HYDROLOGY AND GEOCHEMISTRY OF
A HAWAIIAN GEOTHERMAL SYSTEM: HGP-A

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ABSTRACT

A water quality monitoring program of the Hawaii Geothermal Project well A (HGP-A) was conducted for downhole depth samples and continuous discharge samples in 1976 to 1977. The well water was slightly saline (about 5-10 percent ocean water) and nearly depleted of magnesium, but contained high concentrations of silica and sulfide. The chemical composition of the well water did not vary much with depth even though the sampling reached the well bottom [approximately 1768 m (5800 feet) below sea level]. The well fluid temperature was higher than that of any Hawaii ground water; a maximum of 358°C (676°F) was recorded at the bottom of the well. The water was low in tritium but unexpectedly high in carbon-14 when compared with the surrounding ground water [sampled as close as ~1609 km (1 mile) away]. Mass balance calculations involving carbon and its isotopes are consistent with a model proposing that 13 percent of recharge is from sea water. During continuous flow tests, the total well yield was 83,400 lb of steam per hour, equivalent to ~150 gpm with 70 percent steam and the rest water. For most constituents measured, there was a one to three day buildup period before approach to a steady state concentration. Water quality data, coupled with other measurements, indicate that the well is either poorly developed or located in a formation of low transmissivity. The moderately high rainfall and high surficial permeability allow substantial rain water infiltration. Actual subsurface water circulation is open to interpretation because of our uncertainty about geologic formations. Geophysical evidence suggests that deep dikes or intrusive bodies may be located on the ocean side of the well; such barriers would retard the encroachment of sea water into the well.

 

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PREFACE

Exploration for and exploitation of geothermal energy resources underlying an oceanic island necessitate detailed understanding of the island's complex hydrologic system. The problems of well siting, well evaluation, and environmental impact require information on the locations, temperatures, isotopic, and geochemical characteristics of accessible geothermal sources; the characteristics, production rates, and migration paths of magma-derived (primary geothermal) fluids and gases; the natural rate of flow and pathway of fresh ground water recharge to a thermal source; and the residence time, homogeneity, and reservoir size of composite (fresh water, sea water, magmatic fluid) 'geothermal' fluids. We must also consider how the answers to the preceding questions change in response to drilling and artificial withdrawal of brine, steam, or other materials--that is, what are the short-term and long-term dynamic responses of the system to exploitation? Non-thermal water and related resources (e.g., ground water suitable for potable, agricultural or industrial use, coastal fisheries, recreational, and aesthetic aspects of both fresh and ocean waters) exist in the geothermal areas, and the effects of fluid removal and disposal must be monitored.

This report represents the fourth in a series which will attempt to provide the information needed to properly assess the potential for the large-scale withdrawal of geothermal fluids. A combination of hydrologic, isotopic, and geochemical techniques have been used. Geophysical techniques have also been extensively employed but are reported elsewhere (A. Furumoto and M. Broyles, in prep.). We discuss here the chemistry of several Puna area wells sampled previous to the drilling of HGP-A (baseline measurements) and the water quality of fluids collected from HGP-A from its first flow on July 19, 1976 to February 10, 1977.

INTRODUCTION

The Hawaiian geothermal system is of more than academic interest; it has many far-reaching applications to the geothermal study of other areas. This is clear from a consideration of plate tectonics theory. According to this theory, material from the deeper parts of the mantle upwells along oceanic rift zones (crustal spreading centers). The ocean floor and lithosphere thus move along on a giant conveyer belt and then plunge back into the mantle at points of crustal convergence such as island arcs and continental margins (subduction zones). Most of the volcanoes of the world occur along subduction zones.

Other mechanisms must be postulated, however, to explain the Hawaiian volcanic archipelago, which occurs in the middle of the Pacific Ocean (no subduction zone) but where mantle material nevertheless has broken through the lithosphere. One is that it represents the consequence of the Pacific crustal plate migrating across a "hot spot" in the mantle. Under this concept there is only one center of volcanism (that now beneath the island of Hawaii), and the archipelago extending up to Midway Island marks the trail of crustal migration. Another concept is that the archipelago represents the path of a crustal rift with active volcanism on its leading edge where the rift, as it grows like a crack migrating across a plate glass window, intersects transform fault fractures. Either concept satisfies the increase in progressive age of the archipelago from the island of Hawaii where there is present volcanism to the older northern islands. The latter theory has several points in common with spreading centers in that volcanism would occur where there is an opening in the crust and reduction in confining pressure. Unlike other spreading centers, the Hawaiian volcanoes are exposed at ground surface, and thus they can be readily studied and experiments easily performed that would be difficult, if not impossible, elsewhere. The experience gained in Hawaii will thus be applicable to the study of other potential geothermal areas.

The island of Hawaii is made up of five volcanoes (Fig. 1): Kohala, Hualalai, Mauna Kea, Mauna Loa, and Kilauea. With each volcano are associated rift zones; each rift zone is named according to the direction in which it radiates. For example, Mauna Loa has four rift zones, southwest, west, north and north-east; Kilauea has two rift zones, southwest and east. The area through which the east rift of Kilauea runs is called the Puna district, which includes the villages of Kapoho and Kalapana. The flank of the east rift erupted in 1955, 1960, and 1977, and the southwest rift was active in 1971. The east rift starts from Kilauea caldera in a southeasterly direction, and then about 8 or 9 km from Kilauea crater, the rift makes a nearly right angle bend and heads east-northeast to enter the sea at Cape Kumukahi (Kapoho). Along the rift zone are pit craters, cinder cones, open cracks in the ground, and some steaming vents.

HGP-A is situated in the Puna area along this east rift zone (Fig. 2). A platform formed by Mauna Loa lava flows underlies the Puna area, and on this platform lie the lava flows and ash deposits from Kilauea (Stearns and Macdonald, 1946; Macdonald and Abbott, 1970; Stone, 1977a). The well is the deepest drilled well in Hawaii, extending 1967 m (6455 ft) from an elevation of 194 m (604 ft). The maximum fluid temperature of 358°C (676°F) occurs in the bottom of the well; a secondary maximum occurs at ~1370 m (4500 ft) (Fig. 30).

Figure 1. Map of the island of Hawaii illustrating the major volcanoes and rift systems (after Macdonald, 1956).

Figure 2. Map of the Puna district of the island of Hawaii. The locations and temperatures of all ground water sources are shown.

The well fluid is a mixture of water (~70 percent steam) with a small amount of other gases consisting mostly of CO₂, H₂S, N₂, and H₂ (Thomas and Kroopnick, "Isotopes and Gases in the Hawaiian Geothermal System: HGP-A", in prep.). After 42 days of discharge through a 7.6-cm (3 in) orifice, it was producing at 83,400 lb/hr (~150 gal/min), the well head pressure was 168 PSIG, the temperature was 190°C, and its enthalpy was 890 BTU/lb.

The well is cased to a depth of about 692 m (2270 ft). Below this depth a 19.4-cm (7-5/8 in) slotted liner was used to permit fluid penetration (Kingston et al., 1976). The volume of the well bore is about 69,000 liters (18,000 gallons). Samples of gas, steam, and water were collected downhole, at the surface using a twin cyclone separator or condenser, or at the weir after steam-water separation in the silencer stack (Fig. 3).

Figure 4 chronologically summarizes the flow periods and dates of water samplings of HGP-A well waters. Starting in July 1976, three sub-four hour discharge periods preceded four periods of longer duration: 14 days in November 1976, 6 days in December 1976, 15 days in January-February 1977, and 42 days in March-May 1977. Downhole (depth) samples were collected in August, October, and December of 1976, and in January and February of 1977 under no-discharge conditions. One set of downhole samples was collected during low-flow conditions (January 26, 1977). Samples were collected at the weir and from a condenser on an irregular basis during all flow periods.

