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"A Summary of the Chemical Characteristics of the HGP-A Well; Puna, Hawaii"

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ABSTRACT

The HGP-A geothermal well is located on the Lower East Rift Zone of Kilauea Volcano. It was completed in 1976 to a depth of 1966 meters and has a bottomhole temperature of 360°C. Evaluation of the chemistry of the fluids produced indicate that recharge to the reservoir discovered by the HGP-A well is largely fresh meteoric water with smaller amounts of seawater recharge. The changes in fluid chemistry during production suggest that at least two separate aquifers are providing fluids to the well and that silica deposition is occuring in the reservoir formation. Isotopic data indicate that the fluid circulation and residence times in the reservoir are relatively short and that the heat source for this part of the rift zone is either very young or relatively large.

Introduction

HGP-A geothermal well was completed in 1976 on the lower East Rift Zone of Kilauea Volcano. The total depth of the well is 1966 meters and under static conditions has a bottomhole temperature of approximately 360°C. Production testing of the well indicated that it was capable of producing approximately 50,000 kg/hr of a mixed fluid having a steam quality of about 48%. In 1981 a 3 megawatt electrical generator was installed on the well as a "proof of feasibility" project (jointly sponsored by the U.S. Department of Energy, the State and County of Hawaii and Hawaiian Electric Co.) to demonstrate the technical feasibility of generating electrical power from the reservoir discovered by HGP-A. At the present time the wellhead generator is producing a gross output of 2.9 MW.

Well Fluid Chemistry

During the initial testing of HGP-A samples of downhole and production fluids were analyzed for major trace element compositions and noncondensable gas concentrations. More recently, production fluid chemistry has been monitored on an intermittent basis since the generator facility began operations in June 1981. The chemical data acquired during the testing and production from HGP-A have provided a number of insights into the properties of the reservoir as well as the production characteristics of the wellbore itself.

Downhole Chemistry

Downhole sampling in HGP-A was conducted during the periods of wellbore shut-in that were interspersed with short duration production flow testing and thus were able to monitor changes in production formations induced by well flow. Figures 1 and 2 and Table 1 present a selected set of downhole chemistry data collected during the first twelve months of production testing.

The chloride concentrations observed in the wellbore fluids (Figure 1) were relatively uniform at all sampling depths through December 1976. The two subsequent downhole profiles indicate, however, that higher salinity fluids were produced from two intermediate depth aquifers after the December 1976 flow test. These data suggest that the initial production from HGP-A was entirely from a single aquifer but, after repeated testing, higher salinity aquifers began providing fluids to the well. A change in aquifer productivity is supported by engineering data that indicated increased mass flow rates with each flow test performed. On this basis it is suggested that substantial skin damage occurred to the wellbore by lost mud during drilling and completion operations and that repeated thermal and pressure shocks associated with production testing were required in order to clear the damaged aquifers.

It is of note that magnesium ion concentrations (Figure 2) in the downhole samples do not follow the chloride concentrations on a one to one basis. Although there is a substantial increase in magnesium ion associated with the upper saline aquifer, the higher salinity fluids in the deeper production zone have a much smaller change in magnesium concentration. It has been found that magnesium ion is strongly depleted in thermally altered groundwaters in Hawaii (Cox and Thomas, 1979) through the formation of the alteration mineral chlorite. These data suggest that the saline fluids entering the wellbore at depth have come to chemical and thermal equilibrium with the reservoir rocks whereas the fluids entering at shallow depths are relatively unaltered seawater. Thus it is probable that the upper saline aquifer was producing low temperature fluids to the wellbore and thereby reducing the average discharge

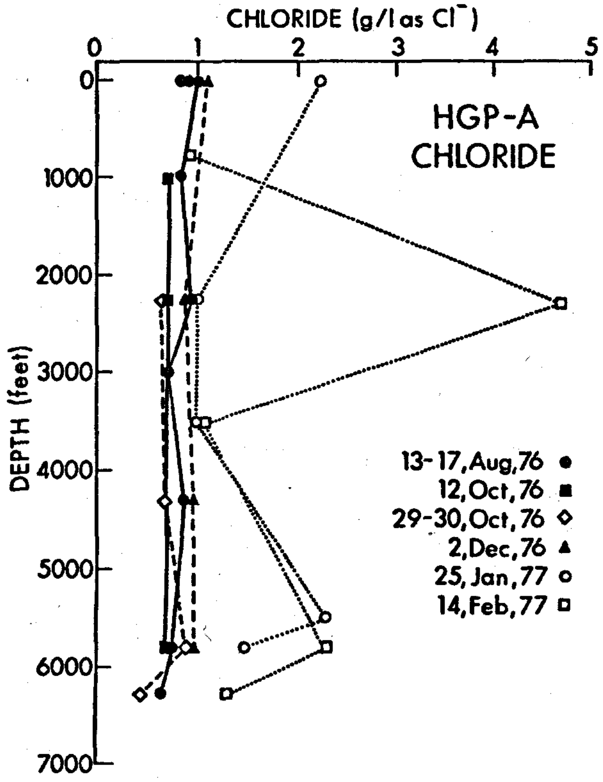

Figure 1 Plot of Chloride Concentration versus depth for downhole profile samples.

