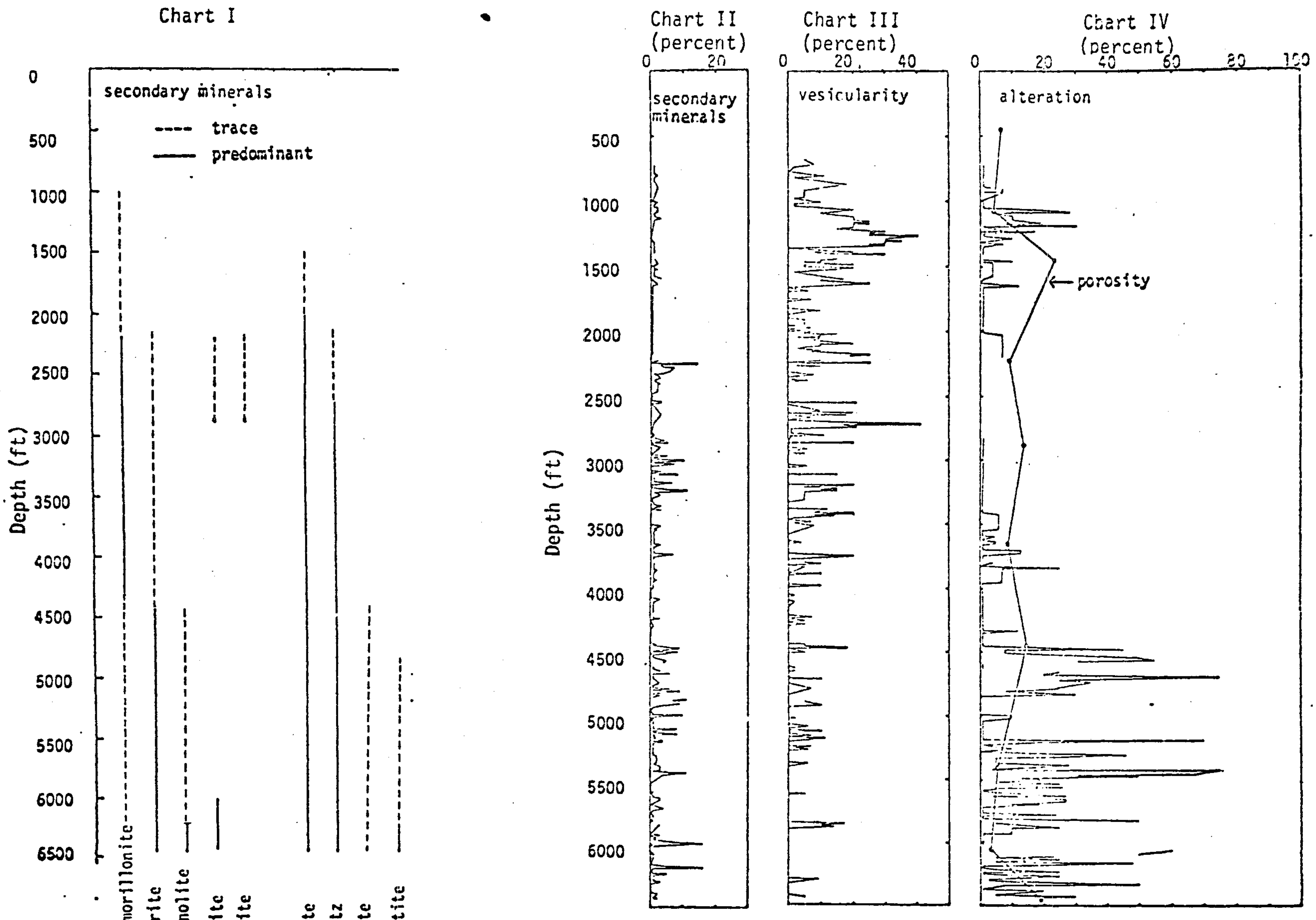


Chart I: X-RAY ANALYSIS DONE BY C. STONE
Charts II-IV: MACROSCOPIC ANALYSIS DONE BY D. PALMITER AND C. STONE

TABLE 3 SUMMARY OF CORE DATA

Core	Depth(ft)	% Vesicularity	Degree filled	% Alteration
1	438.0 *	6	unfilled	none
	439	8	unfilled	none
	439.6	18	unfilled	none
2	1043	13	unfilled	none
	1048	13	unfilled	none
3	1396 *	31	slightly	trace
	1401	25	slightly	trace
	1404	20	slightly	trace
4	2214	4	mostly	12
	2215	28	mostly	14
	2217	4	mostly	19
	2218 *	4	mostly	19
	2221	0	--	10
5	2858	20	mostly	45
	2861	trace	completely	20
	2867 *	0	--	13
6	3648	0	--	23
	3651 *	0	--	23
	3652	1	completely	23
	3658	6	completely	12
7	4429	0	--	50
	4432 *	0	--	50
	4435	0	--	55
	4439	0	--	53
8	5381 *	0	--	37
	5382	0	--	37
	5387	1	completely	37
	5389	2	completely	45
9	6015 *	0	--	87
	6017	0	--	80
	6020	0	--	75
10	6429.8*	trace	mostly	84
	6430	12	mostly	96
	6434	6	mostly	95

* point count

MICROSCOPIC AND X-RAY ANALYSIS DONE BY C. STONE present day lava flow. (M. Ryan, personal communication, 1980). Assuming, then, that the basaltic rock located below the HGP-A well site was originally similar in chemical make-up, the temperature and chemical composition of the fluids traveling through the rock layer and the permeability of the formation influence the degree of alteration a rock stratum undergoes.

Temperature controls the amount of rock minerals that will be dissolved from the formation by the circulating fluids and also acts as a catalyst to accelerate chemical reactions between the fluids and the rock formation. The permeability of the rock strata determines the direction of fluid flow and controls the volume of fluid passing through the formation. Generally, the hotter the circulating fluid and the more fluid passing through the formation, the more intense the degree of alteration. It is erroneous to conclude, however, that a high degree of alteration always indicates the presence of permeable strata. It