EXPERIMENTAL METHODS

Downhole samples were collected using a 'Klyen' water sampler capable of withstanding extremely high temperatures and pressures (Fig. 5). Because the maximum observed temperature of HGP-A (358°C) and pressure (160 kg/cm² ≈ 2275 PSI) exceed the design specifications of the sampler, it was necessary to modify the shutoff valve plunger before reliable samples were obtained. Despite the modification, it is still possible that the results listed in Appendix 1 do not correspond exactly to the listed depth.

To assess the possibility that water is flowing into the well at intermediate depths, several attempts were made to collect "downhole" samples just prior to the onset of 'flash'. Figure 3 shows the well head configuration that permits downhole sampling during flow conditions. Several attempts to collect water from downhole while the well was flashing did not yield enough water for analyses. Additional water samples were

Figure 3. The flow test equipment and instrumentation installed on HGP-A.

Figure 4. The well discharge and water sampling schedules for HGP-A.

Figure 5. The Klyen deep well subsurface sampler used to collect the downhole samples. Upon arrival at the proper depth the suspension wire is vigorously shaken causing the inertia mechanism to fracture the glass tube. Water pressure opens the non-return valve and allows the vessel's interior and exterior pressures to equalize. When the interior pressure rises sufficiently, the valve spring returns to the closed portion, entrapping a sample at the downhole pressure.

collected at the weir, from a condenser coil located 'upstream' from the orifice plate and from a twin cyclone separator (Ellis et al., 1968) located so as to permit collection of samples at different pressures (Fig. 3).

The water samples were immediately transferred to plastic bottles and returned to the laboratory for analyses. As noted in the data tabulation, pH, conductivity, salinity, and alkalinity were occasionally measured at the well site within minutes of collection.

The analytical techniques used for water analyses are tabulated below:

pH	Photovolt model 126A pH meter
Conductance	Yellow Springs Instrument model 33 S-C-T meter
Salinity	Yellow Springs Instrument model 33 S-C-T meter
Chloride	As per <u>Standard Methods for the Examination of Water and Wastewater</u> , 14th ed., 1975, APHA-AWWA-WPCF, Section 3088, Mercuric Nitrate Method utilizing high chlorides mercuric nitrate titration.

All samples were bubbled with nitrogen gas to reduce the H_2S concentration prior to titration.

Silica	As per <u>Methods for Collection and Analysis of Water Samples</u> , Geological Survey Water Supply Paper 1454, <u>Rainwater and Thatcher</u> , Section D: 34a-1, Molybdate Blue Method.
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Silica in solution as silicic acid or silicate reacts with ammonium molybdate under acid conditions to form yellow-colored silicomolybdate complex, which is in turn reduced by sodium sulfite to form the molybdate color. Colormetric determination conforms to Bier's law under concentrations of 100 mg/l.

All samples were run at a 10:1 dilution. Colormetric determinations were performed on a Perkin-Elmer Coleman 46 Spectrophotometer at 700 nm.

Sulfide	Modified as per <u>Standard Methods for the Examination of Water and Wastewater</u> , 14th ed., 1975, APHA-AWAA-WPCF, Section 428D, Titrimetric (Iodine) Method.
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100-ml sample bottles containing 2 ml of 2N zinc acetate $(ZnC_2H_3O_2)_2 \cdot 2H_2O$ were filled with

sample in the field. Laboratory analysis with iodine addition and subsequent sodium thiosulfate back titration were performed on unfiltered samples with no pretreatment.

Bicarbonate As per Standard Methods for the Examination of Water and Wastewater, 14th ed., 1975, APHA-AWWA-WPCF, Section 403, Alkalinity.

Field determination of alkalinity was measured by phenolphthalein and methyl orange indicators with Photovolt Model 126A verification. The dominant alkalinity form, due to pH considerations, was bicarbonate alkalinity. To conform to hydrology standards, however, the bicarbonate alkalinity (HCO_3^-) is reported as calcium carbonate (CaCO_3) as defined in Table 403 I of Section 403.

Cations
(magnesium,
calcium,
potassium,
and sodium) As per Analytical Methods for Atomic Absorption Spectrophotometry, Perkin-Elmer, Norwalk, Connecticut, U.S.A.

Samples were prepared by initial filtering through Whatman 40-Ashless Medium speed filter paper. Calcium and magnesium samples were diluted to 0.25 percent (W/V) Lanthanum solution (La) and 5 percent (V/V) HCl prior to analysis. Potassium and sodium samples were run at the appropriate dilution with no additions.

Atomic absorption spectrophotometry was performed on a Perkin-Elmer Model 303 Atomic Absorption Spectrophotometer. All samples were atomized into an air-acetylene flame under the standard conditions indicated in the reference manual.

Tritium and Carbon-14 The method used for the tritium analysis of water samples consists of enrichment by electrolysis and liquid scintillation counting (Hufen et al., 1974a). The precision of the analyses represented here is approximately ± 1.2 TU where TU stands for tritium unit. Carbon-14 analyses were performed by extracting the total inorganic carbon from a water sample, converting the gas to benzene, and finally measuring the activity via a liquid scintillation counter (Hufen et al., 1974a).

RESULTS: PUNA AREA WELLS

Mean annual rainfall is about 125 inches in the Puna area. Because of the highly permeable young basalt on the surface, there are no surface streams. The vegetation is dominantly guava forest with shrub and some papaya plantations; the land is sparsely populated. Household water supply is by roof catchment and cistern.

Eight major sources of ground water (wells, shafts, and springs) were studied (Fig. 2 and Table 1). All were sampled (surface samples) in January and July, or in January and October of 1975. Rain water samples were also collected and analyzed. Geothermal #3 is the hottest and most saline well and is the only well showing a distinct thermocline. Consequently, it was sampled both at and below the surface layer. In comparing these results with those of HGP-A, it should be remembered that only HGP-A penetrates appreciably below sea level.

In general, the ground waters within ~4827 km (3 mi) of HGP-A are brackish and unusable as potable water. The four wells surrounding HGP-A all have elevated temperatures, but appear on the basis of their chemistry to be of a basal nature.

The major ion in water chemistry seems to be dependent upon the well temperature. With the exception of the Allison well, the SiO_2 content increases as water temperature increases. With the exception of the Kalapana well, the Mg/Cl ratio decreases as temperature increases. The systematics in these data are most easily discussed if one considers the well water to be a mixture of sea water and rain water. The chloride concentration is used to calculate the percentage of sea water contributing to the sample. The other ions are expressed as the percentage excess over that expected if they are derived from the simple mixture. Figure 6 shows the percent excess for the four major cations. The wells are arranged in order of increasing temperature. In general, we see that as temperature increases, the Na and K also increase, while Ca and Mg decrease. This effect is due to water/mineral chemical reactions occurring in the aquifer. The use of these relationships as a geothermometer is discussed later in this report. Note that the chemistry of HGP-A is consistent with the trends shown by the shallow wells.

The tritium contents of the waters are all within or only slightly below the range of values for contemporary rain water (a long and continuing series of rain water H^3 measurements on Oahu provide comparison data; Hufen et al., 1974b and unpublished data). Even without allowance for the (unknown) tritium activity of the saline water component in the saltier water sources, the tritium contents indicate that the mean residence time of all of these waters does not exceed a few years. This conclusion is supported by the similarity between the $\delta^{18}\text{O}$ contents of the

Table 1. Chemical data for Puna area wells (a)