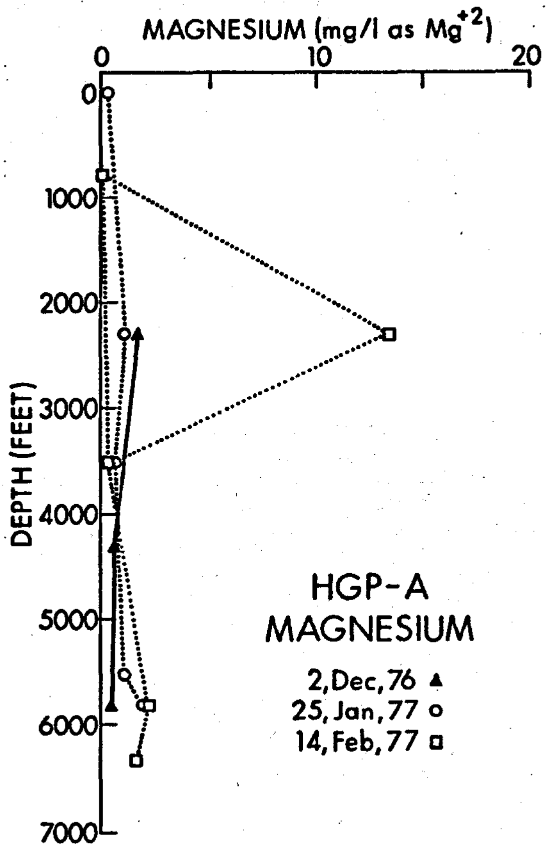

Figure 2 Plot of Magnesium Ion Concentration versus depth for downhole profile samples.

enthalpy from HGP-A. During subsequent operations this upper zone was cased off. However, as a result of the recasing program, damage was sustained to the slotted liner in the deeper wellbore and no further downhole sampling has been possible.

Production Chemistry: Brine

During early flow testing of HGP-A the salinity of the fluids produced (Table 2) was quite low and. even though the salinity has increased during recent production periods, the total dissolved solids content of the reservoir fluids has remained well below seawater abundances. The low salinity of the geothermal fluids was unexpected since the primary production zones in HGP-A are located nearly 1500 meters below the bottom of the Ghyben-Herzber- fresh water lens that was initially thought to be present in this area.

The relatively small amounts of sea water present in the HGP-A reservoir may be the result of the permiability structure of the Kilauea East Rift Zone. The rift system is made up of numerous vertical or near vertical dikes and fractures trending in an east-west direction. The fracturing in the rift system allows rapid recharge and fluid circulation in a vertical and east-west direction but the numerous dikes within the rift zone presents a virtually impermiable barrier to seawater intruding into the system from the south. Thus rapid vertical and east-west circulation of freshwater through the rift system tends to dilute the relatively smaller amounts of intruding seawater present in the deeper parts of the rift zone.

The chloride concentrations in the reservoir fluids suggests that approximately 10% to 20% of the recharge to the reservoir is of seawater origin. However, it is apparent that the cation concentrations in the saline component have been substantially altered from those present in seawater. Both calcium and magnesium have been heavily depleted whereas potassium and sodium have been enriched relative to seawater by about 450% and 5% respectively. Magnesium depletion, as noted above, is probably the result of chlorite formation in the reservoir whereas the retrograde solubility product constant of calcium and sulfate ion may provide the controlling mechanism for the removal of calcium ion from seawater. Both chlorite and anhydrite have been found in cores from the deeper part of HGP-A; ther former as an alteration product and the latter as a vein filling mineral (Stone, 1977). It is of note that anhydrite deposition may also provide a secondary controlling mechanism for the exclusion of

Table 1. Downhole Water Chemistry Data (mg/kg)

Date	Depth (meters)	Cl	Na	K	Mg	Ca
12/2 /76	690	910	500	77.5	1.9	21
12/2 /76	1310	920	480	85	0.7	17.3
12/3 /76	1770	980	500	223	0.6	22.6
2/14/77	690	4800	2160	248	14.7	465
2/14/77	1070	1030	600	82.5	0.4	39.3
2/14/77	1770	2330	1080	160	2.0	161
2/14/77	1920	1310	620	87.5	1.9	95.7