does indicate that this zone was permeable at one time, but it does not necessarily mean that it is still permeable; observations elsewhere have shown that hydrothermal alteration can, over a period of time, cause a self-sealing effect through the deposition of secondary minerals (E. Facca, 1965 and G.W. Grindley, 1975).

Secondary mineralization takes place when dissolved minerals in the circulating hydrothermal fluids travel into the cooler regions of the formation and precipitate into open vesicles and fractures. Commonly, quartz is the most abundant secondary mineral deposited, but other minerals such as calcite, zeolites, feldspars, and hematite also help decrease the permeability of the formation (G.W. Grindley, 1975).

The vesicularity of the formation is important in rock permeability if the pores are interconnected to allow the movement of fluid through them. At HGP-A, it is believed that vesicularity does not play an important part in the permeability of the rock formation. The vesicles are poorly connected and rock permeability results from fractures, spaces between fragments in the aa clinkers, and lava tubes (G. Macdonald, 1976).

What we are seeking in the analysis of the subsurface geology, then, are hot, highly fractured strata displaying a considerable degree of alteration but also having a low percentage of secondary mineral deposition. Only the geology below 3000 feet will be considered since this depth marks the boundary between the solid casing and the slotted liner.

GEOLOGY BETWEEN 3000-4500 FEET

In his report, Palmiter states that the section from 1700-4500 feet consists of 34 individual flow units averaging 70 feet in thickness. He also mentions that the layer between 3300-4500 feet is highly fractured, but the fractures and vesicles between 3000-3450 feet are filled with secondary mineral deposits. Secondary mineralization, then, decreases noticeably between 3450-4500 feet (Figure 8, Chart II).