USGS/BWS No.	Name	Date	T (°C)	pH	Na	K	Ca	Mg	Cl	HCO ₃	SO ₄	SiO ₂	T ^(d)
2986-01 9-5	Pahoa Station elev. 705' pumped	01-06-75		7.30	36.0	2.72	1.58	2.7	13.5	48	21.1	50.0	9.9
		07-21-75	23.3	6.65	19.3	2.7	1.6	1.9	9.8	44	27.3		10.6
2487-01 9-7	Kalapana Station elev. 752' pumped	01-06-75	28.5	7.68	89.6	5.20	5.30	6.6	132.2	38	37.2	44.5	16.7
		07-21-75	20.8	7.05	78.8	5.0	5.9	5.6	120	36.8	28.6		18.0
3080-02 9	Kapoho Shaft elev. 38'	01-06-75	25.5	7.80	85.8	6.60	42.4	37	16.9 ^(b)	372	20	53.6	14.1
		07-21-75	22.1	7.10	86.5	6.2	23.2	25.7	95.7	328	22.7		10.5
		10-27-75			92.0	5.8	32.0	27.8	105	330	23.0		--
3081-01 9-6	Airstrip Well elev. 287' depth 285'	01-06-75	36.8	7.42	238	13.6	23.0	28	303.5	48	204	71.3	--
		07-22-75	33.5	7.75	223	16.8	12.5	27.2	316	44	211		11.1
2881	Allison Well elev. 140' depth 144'	01-07-75	37.8	7.35	216	10.8	13.4	15	281	132	69.2	24.1	12.9
	Isaac Hale Park Spring	01-07-75	36.0	7.75	2020	86.0	32.4	200	3534	56	507	81.5	8.5
		10-27-75			2140	87.5	98.0 ^(b)	239	3660	61.0	552		--
2783-01 9-9	Malama Ki Well elev. 274' depth 276'	01-07-75	52.2	7.02	2105	109	66.8	210	3811	144	471	100.7	15.6
		07-22-75		7.45	2890	149	117	293	5120	128	598		8.6
G3	Geothermal #3 elev. 600' depth 550-600'	01-07-75	93.0	6.85	2050	190	76.8	52	3274	30	314	96.6	10.3
		07-21-75			2000	195	81	59	3410		335		7.3
G3-T	Geothermal #3 ^(c) (Thief)	07-21-75	74	1.4	1740	158	71	62.5	2980	20	317		9.1

(a) All concentrations are in mg/l

(b) Suspect datum

(c) This sample taken 50-60' below water surface

(d) Tritium reported in tritium units

Figure 6. Major ion concentrations of Puna area wells expressed as the percent excess (or depletion) over that expected if they were formed by mixing fresh water with sea water. The wells are arranged in approximate order of increasing temperature: Pahoa, 1; Kapoho, 2; Allison, 3; Malami Ki, 4; Geothermal 3 Thief Sample, 5; Kalapana, 6; Airstrip, 7; Isaac Hale, 8; Geothermal 3 Surface, 9; HGP-A, 10. The Pahoa well is slightly depleted in chloride with respect to sodium.

local rain water and well waters (D. Thomas and P. Kroopnick, "Isotopes and Gases in the Hawaiian Geothermal System: HGP-A", in prep.), for the hot as well as the normal temperature waters. In summary, results indicate that the shallow wells in the Puna district are recharged locally and that the residence time of the ground water is a few years.

RESULTS: HGP-A DOWNHOLE PROFILES

pH

In general the pH is low, as depicted in Figure 7. Below the cased portion of the well [~ 692 m (2270 ft)], the pH rarely exceeds 5.0. The February 14, 1977 depth profile collected shortly after the well was quenched represented the only set of samples with significantly higher pH values as a function of depth. At present, this sample is regarded as anomalous, but the reader should note that the anomaly persists for all water quality parameters analyzed from the sample collected that day. These samples also show high value of conductivity, salinity, chloride, and major cations. Inclusion of this sample will raise the values in statistical reporting, as illustrated in Table 2. Depth samples taken immediately after continuous flow discharge would be desirable in future tests to further evaluate the February 1977 depth profile results.

Conductivity, Salinity, and Chloride

Because of the interdependence of these three parameters and the similarity of depth profiles, results of conductivity, salinity, and chloride are presented together. In general, all three parameters exhibited low values in comparison with those for open ocean water. The three parameters can be characterized as relatively free of variation with depth (Figs. 8 and 9). The February 14, 1977 data are again anomalous and are not included in the statistical calculations that follow.

Mean and median values for conductivity were 3,500 $\mu\text{mho/cm}$ and 3,100 $\mu\text{mho/cm}$, respectively, with the standard deviation of 1,360 $\mu\text{mho/cm}$ and coefficient of variation of 39%. Table 2 summarizes the statistical calculations for all the downhole profiles.

As with conductivity, salinity values are low. Typical open ocean salinity near Hawaii is 33.4% (% = per mil = parts per thousand). The mean and median salinity of the depth samples were 2.6% and 2.3%, respectively. The standard deviation of all samples was 1.0%. This corresponds to a coefficient of variation of 39%.

Figure 7. The downhole distribution of pH for HGP-A.

Table 2. Summary of downhole chemical parameters*

Parameter	Mean	Median	Standard Deviation	Coefficient of Variance
Conductivity	3670 $\mu\text{mho/cm}$ 3500 $\mu\text{mho/cm}$	3100 $\mu\text{mho/cm}$	2270 $\mu\text{mho/cm}$ 1360 $\mu\text{mho/cm}$	62% 39%
Salinity	2.8‰ 2.6‰	2.3‰	1.4‰ 1.0‰	51% 39%
Chloride	1160 mg/l 1040 mg/l	925 mg/l	810 mg/l 465 mg/l	69% 45%
Silica	440 mg/l	420 mg/l	230 mg/l	52%
Sulfide	135 mg/l	100 mg/l	96.4 mg/l	71%
Sodium	830 mg/l 730 mg/l	600 mg/l	460 mg/l 270 mg/l	55% 37%
Potassium	135 mg/l 123 mg/l	123 mg/l	56.0 mg/l 46.4 mg/l	42% 38%
Calcium	84.2 mg/l 53.8 mg/l	40 mg/l	120 mg/l 49.5 mg/l	142% 92%
Magnesium	2.1 mg/l 1.0 mg/l	1.0 mg/l	3.8 mg/l 0.7 mg/l	62% 69%

*Where two values appear the upper value includes all samples, but the lower value excludes February 1977 depth samples at 692 m (2270 ft).

Figure 8. The downhole distribution of conductivity for HGP-A.

Figure 9. The downhole distribution of chloride for HGP-A.

Chloride also exhibited low values and small fluctuations as a function of depth. Typical values for chloride in sea water approach 19,000 mg/l. Depth sampling indicated a mean chloride concentration of 1,040 mg/l and a median concentration of 925 mg/l, equivalent to approximately 5% of ocean water. Statistically, the standard deviation of the samples was 465 mg/l and the coefficient of variation was 45%.

Silica, SiO₂

All measurements indicated abnormally high silica levels at the HGP-A well when compared with normal Hawaii ground water and surface ocean water. Ground water silica levels rarely exceed 80 mg/l. Silica concentrations at depth in the HGP-A well showed a mean of 440 mg/l and a median of 420 mg/l (Fig. 10). Petrography of typical historic and prehistoric lava types for Mauna Loa and Kilauea demonstrated a predominance of silica (SiO₂) in all rock forms. The percentage make-up of volcanic rock forms in the Kilauea areas was approximately 50%, followed distantly by aluminum oxide (Al₂O₃) at 12% (Stearns and Macdonald, 1946; Stone, 1977a). Individual silica profiles showed little variation with depth, but large variations were observed between sampling periods. The standard deviation was 230 mg/l. The coefficient of variation was 52%.

Sulfide, S⁼

Sulfide data contained in the HGP-A well depth profiles (Fig. 11) indicated high levels. Any trend with respect to depth is not apparent because of relatively few data points and possible inconsistencies in sample preservation and analytic methods. The data available to date exhibit mean and median sulfide concentrations of 135 mg/l and 100 mg/l, respectively.

Major Cations

Analysis of cation concentrations was not actively pursued in depth samples prior to December 1976. Sodium, potassium, calcium, and magnesium depth profiles are presented in Figures 12, 13, 14, and 15, respectively. As with all other profiled water quality parameters, the cations appear relatively free of variation with depth. The February 14 samples are again regarded as a possible anomaly. The fact that the same anomaly is present in the seven parameters analyzed confirms the analytical validity of the anomaly; and the absence of possible sample contamination would imply that the water entering at ~692-m (2270-ft) depth had a higher proportion of sea water or saline water than water entering at other depths in the well on that occasion.

Figure 10. The downhole distribution of silica for HGP-A.

Figure 11. The downhole distribution of sulfide for HGP-A.

