

THE GEOCHEMISTRY OF THE HGP-A GEOTHERMAL WELL:  
A REVIEW AND AN UPDATE

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ABSTRACT

The HGP-A geothermal well, located on the lower east rift system of Kilauea volcano, has provided steam and hot water to a 3MWe wellhead generator facility on a continuous basis since December 1981. Since production began there have been substantial changes in the composition of the reservoir fluids that suggest several important conclusions regarding the HGP-A well and the reservoir associated with the Kilauea east rift zone. Among these are: that preproduction reservoir fluids have moderate to low dissolved solids concentrations; that long-term fluid production can result in encroachment of heavily modified seawater into the geothermal system; and that deposition of secondary minerals from the intruding seawater may result in the obstruction and eventual sealing of the saline aquifers.

INTRODUCTION

The HGP-A geothermal well, located on the lower east rift zone of Kilauea, was drilled in 1976 to a total depth of 1966 meters. Initial testing of this well showed that it had a bottom hole temperature of 358°C and was capable of producing approximately 50 tonnes of geothermal fluid per hour (Yuen et al., 1978). The fluid discharged by this well was composed of approximately 43% steam and 57% liquid brine (at a separation pressure of approximately 1200kPa (175psia)) indicating that the resource encountered was liquid dominated. In order to demonstrate the technical feasibility of producing electrical power from the geothermal reservoir discovered by the HGP-A well, the U.S. Department of Energy, the State of Hawaii, and Hawaiian Electric Company provided funds to construct a single-flash 3MWe wellhead generator facility. This facility was completed in June 1981 and, after a lengthy shake-down period, began continuous operation in March 1982 (Thomas, 1982). During the subsequent five years of operation the chemical composition of the reservoir fluids discharged by HGP-A have been carefully monitored in an effort to identify the source of the fluids produced by this well and to provide technical information that may be of value in the design of larger commercial geothermal generator facilities. Some of the more important findings of this monitoring program are presented below.

HGP-A FLUID CHEMISTRY

Analysis of the steam and brine discharged by the HGP-A well during initial flow testing found that the reservoir fluids in the Kilauea east rift zone contained only moderate concentrations of dissolved solids (about 3000mg/kg) and gases (about 0.25%) (Kroopnick et al., 1978, Thomas, 1980). The principal dissolved species found in the liquid phase were sodium, chloride, and silica and the major non-condensable gases present were carbon dioxide, hydrogen sulfide and nitrogen. Although the levels of dissolved solids present in the geothermal fluids were well below those anticipated in the interior of the Kilauea east rift, continuous production of fluids during the subsequent five years of operation of the facility resulted in an approximately tenfold increase in the solids concentrations (Thomas, 1986). A plot of chloride ion concentration in the brine phase versus time shows the general trend of the major dissolved ions: an initially steep rate of increase that, with time, has gradually levelled off. More recently, however the trend has undergone a reversal with a very slight decline in the dissolved ion concentrations. Although the other major dissolved ion concentrations have followed a similar trend during this period, only sodium increased at the same rate as chloride whereas calcium and magnesium increased more rapidly and potassium and lithium increased more slowly. It is noteworthy, however, that the dissolved silica and the non-condensable gases have not followed the same trend as the dissolved ions but have maintained relatively constant values in the brine and steam phases respectively.

DISCUSSION

The concentrations of the dissolved solids present in the deep reservoir fluids discharged by the HGP-A well during the initial testing were substantially below those anticipated on the basis of the Ghyben-Herzberg model of island hydrology. This model predicted that, in the location of the HGP-A well, only a thin (<200m thick) fresh water layer should have been present and that this layer would be underlain by seawater saturated basalts at the depths of the production intervals drawn upon by the HGP-A well. The presence of only slightly brackish water at 2km depths suggested that some mechanism associated with the rift zone