There appears to be one zone between 3400-4500 feet in which some alteration has occurred (Figure 8, Chart IV). Elsewhere within this region, hydrothermal alteration of the rock formation is insignificant.

GEOLOGY BETWEEN 4500-6445 FEET

According to Chart IV (Figure 8), there is a drastic increase in rock alteration below 4500 feet. Between 4500-4800 feet, most of the rock cuttings have been altered by at least 30 percent. Nowhere else on Chart IV is there indicated a comparable degree of alteration over an equivalent span of depth.

Between 4800-5300 feet, hydrothermal alteration diminishes and is at times nonexistent (Chart IV). This is in part supported by the core data (Table 3). Core 7 (4430-4440 feet) has an average alteration of about 52 percent whereas Core 8 (5379-5389 feet) has been altered by 39 percent.

Below 5300 feet, the degree of alteration fluctuates with depth, reaching highs of about 80 percent and lows of about 1 percent (Chart IV), but most of the rocks have been altered by at least 10-20 percent. The core data (Table 3) seem to indicate that hydrothermal alteration of the deeper parts of the well is much higher than indicated on Chart IV. As stated earlier, the core data give more accurate figures while information from the chips gives approximate values.

The amount of secondary mineralization below 5300 feet is also erratic. According to Palmiter's observations, fractures in this zone occur both along the boundaries between lava flows and within the individual flow units themselves. Secondary mineral deposition in these fractures is complete in narrow zones (4580, 4890, 5080, 5130, 5640, 5990, and 6180 feet). Only partial filling seems to be occurring between these zones, the thicknesses of which can be approximated to range between 30-120 feet (Chart II).

At 6214 feet, actinolite surpasses chlorine as the dominant alteration product and hematite becomes the dominant opaque mineral (Chart I). Stone states that the occurrence of hematite along with actinolite indicates either

1). higher temperature at that depth,
2). a hydrous regime, or
3). a different type of alteration process.

The first condition can probably be discounted since numerous downhole temperature profiles have revealed that the temperature measured at the bottom of the well is nearly equal to that measured at 4500 feet, and at this depth, hematite and actinolite are only minor constituents. Explanations 2 and 3 are both probable but there is not enough available data to determine which of the two conditions dominates.

Macdonald has reported that Core 10 (6429-6439 feet) has an extremely fractured nature. Many of these fractures appear slicken-sided and some are coated with a whitish precipitate, suggesting that these fractures are fairly old.

CONCLUSIONS FROM THE GEOLOGIC DATA

The geologic evidence suggests that a physical process dominates below 4500 feet different from that in the shallow layers. This is due to a notable increase in the percent of secondary mineralization and an abrupt rise in the degree of hydrothermal alteration the rocks have undergone below that depth. It is believed that 4500 feet marks the upper boundary of an active hydrothermal convection system (D. Palmiter, 1976). Assuming that this is true, the permeable zones located below this depth are all potential producing zones because the convecting hydrothermal fluids will travel through the permeable regions of the formation.

The zone between 4400-4800 feet is an area of fairly extensive alteration and although secondary mineral deposits also increase, these deposits are rather erratic and only partial closing of this region is probably occurring. The fact that nearly all the rocks in this zone average at least 30 percent alteration, far more than seen elsewhere in the geological profile over a comparable depth, seems to indicate that this region has a high ability to pass fluids and could possibly represent a major production region. This zone is then followed by a layer of relatively low alteration between 4800-5400 feet which is most probably a region of low permeability. Below 5400 feet, both the degree of alteration and the amount of secondary mineralization fluctuate. Secondary mineral deposits fill the formation at sporadic intervals and this intermittent plugging of certain strata is evident between 4580-6180. This region may represent several thin permeable producing zones alternating with strata rendered impermeable by secondary mineral deposits. There could be another major producing zone located below 6200 feet: the dominance of hematite and actinolite possibly indicate a more hydrous regime. Macdonald has also noticed that the final core taken was extremely fractured and these fractures were fairly old. And Stone adds this interpretation on the location of the geothermal reservoir at HGP-A.