Figure 12. The downhole distribution of sodium for HGP-A.

Figure 13. The downhole distribution of potassium for HGP-A.

Figure 14. The downhole distribution of calcium for HGP-A.

Figure 15. The downhole distribution of magnesium for HGP-A.

Tritium

Three samples were collected for tritium analysis [weir box, 692 m (2270 ft), and 1575 m (5500 ft)]. All showed less than 0.2 tritium units of radioactivity. Thus the water is at least 50 years old ($t_{1/2} = 12.5$ years) or has been substantially diluted with older water.

Carbon-14 analyses were also performed and will be used in a later section to place an upper limit on the age of the water.

LOW-FLOW DEPTH PROFILE: HGP-A

The rationale for collecting this set of samples was to test whether there is a significant flow into the well at ~692 m (2270 ft). The test procedure was to allow the well to discharge at a rate just slow enough to prevent flashing (50 gal/min), thus permitting aquifer water to enter the well and perhaps permitting the normal circulation of water with the country rock.

Test results of water samples collected at ~732 m (2400 ft), ~692 m (2270 ft), and ~638 m (2092 ft) show relatively small changes in constituent concentrations as a function of depth (Fig. 16). Most water quality parameters exhibited a range of variation of less than 10% of either the mean or median values for each parameter. Magnesium and calcium demonstrate the largest variation, but these values are substantially below the median level for the no-flow depth sampling program.

The results of the low-flow depth sampling suggest, but do not conclusively show, that there was significant infiltration of water of different quality than that already present in the well. Insufficient flushing of the well could be responsible for the small shifts, because at the time of sampling only approximately 7000 gallons of water were withdrawn from a well whose volume is approximately 18,000 gallons.

CONTINUOUS FLOW SERIES UP TO FEBRUARY 1977: HGP-A

The continuous flow condition was characterized by well discharge during flashing. Samples of the well fluid are collected and condensed at the condensate sampling station (Fig. 2). Subsequent to steam separation, the liquid portion of the well fluid is sampled from the weir box. The results of the January-February 1977 continuous flow test are discussed here in detail.

Figure 16. Summary of the data collected during low-flow conditions. The samples collected from 692 m (2270 ft) appear anomalous for all the elements measured. The highest and lowest values for each parameter are listed below each profile.

pH

A steady state condition for pH was established rapidly in both weir effluent and condensate samples (Fig. 17). The steady state pH value was 8.5 at the weir and 4.8 in the condensate. The pH increase in the weir sample is expected since most of the acidic gases (CO_2 , H_2S) were lost to the steam phase, exiting the cyclone separator.

Conductivity, Salinity, and Chloride

As with the depth profiling, the interdependence of electrical conductivity, salinity, and chlorides affords a convenient simultaneous evaluation. In general, all three parameters appear to be approaching or to have reached a steady-state concentration in the weir samples. The time required to reach or approach steady state is on the order of two to three days and is thus considerably longer than for pH.

The steady-state value for conductivity is about 5900 $\mu\text{mho/cm}$ for weir samples (see Fig. 18). Because of missing samples, the steady-state value for the condensate samples was not available over the entire sampling period. The conductivity of the condensate samples never exceeded 2400 $\mu\text{mho/cm}$.

Salinity appeared to level off at approximately 4.6% for weir samples. As with conductivity, there is no definable steady-state value for the condensate water for salinity because of missing samples. The salinity of the condensate samples never exceeded 1.4%.

Chloride (Fig. 19) appeared to level off near 2600 mg/l for weir samples. The condensate level is approximately 850 mg/l.

These and several other chemical parameters indicated a discontinuity or abrupt reversal in concentration four hours after the start of flashing. This was close to the time necessary to discharge one total well volume of liquid. Thus, the concentration discontinuity might reflect the flushing of the bore in order to obtain a truer aquifer water sample and hence be indicative of more than one source of the recharging water.

Alkalinity

Reliable alkalinity data can only be obtained by measurement of the samples in the field. Unfortunately, lack of manpower prevented us from measuring alkalinity on any samples other than those collected in January 1977. The alkalinity, reported as calcium carbonate (CaCO_3), was actually present as the carbonate (CO_3^{2-}) species due to the high pH observed. The concentration variation with time is erratic and did not indicate any steady state (Fig. 20).

Figure 17. The approach of pH to steady state for water samples collected at the weir and from the condenser.

Figure 18. The approach of conductivity to steady state for water samples collected at the weir and from the condenser.

Figure 19. The approach of chloride to steady state for water samples collected at the weir and from the condenser.

Figure 20. The approach of alkalinity to steady state for water samples collected at the weir and from the condenser.

Silica, SiO₂

There appeared to be a steady-state concentration of silica of about 135 mg/l in the weir discharge, whereas the concentration in the condensate was about 285 mg/l (Fig. 21). Between the condensate sampling port and the weir discharge, a large proportion of the silica was lost, probably as a result of precipitation. Based on an average value of 70% for steam quality and a total mass flow rate of 76,000 lb/hr, the resultant loss in silica amounts to approximately 450 lb/day.

Major Cations

With the exception of magnesium, all cations exhibited a near steady-state condition after a relatively long (36-hr) equilibrium period. As with the majority of parameters, data were insufficient to define the steady-state concentrations for the condensate.

Sodium reached a steady-state concentration of approximately 1300 mg/l in the weir samples but never exceeded 400 mg/l in the condensate samples (Fig. 22). Potassium levelled off at the 225-mg/l mark for the weir discharge. The condensate samples never exceeded 70 mg/l (Fig. 23). The steady-state concentration for calcium is 80 mg/l (Fig. 24). The condensate calcium concentration never exceeded 20 mg/l.

Trace Elements

The concentrations of the transition metals copper, chromium, and nickel were all less than 0.1 mg/l (limit of detection). The zinc and manganese concentrations were about ~.20 mg/l on unfiltered samples. Mercury is present and varies from less than 50 µg/l at the end of the production test to several hundred at the beginning (S. and B. Siegel, personal communication). Cadmium and lead were barely measurable at the .01-mg/l detection level.

CONTINUOUS FLOW TEST, MARCH-MAY 1977: HGP-A

The March-May 1977 flow test data are generally consistent with prior flow test data in terms of patterns and trends. However, the magnitude of many water quality parameters including chloride, conductivity, salinity, silica, sodium, and potassium reached higher values for this, the longest flow test permitted so far. For example, the chloride concentration in the weir samples increased from generally 2500 mg/l or less for the first

Figure 21. The approach of silica to steady state for water samples collected at the weir and from the condenser.

Figure 22. The approach of sodium to steady state for water samples collected at the weir and form the condenser.

Figure 23. The approach of potassium to steady state for water samples collected at the weir and from the condenser.

Figure 24. The approach of calcium to steady state for water samples collected at the weir and from the condenser.

three tests to about 3200 mg/l in the last test (Fig. 25). This increase may be interpreted as an indication of drawing of higher saline water into the geothermal reservoir as well discharge is maintained over a long period of time.

DISCUSSION

Well Bore Permeability

The results of the continuous flow series indicate that after the initial flushing, most of the parameters exhibit a slow buildup toward a steady state. This is not typical for the normal Hawaiian ground water well. In general, Hawaiian water wells achieve quick equilibrium with respect to drawdown within a few minutes and water quality parameter concentrations within one-half hour of activation, reflecting the high permeability of the aquifer rock structure. HGP-A's retarded equilibrium period appeared attributable, at least in part, to low rock permeability and in part probably to incomplete clearing of drilling mud from the surrounding rock. The average formation transmissibility at the HGP-A well is approximately 1 millidarcy-foot, based on preliminary analysis of flow test data (Chen et al., 1976). This magnitude is miniscule compared with 10^5 millidarcy-foot for the very productive yet much shallower Hawaii water wells.