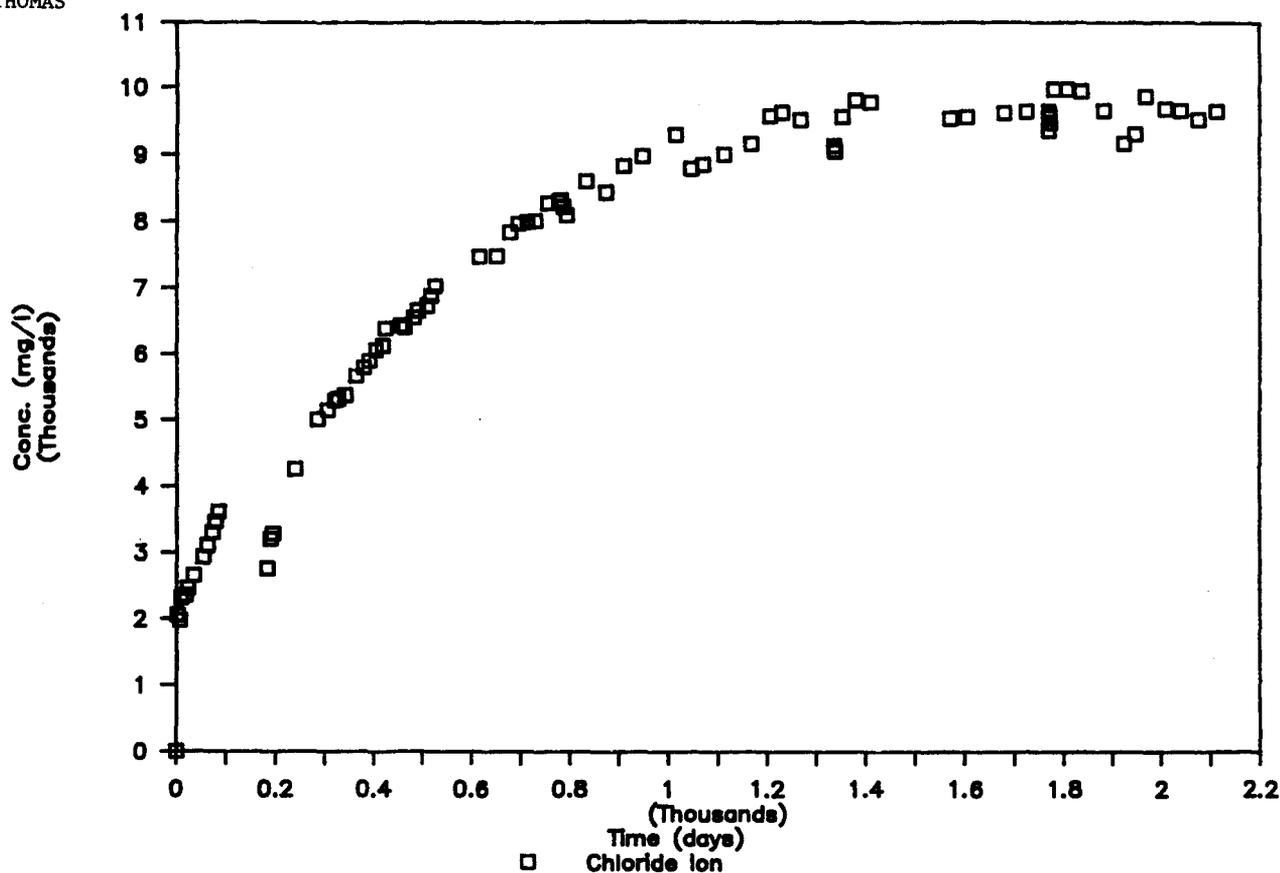


Fig. 1. Chloride concentration in HGP-A brine versus time.

was responsible for exclusion of seawater from the interior of the geothermal reservoir. The mechanisms that have been suggested have included: inhibition of cross-rift seawater intrusion by the less permeable dike complex within the deeper part of the rift; rapid convective overturn and mixing of hot, less dense saline waters with colder, denser, fresh meteoric recharge; or the alteration of the reservoir basalts and the deposition of secondary minerals along the southern boundary of the hydrothermal system (Thomas, 1987). The changes in ion chemistry that occurred during the long-term production of the well now suggests that all three mechanisms may play a role in controlling fluid flow within the lower east rift system.

The very steep increases in the dissolved ion concentrations that accompanied long-term production of fluids from HGP-A suggested that withdrawal of reservoir fluids was permitting seawater intrusions into the hydrothermal system tapped by the well. This inference is substantiated by the coincident increases in the sodium and chloride ion concentrations which have maintained a Na:Cl ratio that is nearly identical to that of seawater. The concentrations of several other major ions, relative to that of chloride, indicated however that the intruding seawater had been heavily

modified: lithium and potassium were enriched in the HGP-A brines relative to seawater, by factors of fifteen and five respectively, calcium was depleted by 40%, and magnesium and sulfate were depleted by more than 99.9%. This pattern of enrichment and depletion is very similar to that found in seafloor hydrothermal vent systems and in laboratory experiments of high-temperature reactions between seawater and basalts (Mottle, 1983; Bischoff and Dickson, 1975). These, and other studies, have shown that seawater undergoes a complex chain of reactions when exposed to high temperature basalts that results in both modification of the seawater composition and intensive alteration of the reservoir basalts.