> Beneath a zone of unaltered lavas, high temperatures and hydrothermal fluids have created three altered zones, each marked by the dominance of a particular mineral. The uppermost altered zone, 675 m - 1300 m [2215-4265 ft] is characterized by montmorillonite with minor calcite, quartz, one or more zeolites, and chlorite. Vesicles in this zone are only partly filled with secondary minerals. The second hydrothermal zone, 1350 m - 1894 m [4429-6214 ft] begins with the occurrence of extensive chlorite replacing montmorillonite as the dominant alteration product. Quartz, actinolite, and montmorillonite are the accessory secondary minerals. All vesicles and fractures are completely filled with this zone.
>
> The third zone of alteration is observed beginning in core 9, 1894 m [6213 ft] and is dominant in core 10, 1959 m [6427 ft]. Actinolite is the dominant mineral; chlorite, quartz, opaque grains are the accessory alteration products. Both the degree and type of alteration found in core 10 are distinct from those encountered in the lavas above. It is far more extensive than alteration at shallower depths although it is beginning to be seen in core 9.... From these observations, realizing that the cores constitute less than two percent of the well, it could be concluded that the first zone of hydrothermal alteration, between 675 m - 1350 m [2215-4429 ft], is relatively permeable, allowing groundwater coming from or heated by conduction from greater depths to circulate freely. The zone between 1350 m - 1959 m [4429-6428 ft] is relatively permeable, a self-sealed rock capping the geothermal reservoir. Below 1959 m [6428 ft] is the geothermal reservoir itself, a moderatly permeable zone allowing thermal fluids to move with relative ease. The decrease in quartz in this zone and the high concentration of silica found in thermal waters issuing out at the surface indicate that the thermal waters may originate from this zone.

CONCLUSIONS

Table 4 summarizes all the data analyzed in this paper by separating them into two sections. The first consists of data which determine the producing regions of the well and the second indicates areas of permeability which can be associated with a producing region.

Strata around 4300-4500 feet and 6000-6400 feet show the strongest evidence of being major producing regions. Between 4600-5900 feet, some production appears to be occurring. Based on the geological data, this region is composed of several thin strata of alternating permeability and impermeability. The region below 4500 feet seems to mark the upper boundary of an active hydrothermal convection system. If this assumption is valid, and the geological data seem to indicate so, it is highly probable that the permeable zones below 4500 feet are production regions.

As a final note, it must be emphasized that the theory advanced in this paper is highly speculative since all the data analyzed were obtained from a single well. Several more step-out wells must be drilled before a clearer understanding of the Hawaiian geothermal wells can be established.

TABLE 4 SUMMARY OF ALL DATA ANALYZED

	EVIDENCE	4300	4400	4500	4600	4700	4800	4900	5000	5100	5200	5300	5400	5500	5600	5700	5800	5900	6000	6100	6200	6300	6400
		DEPTH BELOW GROUND SURFACE (feet)																					
PRODUCTION	Flow Meter			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
PRODUCTION	Pressure	x	x	x																		x	x
PRODUCTION	Temperature 1) After Flashing	x	x																x	x	x	x	x
PRODUCTION	Temperature 2) After Pump Down	x	x																x	x	x	x	x
PERMEABILITY	Geology		x	x	x	x	x							•	•	•	•	•	•	•	x	x	x
PERMEABILITY	Drilling Mud 1) Before																	x	x	x	x		
PERMEABILITY	Drilling Mud 2) After				•					•	•	•											
	High probability of being permeable/producing 3 or more x	*	*	*															*	*	*	*	*

LEGEND:

x Permeable/Producing Depth

• Questionable whether permeable/producing. Not enough available data.

* High probability of being permeable/producing 3 or more x.

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