Table 2. Chemical Analyses of HGP-A Brines During Production (mg/kg)

	Cl^-	Na	K	Mg	Ca	SiO_2
11-8 -76	2190	1200	212	<0.5	81.9	
11-17-76	2520	1320	223	0.5	78.8	
1-29-77	2590	1260	225	0.5	78.2	
4-11-77	3050	1460	266	0.1	77.3	710
6-15-78	2420	1500	250	0.08	56.6	
1-14-80	2450	1440	216	0.1	33.2	
6-12-81	1593	806	154	0.02	18.5	1200
9- 4-81	3700	2190	250	0.1	72	800
12-22-81	3261	1745	281	0.04	58.3	1100
3-22-82	5050	2655	431	0.080	121.	
4-19-82	5293	2792	472	0.134	123.	799
5-17-82	5489	3066	508	0.060	124	802
6-14-82	5677	3200	513	0.070	149	818
7-14-82	6044	3300	536	0.073	157.	

seawater from the interior of the rift zone. The enrichment of potassium in the reservoir fluids is largely the result of alteration of small amounts of plagioclase or interstitial glass present in the reservoir basalts (Bischoff and Dickson, 1975).

As noted above, the chloride and total dissolved solids content of the geothermal brines has increased throughout the production history of HGP-A. This increase has been of major concern not only from the engineering aspect of handling higher salinity fluids but also in terms of the possibility that cold seawater is intruding into the reservoir tapped by HGP-A. An evaluation of the major element chemistry changes indicates that the cation to chloride ion rations have remained relatively constant; if cold seawater were entering the reservior we would expect to see a trend of increasing calcium and magnesium to chloride ion ratios. Thus it is likely that, if seawater is entering the HGP-A reservoir, it has come to chemical and thermal equilibrium with the reservoir conditions and may not pose an immediate threat to the enthalpy of the production fluids.

An alternative explanation for at least part of the observed increase in fluid salinity is that steam formation in the production aquifers is gradually mining more heat from the reservoir rock and thereby increasing the overall steam quality. During recent production periods the steam quality of the well discharge has been observed to increase at constant or declining total flow during the first hundred hours of production and thus this may provide one mechanism for increasing the residual fluid salinity. However, the entire change in TDS concentrations during the current production period cannot be accounted for by this mechanism alone: the steam quality has increased by approximately 30% beyond its initial value whereas the total dissolved solids concentrations increased by approximately 300%.

The application of cation geothermometers (Fournier and Truesdell, 1973) to the reservoir fluid compositions have been attempted on a number of occasions. The results of these calculations yield reservoir temperatures that range from 80°C to 120°C below the measured static bottom hole temperature in HGP-A. The lack of agreement between the cation geothermometer and the measured temperature is considered to be largely due to the general deficiency of potassium bearing minerals in Hawaiian basalts. Silica geothermometry calculations have also been attempted with similar results. Although the silica concentrations are quite high in the initial fluids produced, the concentrations drop off rapidly after production begins. This suggests that silica is rapidly reequilibrating in the flashed geothermal brines by deposition of silica in the reservoir formation. Calculation of silica temperatures on the flashed brines using Fournier and Potter's (1982) revised silica geothermometer yield temperatures (345°C) at the upper end of the applicable temperature range of the thermometer and slightly below the maximum measured downhole temperature of 360°C.

The deposition of hydrothermal minerals in the reservoir rock due to steam formation is of major concern for the future productivity of the resource. As noted above, it is highly probable that silica is being deposited from the thermal fluids during the flashing process. However, evaluation of the major element chemistry suggests that deposition of other scale minerals is not presently occurring. Comparison of the cation concentrations to the chloride ion indicates a nearly constant ratio during present production periods even though the individual concentrations have increased by 300%. If deposition were occurring one would expect a gradual decline in the ratio of the cation being deposited to the chloride ion concentration.

Non Condensable Gas Compositions

The concentration and composition of non-condensable gases in the steam phase have been monitored since the completion of HGP-A (Table 3). Preliminary analyses of the gases during short duration testing indicated quite variable compositions and concentrations; more recent intensive monitoring of the steam chemistry during start up operations has indicated that the concentration of non-condensable gases changes quite radically during the first hundred hours of production and then gradually stabilizes. The observed changes are thought to be due in part to the development and migration of the flash front out into the reservoir.

The total concentration of non-condensable gases in the steam phase is not appreciably higher than that observed in other geothermal systems worldwide. However, the composition of the non-condensable gases is quite different: hydrogen sulfide makes up approximately 40% of the total mass and hydrogen is present in a nearly equal molar concentration to nitrogen. In addition, recent analysis of the steam phase for trace volatiles has been unable to detect ammonia, mercury, boron, or arsenic.