The degree of enrichment and depletion of the ionic species during the early production period indicated that the seawater:basalt ratios were quite low (<0.1) (Thomas, 1983). However, as the salinity of the production fluids increased with time, the degree of enrichment of lithium and potassium, and the depletion of magnesium, declined while calcium ion concentrations changed from being depleted to being substantially enriched (Figure 2). The observed trend of relative ion concentrations suggest two possible interpretations. The first is that the observed

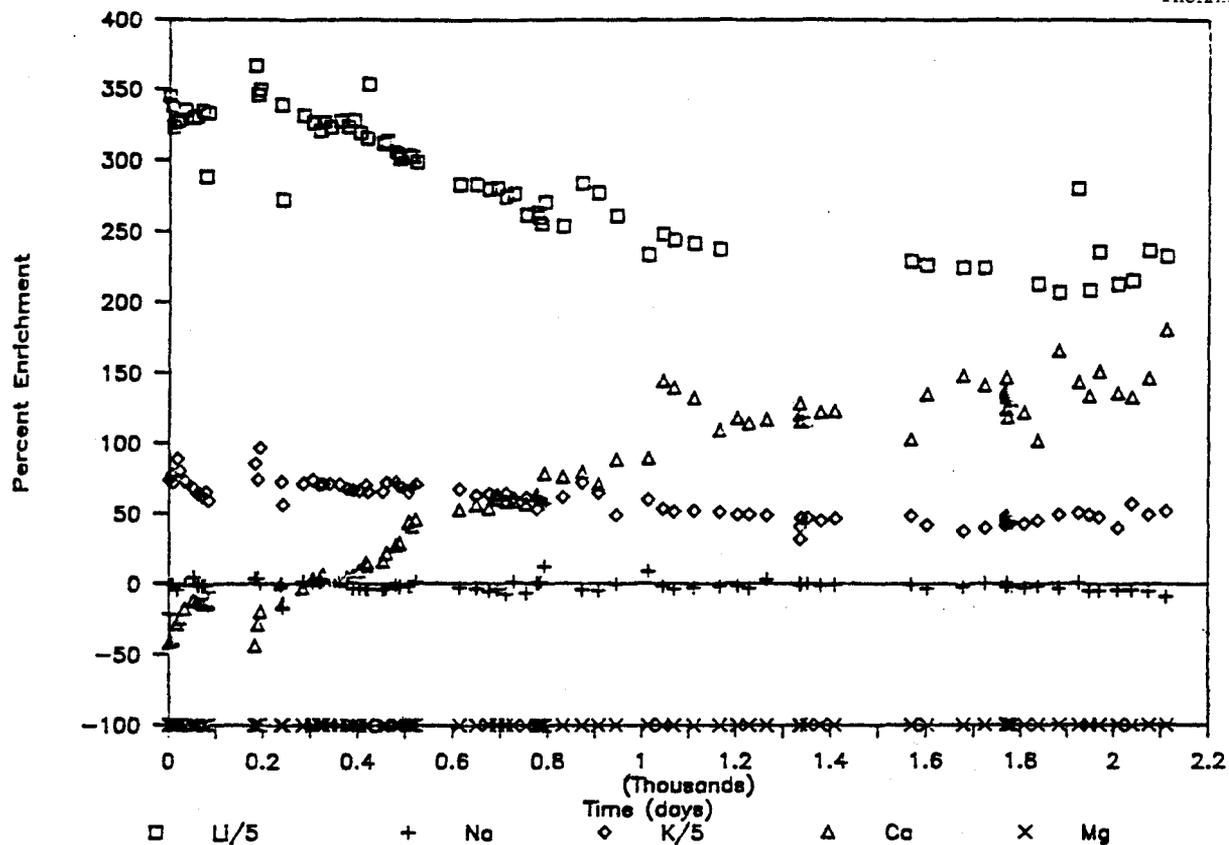


Fig. 2. Percent enrichment or depletion of major cations with respect to seawater of equal chloride concentration.

changes in ion ratios reflect a progressively increasing seawater:basalt ratio in the geothermal reservoir; as progressively more seawater passes through, and reacts with, the wall-rock of the intrusion aquifer, the rocks became progressively altered, depleting more soluble ions from the solid phase. The degree of enrichment of potassium and calcium suggest that the effective water rock (W:R) ratio is currently approximately three. This W:R ratio is well within the range of seawater:rock ratios observed in seafloor hydrothermal systems and in a similar land-based, seawater dominated hydrothermal system on the Reykjanes peninsula in Iceland (Mottl and Seyfried, 1980).