Steam Quality

The water quality data obtained from the continuous flow tests can be used to compute the steam fraction of the total discharge. When we use conservative water quality parameters such as chloride and recognize that the condensate samples represent a combined steam and water sample and that the weir samples indicate the water portion only, we can calculate the steam quality (f) as follows:

$$f = \left[1 - \frac{C_c}{C_w} \right]$$

where

C_c = concentration in the condensate sample

C_w = concentration in the weir sample.

The steam quality calculations were performed using conductivity, chloride, and sodium data. These parameters should represent the conservative indicators. 'Conservative' in this case is used in

Figure 25. The chloride concentrations of samples collected from the weir plotted versus the date of sampling. The steady rise after each well has not reached equilibrium with the surrounding waters. To compare these results the reader must multiply them by $(1-f)$ where f is the steam fraction of the discharge.

Table 3. HGP-A steam quality (%)

Sampling Date/Time	Conductivity	Chloride	Sodium	Average	Computed from Thermodynamic Data
26 January 1977 4:30 p.m.	68	71	75	68	58
26 January 1977 8:00 p.m.	69	70	69	70	77
26 January 1977 12:01 a.m.	65	63	67	66	83
26 January 1977 8:00 a.m.	69	65	71	69	81

Average for Parameter	68	66	67	71	75

Figure 26. The mixing relationship between chloride and sodium. The line labeled S.W. represents the expected values for the dilution of sea water with fresh water.

Figure 27. The mixing relationship between chloride and potassium. The line labeled S. W. represents the expected values for the dilution of sea water with fresh water.

Figure 28. The mixing relationship between chloride and calcium. The line labeled S.W. represents the expected values for the dilution of sea water with fresh water.

Figure 29. The mixing relationship between chloride and magnesium. The line labeled S. W. represents the expected values for the dilution of sea water with fresh water.

Figure 30. The mixing relationship between chloride and the sum of the major cations. The line labeled S.W. represents the expected values for the dilution of sea water with fresh water.

In a petrographic description of the cuttings and core obtained during the drilling of HGP-A, Stone (1977) reports that montmorillonite is the dominant clay mineral between 594 m (1950 ft) and 1189 m (3900 ft). Below 1189 m (3900 ft) chlorite is the dominant clay; minor amounts of actinolite $[\text{Ca}_2(\text{Mg}, \text{Fe}^{+2})_5(\text{Si}_4\text{O}_{11})_2(\text{OH})_2]$ and albite $[\text{NaAlSi}_3\text{O}_8]$ also are present. Thus, these reactions can explain the observed depletions of potassium and magnesium. The reactions of calcium will be discussed in the next section.

Geothermometry

Mahon (1966) and Fournier and Rowe (1966) observed independently that the silica content of high-temperature waters within hydrothermal areas is determined by the quartz-water equilibrium solubility. This has made possible a simple chemical method for determining the temperatures of the waters supplying drillholes. By assuming that waters reach the surface by an adiabatic isenthalpic expansion of the original high-temperature water to a steam-water mixture, the silica concentrations on boiling surface waters that correspond to underground waters of certain temperatures can be calculated. Use of this method has enabled the measurement of temperatures in New Zealand geothermal areas to within about $\pm 2^\circ\text{C}$ (Mahon, 1966).

Using the Fournier and Rowe solubility data for quartz, $t = [1311/(5.196 - \log \text{SiO}_2)] - 273$, we calculate that the host rock surrounding HGP-A should have a temperature of 240°C (Table 4). This estimate represents the minimum temperature expected, since cooling in the bore or mixture with meteoric water would decrease the calculated temperature. The maximum recorded temperature in the well was 358°C under static conditions. The highest temperature measured downhole during high volume discharge was 275°C (Fig. 31).

The Na/K ratio in natural hot waters is controlled by a reversible temperature-dependent rock mineral equilibrium involving potash mica, potash feldspar, and albite (Ellis, 1970). Experimental high-temperature rock/water interactions (Ellis and Mahon, 1964, 1967), field results, and the results of Hemley and Jones (1964) have enabled an approximate relationship to be established between the Na/K ratio in natural hot waters and temperature. The sodium/potassium equilibrium adjusts relatively slowly after a temperature change, which enables useful information on conditions in the deep aquifer to be obtained.

Applying the Na/K thermometer of White and Ellis, $t = [855.6/(0.6269 + \log(\text{Na/K}))] - 273$ to the average values for HGP-A samples gives a temperature of 250°C . Fournier and Truesdell (1973) also derived a Na/K geothermometer from which we calculate a temperature of 252°C ($t = [777/(0.4693 + \log(\text{Na/K}))] - 273$). Fournier and Truesdell then extended their model to include the calcium ion concentration:

Table 4. HGP-A geochemical summary (concentrations in mg/l of total discharge)

	Cl	Na	K	Ca	Mg	SiO ₂	S ⁼⁼	pH	TRIT.	t* qtz	t** Na/K	t*** Na/K/Ca
DOWNHOLE	1040	730	123	53.8	1.0	440	135	3	<.1	240°C	250(WB)	231
Non-flowing (ave. of 5 profiles): mean σ	1040 465	730 270	123 46	53.8 49.5	1.0 .7	440 230	135 96	3	.1	240°C	250(WB) 252(FT)	231
2270' (02/14/77)	4720	2008	245	445	14.0	432	.66	3	-	240°C	211(WB) 210	210
Low flow (ave. of 4 samples)	1040	480	103	22.6	.25	710	-	2.5	-	286°C	287(WB) 294(FT)	248
WEIR BOX												
approximate steady-state (01/30/77)	780	390	68	24	.11	41	-	8.5	-	93	256(WB) 259(FT)	229

* Fournier and Rowe (1966): $t = 1311/[5.196 - \log(\text{SiO}_2)] - 273$; SiO in ppm.

** White (1968) and Ellis (1969): $t = 855.6/[\log(\text{Na/K}) + .6269] - 273$; Na and K in moles.
Fournier and Truesdell (1973): $t = 777/[\log(\text{Na/K}) + .4693] - 273$; Na and K in moles.

*** Fournier and Truesdell (1973): $t = 1647/[\log(\text{Na/K}) + \frac{1}{3} \log(\sqrt{\text{Ca/Na}}) + 2.24] - 273$; Na, K, and Ca in moles.

Figure 31. The downhole temperature for HGP-A on August 29, 1976 after a long period of stabilization (□) and during the February 9, 1977 discharge through a 4.5-cm (1-3/4-in) orifice (○).

$$t = \frac{1647}{\log \frac{\text{Na}}{\text{K}} - \frac{1}{3} \log \frac{\text{Ca}}{\text{Na}} - 2.24} - 273 .$$

The temperature calculated for HGP-A using this equation is 231°C (Table 4).

The temperatures calculated from samples collected downhole during flow give the highest values, and the silica results and the Na/K results agree remarkably well (Table 4). When differences are found between the various formulas for calculating temperatures (e.g., weir box sample), the silica temperature corresponds very closely with that of the outflow water, whereas the Na/K ratio temperature relates to the downhole temperature. With cooling of water (e.g., through boiling on rising toward the surface), the Na/K exchange reaction is slower to readjust than the silica equilibrium (Ellis, 1970). The calculated temperatures during the low-flow conditions are thus in excellent agreement with the observed downhole temperatures during discharge (see Table 4 and Fig. 31).

The equations used to calculate the temperatures were derived for areas where the host rocks are of rhyolitic, ignimbritic, and/or sedimentary composition. Application of the geothermometers discussed above implicitly assumes the presence of minerals such as albite, K-feldspar, and plagioclase. The island of Hawaii is made up of layers of olivine basaltic flows and cinders. Mineralogic analysis of HGP-A cuttings and cores indicate the presence of olivine, plagioclase (An 75-80), clinopyroxene, augite, and magnetite in the upper section. At ~762 m (2500 ft), pyrite and quartz, along with vesicle fillings of quartz, calcite, montmorillonite, and zeolite have been found. Below 1372 m (4500 ft), the rocks have been hydrothermally altered and are composed of the above minerals plus chlorite, actinolite, hematite, and albite. In view of this wide variety of minerals present in the altered basalt at depth in the well it should not be surprising that the geothermometry works so well.