Table 3.
Non-Condensable Gas Compositions (mg/kg)

Date	CO_2	H_2S	N_2	H_2
2/09/77	4431	1435	131	46.3
5/08/77	2378	878	375	15.1
7/19/77	445	112.	116.	2.3
1/19/80	1000	750	168	11.0
5/31/82	1238	886	129	11.0

Stable and Radio Isotopic Studies

Analyses of the light stable isotopes of helium, hydrogen, oxygen, and carbon were performed on the fluids from HGP-A during the initial testing of the well. Helium isotopic analyses yielded ^{3}He/^{4}He ratios of approximately seven times the atmospheric ratio and about half that observed for helium in the Kilauea summit fumaroles. These data suggest that the heat source for the HGP-A reservoir is a relatively young (or large) magma body that has not yet completely outgassed its primordial component of inert gases.

During early production tests, samples of water were analyzed for H/D and ^{18}O/^{16}O isotopic ratios. The results obtained indicated that the majority of the recharge to the geothermal well was meteoric water with minor amounts of seawater and hydrothermal (^{18}O shifted) water present. Although this would suggest extremely short recharge and residence times, more complete hydrogen and oxygen isotopic data are required before any firm conclusions can be drawn.

A very limited number of stable carbon isotopic analyses performed on carbon dioxide present in the geothermal fluids have found C-13 ratios ranging from -1.97% to -3.6% versus PDB. These values are considerably heavier than those associated with the expected sources of carbon in the well fluids: biogenic CO_2 at approximately -20% and magmatic carbon at approximately -7%. Although a complete analysis of the carbonate chemistry connot be made with the presently available data, it is highly probable that deposition and remobilization of carbonate is the major controlling factor in the carbon isotopic compositions observed.

Tritium and radiocarbon analyses performed on the brine and gas phase from HGP-A indicate that the age of the recharge water is at least

30 years (no detectable tritium) but is probably less than 12,000 years (carbon-14 approximately 20% of modern). It is of note that the carbon age is considered to be a maximum age in that any contribution by magmatic sources to the biogenic carbon present in the well would yield apparent ages that are older than the true radiocarbon age. Thus the average lifetime of recharge to the portion of the geothermal reservoir tapped by HGP-A is considerably shorter than that observed in most other continental geothermal systems.

Analysis of radon in the geothermal fluids from HGP-A have provided values ranging from 1.16 nanocuries per kilogram (nCi/kg) of steam condensate during early, short period, production testing to 3.7 nCi/kg during longer term production (Kruger, personal communication). The radon concentration calculated for the reservoir fluids from the present data is approximately 1.65 nCi/kg of total fluid. This value is considerably lower than the average observed at The Geysers of 20 nCi/kg (Kruger, personal communication) and is probably the result of the lower uranium concentrations persent in Hawaiian basalts relative to the more silicic volcanic and sedimentary rocks present in continental geothermal fields.

Summary

In summary, the geochemical monitoring conducted at HGP-A has provided information on a number of characteristics of the reservoir discovered by the HGP-A well:

1) seawater intrusion and circulation within the rift zone is severely restricted. It is suggested that the exclusion of seawater is either the result of the permeability structure of the rift zone or by thermal precipitation of alteration and and hydrothermal minerals.

2) Changes in fluid compositions during extended production suggest that multiple aquifers are providing fluids to the well and that these aquifers may have relatively small fluid volumes available.

3) The total non-condensable gas concentrations in the reservoir fluids are within the worldwide range however the concentrations of the individual species are considerably different from those observed in continental environments.

4) Radioisotopic analyses suggest that the recharge-discharge lifetime in the reservoir is relatively short in comparison to those occurring in continental geothermal systems.

References

Bischoff, J. L., and F. W. Dickson (1975) Seawater-basalt interaction at 200°C and 500 bars: implications for origin of seafloor heavy metal deposits and regulations of seawater chemistry, Earth Planet. Sci. Lett., N. 25, p. 385-397.

Cox, M. E., and D. M. Thomas (1979) Chloride/Magnesium ratio of shallow groundwaters as a regional geothermal indicator in Hawaii. Hawaii Institute of Geophysics Technical Report No. 79-9, 51 p.

Fournier, R. O., and R. W. Potter, II (1982) A revised and expanded silica (quartz) geothermometer. Geothermal Resources Council Bulletin, V. II, No. 10, pp. 3-12.

Fournier, R. O., and A. H. Truesdell (1973) An empirical Na-K-Ca geothermometer for natural waters. Geochem. Cosmo. Act., V. 37, pp. 1255-1275.

Stone, C. (1977) Chemistry, petrography, and hydrothermal alteration of basalts from Hawaii Geothermal Project Well-A, Kilauea, Hawaii. Master of Science Thesis, University of Hawaii, 84 p.