An alternative hypothesis that could account for the observed changes in the ion ratios is that they reflect a decline in the temperature of the reservoir due to the influx of cold seawater from outside the rift zone. Calculation of the Na-K-Ca geothermometer temperatures through the period of changing fluid compositions shows that there has been an apparent decline in the fluid temperatures with time (Figure 3). The temperatures calculated for the fluids during the first few weeks of production indicated a temperature of approximately 300°C but, after several years of production, the

apparent cation temperature have fallen to less than 240°C. However, as noted above, the silica concentrations have remained relatively stable at about 800-850mg/kg which yield calculated temperatures of approximately 295°C. The apparent discrepancy in the geochemical temperatures is believed to be the result of the difference in the rate at which these geothermometers approach equilibrium. Because silica approaches an equilibrium concentration more rapidly than does the Na, K, and Ca concentration, the former more accurately reflects the actual reservoir temperatures around the well-bore. Because the Na-K-Ca geothermometer achieves equilibrium more slowly, and may be more sensitive to progressive depletion of these ions from aquifer wall rock (i.e., at higher W:R ratios), the apparent decline in the temperatures calculated from these ion concentrations may correspond to the temperatures of the intruding fluids prior to entry into the hydrothermal system. Thus, the changing ion enrichments may be the result of progressive alteration of reservoir rocks exposed to the intruding seawater.

The reactions that accompany the intrusion of seawater into the geothermal reservoir have several important implications for the chemistry of the geothermal reservoir fluids. The