Kristmannsdottir and Tomasson (1974) have shown that in the Icelandic geothermal fields the change from montmorillonite to chlorite with depth in a well corresponds with a temperature of between 200 and 230°C. In HGP-A this mineralogic change occurred at ~884 m (2900 ft) where the temperature after prolonged shut-in is ~250°C. This agreement may be fortuitous, however, since the pre-production temperature was only ~100°C at this depth.

Isotopic Results

Two large CO₂ gas samples were collected during the March-May 1977 flow test (April 8 and May 15) for radiocarbon analysis. The interpretation of the carbon-14 and tritium data require that

we first account for the source of the carbon dioxide. Analyses of the gases emanating from HGP-A give us a total CO_2 level of 714 ppm. Assuming that the carbon dioxide content of the sea water fraction of the recharge is unchanged during transit, ~9 mg/l of carbon comes from this source. Thomas (1977) presented models of Kilauea and HGP-A in which the C^{13} and O^{18} data were used to calculate that for HGP-A 66% of the recharge water is of meteoric origin, 24% has undergone hydrothermal alteration, and that 20% of the carbon can be derived from organic material leached from the highly porous surrounding rock. Additional carbon comes from the dissolution of deeper hydrothermal calcite and from the outgassing of deep-seated magmatic material.

The C^{14} results indicate that the two samples have an activity of ~21 and 18% of modern living carbon. Such a result could be interpreted as representing a very old age for the water (~12,500 to 13,900 years). These ages are much greater than any that have ever been measured for a Hawaiian dike-confined ground water. Thus, we prefer to interpret the C^{14} data as further confirmation of the mixing model proposed above. According to this model, the live carbon contributed by ground water plus ocean water could be ~20% ($\pm 10\%$) of the total, which easily accounts for the apparent depletion of C^{14} in the samples. Due to the extremely high porosity of the surrounding rock, several tons of organic matter (cottonseed hulks, bagasse, ...) were injected into the well during drilling. While we believe that this material has been cleared from the well, it is possible that some of the modern carbon (C^{14}) is coming from the oxidation of this organic material.

The tritium results showed values of less than 0.2 TU, indicating that no bomb-produced tritium has entered the aquifer and that an age of greater than 50 years is expected. Due to the errors discussed above, it is of course possible that the water has an age of up to several thousand years, but it is impossible to resolve such a time span with the present data.

CONCLUSIONS

- (1) The water quality sampling program of the HGP-A well consisted of a series of five downhole water samplings at various depths under no-discharge condition, one similar sampling under very low discharge condition, and water quality monitoring of the discharge of the longest discharge test, March-May 1977. The median values for the downhole water samples are: pH, <5; conductivity, 3100 $\mu\text{mho/cm}$; salinity, 2.3%; chloride, 925 mg/l; silica as SiO_2 , 420 mg/l; magnesium, 1 mg/l. Tritium values of three samples all showed less than 0.2 TU, or at least 50 years

old. The HGP-A well water is slightly saline and contains about 5-10 percent ocean water. The well water has lost a small amount of potassium and nearly all of its magnesium as compared with diluted ocean water, probably because of subsurface geothermal-geochemical effect. The maximum well fluid temperature of 358°C (676°F) is higher than that of any Hawaiian ground water.

- (2) The HGP-A well fluid, when discharged from the well, is principally a mixture of water and water vapor. Steam accounts for 66-70 percent of the mixture as computed from water chemistry data and confirmed by thermodynamic computations.
- (3) The measured chemical parameters of the well under no-discharge conditions did not vary much with depth even at the well bottom [1783 m (5851 ft) below sea level]. This suggests the possible existence of deep dikes or intrusive bodies located on the ocean side of the well and acting as barriers against sea water encroachment.
- (4) Mass balance calculations involving carbon, its isotopes C^{14} and C^{13} , and water and O^{18} indicate that 10 percent of the water comes from the ocean, 66 percent from ground water, and 24 percent from a hydrothermal source. The radiocarbon activity of 20 percent of modern CO_2 is attributed to dilution of ground and shallow hydrothermal waters with dead magmatic carbon.
- (5) During the flow tests, the concentrations of the water quality parameters in the discharge appeared to approach a steady state after one to three days. The prolonged period required to reach a steady-state concentration suggests incompleteness of well development or low permeability of the formation, or both. The transmissivity of 1 millidarcy-foot is about 5 orders of magnitude smaller than that for normal productive Hawaii water wells that are of much shallower depth than HGP-A. The water discharge rate of HGP-A is small and on the order of 30 gpm, although the total well discharge (water plus steam) was 76,000 lb/hr (equivalent to ~150 gpm).
- (6) During the January-February 15-day flow test, the 'steady-state' concentrations of the major water ions in the water portion of the discharge (weir) were: pH, 8.5; conductivity, 5900 $\mu\text{mho/cm}$; salinity, 4.6%; chloride, 3600 mg/l; silica, 135 mg/l; sodium, 1300 mg/l; potassium, 225 mg/l; calcium, 80 mg/l. A large amount of silica was precipitated out, while the acidic gases CO_2 and H_2S were lost to the steam phase.
- (7) The water level in the well rises from about 275 m (900 ft) below ground level two days after well shut-in to about

30 m (100 ft) below ground level 22 days after well shut-in. This behavior resembled semi-logarithmic recovery in an artesian water well. The slowness of the rise is, however, not typical of artesian water well response but may reflect a condition analogous to a leaky aquifer or may be caused by a combination of the incomplete well development already noted and the recharge effects of the well fluids.

- (8) The moderately high rainfall [mean annual, 318 cm (125 in)] and the high surficial permeability of the Puna area permit substantial rain water infiltration. The circulation of subsurface water, whether it is infiltrated rain water or ground water transmitted to the Kapoho area, is still open to interpretation because of uncertainty about geologic formations for the area. It is fairly certain that the Kapoho reservoir is probably in poor hydraulic communication with ocean water. It is certain, however, that the ground water hydrologic regime tapped by HGP-A is distinctly different from that of adjacent ground water [as close as 1.5 km (1 mi) from the well]. The adjacent ground water is known to be basal water directly recharged by contemporary rain water and only mildly affected by geothermal sources as reflected by warm temperature and a shift in the relative proportion of the chemical constituents.

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REFERENCES

- Arnorsson, S., 1974. Thermal fluids on Iceland as regards composition and geologic structure. In Kristjansson (ed.), Geodynamics of Iceland and the North Atlantic Area, p. 307-323.
- American Public Health Association, 1975. Standard Methods for the Examination of Water and Wastewater. APHA-AWWA-WPCF, Washington D.C., 14th ed.
- Chen, B., D. Kihara, A. Seki, P. K. Takahashi, and P. Yuen, 1976. The geothermal reservoir engineering of Hawaii geothermal project well A: Summary of Activities up to October 31, 1976. Tech. Rept. No. 19, Hawaii Geothermal Project, Univ. Hawaii, Honolulu.
- Ellis, A. H., 1969, Present day hydrothermal systems and mineral deposition, Ninth Commonwealth Mining and Metallurgical Congress, Mining and Petroleum Geology Sect., Paper 7, 30 p.
- Ellis, A. M., 1970. Quantitative interpretations of chemical characteristics of hydrothermal systems. In U.N. Symposium on Development and Utilization of Geothermal Resources, Pisa. Geothermics, Spec. Iss. 2, p. 516-528.
- Ellis, A. J., and W. A. J. Mahon, 1964. Natural hydrothermal systems and experimental hot water/rock interactions, Part I. Geochim. Cosmochim. Acta, v. 28, p. 1323.
- Ellis, A. J., and W. A. J. Mahon, 1967. Natural hydrothermal systems and experimental hot water/rock interactions, Part II. Geochim. Cosmochim. Acta, v. 21, p. 519.
- Ellis, A. J., W. A. J. Mahon, and J. A. Ritche, 1968. Methods of collection and analyses of geothermal fluids. New Zealand Dept. of Scientific and Industrial Research, Rept. No. C.D. 2103, Taupo, New Zealand, 2nd ed.
- Fournier, R. O., and J. J. Rowe, 1966. Estimation of underground temperature from the silica content of water from hot springs and wet steam wells. Amer. J. Sci., v. 364, p. 685.
- Fournier, R. O., and A. H. Truesdell, 1973. An empirical Na-K-Ca geothermometer for natural waters. Geochim. Cosmochim. Acta, v. 37, p. 1255.

- Gieskes, J. M., 1973. Interstitial water studies, Leg 15-- Alkalinity, pH, Mg, Ca, Si, PO₄, and NH₄. In B. C. Heezen, I. G. MacGregor et al. (eds.), Initial Reports of the Deep Sea Drilling Project, v. 20, U.S. Government Printing Office, Washington D.C., p. 63.
- Hemley, J. J., and M. R. Jones, 1964. Chemical aspects of hydrothermal alteration with emphasis on hydrogen metasomatism. Econ. Geol., v. 59, p. 539.
- Hufen, T. H., L. S. Lau, and R. W. Buddemeier, 1974a. Radiocarbon, ¹³C, and tritium in water samples from basaltic aquifers on the island of Oahu, Hawaii. In Isotope Techniques in Ground Water Hydrology, 1974, v. II, STI/PUB/373, I.A.E.A., Vienna, p. 111-127.
- Hufen, T. H., R. W. Buddemeier, and L. S. Lau, 1974b. Isotopic and chemical characteristics of high level ground water in Oahu, Hawaii. Water Resour. Res., v. 10, no. 2, p. 366-370.
- Kingston, Reynolds, Thom, and Allardice, Limited, 1976. Hawaii Geothermal Project Well Completion Report, HGP-A. K.R.T.A., 44 Wakefield St., Auckland, New Zealand.
- Kristmannsdottir, H., and J. Tomasson, 1974. Nesjavellir. Hydrothermal alteration in a high-temperature area. Proc. Int'l Symp. on Water-Rock Interaction, Prague.
- Macdonald, G. A., 1946. Petrography of Hawaii. In H. Stearns and G. Macdonald (eds.), U. S. Geol. Surv. Bull. 9, p. 187-204 and p. 289.
- Macdonald, G. A., 1956, Structure of Hawaiian volcanoes, Verhandelinger van het Koninklyk Nederlandsch, Geologisch Mijnbouwkundig Geonootschap., v. 16, p.1-22.
- Macdonald, G. A., and A. T. Abbott, 1970. Volcanoes in the Sea: The Geology of Hawaii. Univ. Hawaii Press, Honolulu, 441 pp.
- Mahon, W. A. J., 1966. Silica in hot water discharged from drillholes at Wairakei, New Zealand. N. Z. J. Sci., v. 9, p. 135.
- Rainwater, F. H., and L. L. Thatcher, 1960. Methods for Collection and Analysis of Water Samples. U. S. Geol. Surv. Water Supply Paper 1454, 301 pp.
- Stearns, H. T., and G. A. Macdonald, 1946. Geology and ground water resources of the island of Hawaii. Hawaii Div. Hydrog. Bull. 9, 363 pp.

Stone, C., 1977a. Chemistry, petrography, and hydrothermal alteration of basalts from Hawaii Geothermal Well A, Kilauea, Hawaii. M.S. Thesis, University of Hawaii Honolulu.

Stone, C., 1977b. Geochemistry. In Progress Report for Third Quarter of Federal Fiscal Year 1977, Phase III, Well Testing and Analyses, Hawaii Geothermal Project, Univ. Hawaii, Honolulu.

Thomas, D., 1977. The isotopic profile of gases from the summit and flank of Kilauea volcano. Ph.D. Dissertation, Univ. Hawaii, Honolulu.

White, D. E., 1968. Environments of generation of some base-metal ore deposits. Econ. Geol., v. 63, p. 301-335.

APPENDIX 1

APPENDIX 1. Water Quality Data Tabulation

Sample Description	pH	Cl ⁻	Salinity	Conductance	SiO ₂	Na ⁺	K ⁺	Mg ⁺²	Ca ⁺²	S ⁼	Alkalinity
11/03/76-weir-8:33p	7.0	2170	3.2	5,000	132	1140	205.0	<0.5	46.2	-	-
11/04/76-weir-4:00p	7.0	2180	3.5	5,500	113	1200	209.0	<0.5	54.8	-	-
11/05/76-weir-10:30a	7.0	2210	3.5	5,500	128	1200	205.0	<0.5	56.7	-	-
11/06/76-weir-9:40a	7.0	2225	3.5	5,000	113	1180	215.0	<0.5	60.3	-	-
11/07/76-weir-9:00a	8.8	2350	4.0	6,000	110	1200	207.5	<0.5	60.3	-	-
11/08/76-weir-9:00a	8.8	2190	4.0	6,000	105	1200	212.5	<0.5	81.9	-	-
11/08/76-weir-p.m.	8.8	2330	4.2	6,000	140						
11/08/76-condensate	4.5	660	1.3	2,000	255	360	57.5	<0.5	18.9	-	-
11/09/76-weir-	8.8	2330	4.2	6,000	140					-	-
11/09/76-condensate	5.8	1990	3.5	5,000	123	1000	180.0		54.8	58.0	-
11/10/76-weir-9:00a	8.8	2190	3.9	6,200	145	1260	250.0		81.9	-	-
11/11/76-weir-2:00a	8.9	2350	4.4	7,000	128	1260	212.5		70.4	-	-
11/12/76-weir-9:30a	8.9	2410	4.0	7,000	140	1260	215.0		74.4	-	-
11/13/76-weir-2:45p	8.8	2450	4.0	7,000	150	1280	217.5		74.0	-	-
11/14/76-weir-12:05p	8.8	2450	4.2	7,000	153	1280	215.0	<0.5	68.7	-	-
11/16/76-weir-11:03a	8.8	2530	4.2	7,000	150	1320	225.5	<0.5	75.7	-	-

pH reported in units; Cl, SiO₂, Na, K, Mg, Ca, and S reported in mg/l of indicated form; salinity reported in parts per thousand; conductance in units of $\mu\text{mho}/\text{cm}$; and alkalinity reported as mg/l of CaCO₃.

APPENDIX 1. (con't).

Sample Description	pH	Cl ⁻	Salinity	Conductance	SiO ₂	Na ⁺	K ⁺	Mg ⁺²	Ca ⁺²	S ⁻	Alkalinity
11/16/76-condensate-1:30p	5.6	1870	3.0	5,200	225	980	167.5	<0.5	58.3	-	-
undated sampled labeled first condensate	6.3	1830	3.2	5,200	203	980	165.0	<0.5	56.7	-	-
11/17/76-weir	8.8	2520	7.0	5,000	130	1320	222.5	<0.5	78.8	-	-
12/12/76-weir-11:00a	7	2130	3.5	6,000	140	1040	227.5	0.2	41.4	-	-
12/13/76-weir-11:00a	6	2330	4.0	6,700	130	1170	212.5	0.1	57.2	-	-
12/14/76-weir-9:00a	6	2470	4.0	7,000	140	1220	215.0	0.2	70.0	-	-
12/15/76-weir-10:00a	6	2560	4.5	7,100	130	1300	225.0	0.4	78.1	-	-
01/26/77-weir-1:30p first of flash	7.3	1020	2.0	3,100	160	520	100.0	<0.5	14.7	-	56
01/26/77-condensate-3:30p from last surge	5.4	800	0.5	800	195	160	28.8	0.1	4.1	-	20
01/26/77-weir-4:30p	8.0	2040	3.5	6,000	150	1020	62.0		30.6	-	48
01/26/77-condensate-5:00p	5.3	600	1.5	1,900	160	260	55.0	0.1	6.8	-	40
01/26/77-weir-5:00p	8.5	2110	3.9	6,000	150	1000	210.0	0.4	32.4	-	20
01/26/77-condensate-5:00p	5.0	550	1.0	1,700	280	240	47.5	0.1	7.5	-	32
01/26/77-weir-8:00p	8.5	2190	4.0	6,500	150	1100	220.0	0.1	37.8	-	28
01/26/77-condensate-8:00p	4.8	660	1.2	2,000	280	340	52.5	0.1		-	16
01/26/77-weir-12:00p	8.5	2230	4.0	6,800	150	1100	225.5	0.1	40.6	-	48
01/26/77-condensate-12:00p	4.8	2400	1.3	2,400	340	360	68.5	0.1	13.2	-	72

APPENDIX 1. (con't).