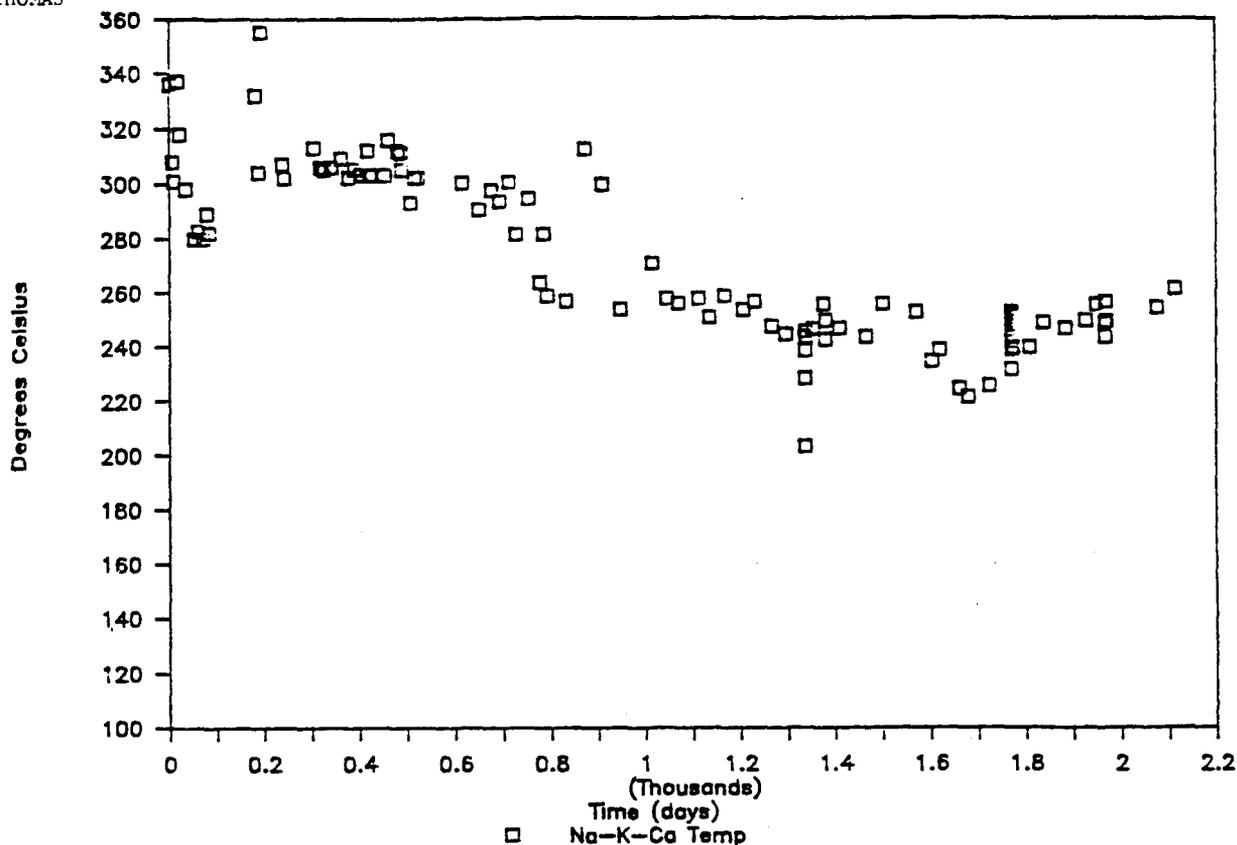


Fig. 3. Calculated Na-K-Ca geothermometer temperature of HGP-A brine.

laboratory studies of seawater:basalt reactions noted above have shown that the pH of the hydrothermally altered seawater is strongly dependent on the W:R ratio. This pH dependency results from a balance maintained between the loss of magnesium from the seawater (as  $Mg(OH)_2$ ), which could potentially lower the pH, and the alteration of calcic plagioclase minerals that can increase the pH and thus buffer the effect of magnesium loss. As these minerals are depleted, however, the buffering capacity of the reservoir basalts is lost and thus the continued removal of magnesium from the intruding seawater can result in a precipitous decline in fluid pH. In extreme cases the pH can fall to levels as low as pH 2. Although there has been a decrease in the pH of the HGP-A brines, from pH 7.4 to pH 6.5, an extreme change in pH is not anticipated to occur until the calcium ion enrichment begins to decline and the magnesium ion concentration increases substantially above its current levels. Nonetheless, continued influx of seawater into this system over an extended period of time could exhaust the plagioclase minerals in the aquifer wall rocks and eventually result in extremely corrosive geothermal fluids.

A second aspect of the intrusion and alteration of seawater in the east rift hydrothermal system is

that the reactions occurring between seawater and basalt result in the deposition of substantial amounts of secondary minerals. The mineral suite deposited includes anhydrite, chlorite, smectites, actinolite, pyrite, and a number of other species depending upon the temperature and the effective W:R ratio in the particular reaction zone. Laboratory studies of the reaction sequence have also shown that the deposition of secondary minerals can result in the obstruction of the intrusion fractures and thus a reduction of the fluid permeability in the reservoir rocks (Pohl and Liou, 1983). The presence of secondary minerals in the cuttings and cores from HGP-A, and other wells in the east rift zone, clearly indicates that these reactions are also occurring in the natural hydrothermal system as well.

The changes that have occurred in the chemistry of the fluids produced by HGP-A during the last five years of production thus suggest three potential trends that might be anticipated for long-term operation of a geothermal well on the seaward flank of the Kilauea east rift zone: because declining apparent cation temperatures approximate the source temperature of the intruding fluids, continued influx of seawater could bring about a significant decline in the temperature of the

production aquifers in the well; depletion of buffering capacity of reservoir basalts at a faster rate than the depletion of thermal energy could result in continued high fluid temperatures but a disastrous decline in pH of the fluids produced; or the deposition of alteration minerals could result in the eventual obstruction of the intrusion aquifers. As noted above, the silica temperature has remained relatively constant and thus suggests that a decline in reservoir temperature is not imminent. However, an observed decline in the brine pH from pH 7.4 (@25°C) to 6.5 (an increase in the hydrogen ion concentration by nearly a factor of 10) indicates that some depletion of the buffering capacity of the reservoir rocks has occurred and that further decline in the pH is quite possible. Nonetheless, the decline in the dissolved ion concentrations in the brine phase that have recently been observed suggest that the fractures through which cold seawater from south of the rift is entering the geothermal system are gradually becoming obstructed and are thus choking off the flow of seawater into the production horizon tapped by HGP-A.

#### IMPLICATIONS FOR FUTURE GEOTHERMAL DEVELOPMENT ON THE KILAUEA EAST RIFT ZONE

Although a projection of the expected production characteristics of an entire geothermal field on the basis of the results derived from a single exploration well must, of necessity, be highly speculative, two tentative conclusions are suggested by the operating history of the HGP-A well. These are as follows:

1. Wells drilled in the interior of the rift are likely to encounter low to moderate salinities but those drilled along the southern boundary of the rift are more likely to encounter a seawater dominated hydrothermal system.
2. Wells drilled along the southern boundary of the rift are more likely to encounter either lower permeabilities or much more acid geothermal fluids than those drilled in the interior of the rift system.

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