Sample Description	pH	Cl ⁻	Salinity	Conductance	SiO ₂	Na ⁺	K ⁺	Mg ⁺²	Ca ⁺²	S ⁼	Alkalinity
10/12/76-1000 ft	4.9	725		1,980	220					250.0	-
10/12/76-2270 ft	1.4	730		3,450	620					-	-
10/12/76-5500 ft	1.9	735		3,050	650					-	-
10/29/76-4300 ft	2.7	685		2,700	630					210.0	-
10/29/76-5800 ft	3.4	850		2,600	630					210.0	-
10/30/76-2270 ft	2.3	685		3,650	630					210.0	-
10/30/76-6300 ft	3.5	440		1,650	630					370.0	-
12/02/76-surface	9.4	1100	7.0	5,000	130					57.0	-
12/02/76-2270 ft	3.4	910	3.8	2,500	760	500	77.5	1.9	21.0	209.0	-
12/02/76-2270 ft	3.6	950	4.8	2,500	740	540	75.0	1.9	24.2	102.0	-
12/02/76-4300 ft	2.8	920	2.0	2,750	740	480	85.0	0.7	17.3	142.0	-
12/02/76-5800 ft	2.6	980	2.0	3,600	740	500	222.5	0.6	22.6	98.0	-
01/25/77-surface	9.7	2230	4.1	7,000	140	1240	155.0	0.2	78.7		-
01/25/77-9:30a off 2" temp. bleed line	8.7	2190	4.0	6,800	140	1120	177.5	0.8	82.8	56.4	-
01/27/77-weir-8:30a	8.3	2360	4.2	7,000	160	1140	222.0	0.1	49.7	9.0	28
01/27/77-condensate-8:30p	4.8	820	1.3	2,200	280	330	57.5	0.1	15.5	232.0	36
01/28/77-weir-8:00a	8.5	2550	4.3	6,000	140	1220	200.0	0.2	70.1	9.2	-
01/29/77-weir-8:00a		2590	4.8	6,700	140	1260	225.0	0.3	78.2	8.3	-

APPENDIX 1. (con't).

Sample Description	pH	Cl ⁻	Salinity	Conductance	SiO ₂	Na ⁺	K ⁺	Mg ⁺²	Ca ⁺²	S ⁼	Alkalinity
01/30/77-weir-10:00a	8.4	2650	4.5	6,100	130	1280	242.5	0.4	84.7	-	-
01/30/77-weir-10:00a	8.5	2650	4.7	6,200	200	1280	235.0	0.3	72.7	-	-
04/05/77-weir-	8.4	2920	5.5	9,000	145	1480	269.0			-	-
04/05/77-condensate-	3.5		1.0	1,600	185	240	40.0			-	-
04/06/77-weir-3:20p	8.4	2940	5.5	9,000	165	1460	247.0			-	-
04/05/77-condensate-3:20p	3.5	520	1.1	1,850	160	260	45.0			-	-
04/09/77-weir-11:00a	8.1	3000	5.3	9,000	140	1400	266.0	0.1	75.6	-	-
04/09/77-condensate-11:00a	4.6	500	1.0	1,700	165	240	35.0	0.1	13.9	-	-
04/11/77-weir-8:45a	8.2	3050	5.4	9,000	150	1460	266.0	0.1	77.3	-	-
04/11/77-condensate-8:45a	5.3	610	1.0	1,850	180	240	40.0	0.1	12.2	-	-
04/16/77-weir-10:00a	8.3	3130	5.4	9,000	145	1480	283.0	<0.1	77.3	-	-
04/16/77-condensate-10:00a	4.6	500	1.0	1,820	185	200	38.0	<0.1	10.5	-	-
04/20/77-weir-12:00 noon	8.1	3150	5.8	9,200	155	1480	288.0	<0.1	80.0	-	-
04/20/77-condensate-12:00 noon	3.6	560	1.0	1,880	190	200	40.0	<0.1	10.5	-	-
04/22/77-weir-7:15a	8.2	3190	5.6	9,200	160	1480	277.0	<0.1	72.2	-	-
04/22/77-condensate-7:15a	4.4	590	1.0	1,900	195	200	45.0	<0.1	12.2	-	-
01/25/77-2270 ft-3:30p	2.3	980	2.2	3,700	670	480	92.5	1.1	13.2	53.5	-
01/25/77-3500 ft-4:30p	2.3	1000	2.3	3,900	670	480	92.5	0.5	10.4	85.0	-

APPENDIX 1. (con't).

Sample Description	pH	Cl ⁻	Salinity	Conductance	SiO ₂	Na ⁺	K ⁺	Mg ⁺²	Ca ⁺²	S ⁼	Alkalinity
01/25/77-5500 ft-5:30p	5.3	2280	4.0	6,900	400	1060	153.8	1.1	121.0	81.0	-
01/26/77-5800 ft-9:15a	3.3	1490	3.0	4,700	580	740	122.5	2.1	79.2	80.5	-
02/14/77-surface	11.5	920	1.9	2,900	170	860	173.8	0.1	11.5	69.4	-
02/14/77-2270 ft	2.9	4620	7.5	12,500	440	2000	240.0	13.0	430.0	3.9	-
02/14/77-2270 ft	3.2	4800	7.9	13,000	425	2160	247.5	14.7	465.0	10.5	-
02/14/77-3500 ft	8.2	1030	2.0	3,500	195	600	82.5	0.4	39.3	56.6	-
02/14/77-5800 ft	5.2	2330	4.0	6,900	170	1080	160.0	2.0	161.0	61.5	-
02/14/77-6300 ft	4.8	1310	2.3	4,000	210	620	87.5	1.9	95.7	50.0	-
01/26/77-cyclone separator upstream of orifice plate		1100				520	20.7	<0.1	18.6	-	-
01/26/77-cyclone separator downstream of orifice plate						860	38.0	<0.1	31.8	-	-
02/09/77-cyclone upstream	5.3	1610	2.9	4,400	170	720	135.0	<0.1	30.1	-	-
02/09/77-cyclone downstream	5.5	1790	3.0	5,000	160	860	157.5	<0.1	32.2	-	-
02/10/77-cyclone downstream	5.6	1690	3.0	5,000	195	860	152.5	<0.1	30.1	-	-
01/26/77-low flow-weir-11:00a	5.8	3090	5.3	8,900	250	1360	188.8	4.8	180.4	-	52.0
01/26/77-low flow-weir-12:00a	5.5	1730	3.0	5,000	360	820	120.0	5.5	88.0	-	100.0
01/26/77-low flow-weir-1:00p	5.8	1080	2.0	3,200	210	500	92.5	0.8	17.7	-	76.0
01/26/77-low flow-weir-1:30p	6.3	1010	2.0	3,180	180	500	92.5	0.7	14.2	-	108.0

APPENDIX 1. (con't).

Sample Description	pH	Cl ⁻	Salinity	Conductance	SiO ₂	Na ⁺	K ⁺	Mg ⁺²	Ca ⁺²	S ⁼	Alkalinity
01/26/77-low flow-2092 ft 11:00a	2.6	1080	2.5	4,100	650	550	95.0	1.1	24.4	-	0.0
01/26/77-low flow-2400 ft 11:50a	2.5	960	2.5	3,950	700	480	87.5	0.5	8.4	-	0.0
01/26/77-low flow-4300 ft 12:30p	2.6	1040	2.4	3,800	710	480	103.8	0.3	22.6	-	0.0
01/26/77-low flow-2270 ft 1:00p	2.9	1000	2.1	3,500	710	500	117.5	0.3	7.5	-	0.0