PROCEEDINGS, Tenth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 22-24, 1985
SGP-TR-84

PRELIMINARY RESULTS OF DRILLING AND TESTING IN THE PUNA GEOTHERMAL SYSTEM, HAWAII

3. L. Iovenitti and W. L. D'Olier

Diamond Shamrock Thermal Power Company
3333 Mendocino Avenue, Suite 120
Santa Rosa, California 95401

ABSTRACT

Diamond Shamrock Thermal Power Company, operator for the Puna Geothermal Venture has drilled and tested two geothermal wells in the Puna geothermal system, Howoii. The wells were drilled to depths of 7290 and 8005 feet and completed with 9-5/8 inch production casing to about 4200 feet and 7 inch perforated liner to bottom. Preliminary short term testing has demonstrated 100% saturated steam production (1185 Btu/lb) at certain wellhead pressures. Cyclic flow with a minimum 55% steam quality has also been observed. Initial estimate of non-condensible gas concentration is 0.2% by weight with an average H_2S concentration of 1100 ppm by weight. The well flowing characteristics appear to stem from a high temperature (greater than 650°F) two-phase liquid-dominated geothermal reservoir which contains a variable steam fraction. Produced steam quality variation at the surface in this field is attributed to both mechanical and reservoir factors.

The geothermal system appears to lie within the East Rift Zone of Kilawa Volcano. It is a blind system masked by overlying groundwaters and effectively sealed by impermeable rocks. Basaltic magma stored in the rift zone is postulated as the heat source. The high temperature portion of the geothermal reservoir begins at about 4000 feet and extends to an unknown depth. The wells are interpreted to have encountered multiple producing horizons and interzonal flow is evident. Saturation conditions prevail below the 9-5/8 inch production casing. The critical point of water may be surpassed at depth in this system.

Initial test results are sufficiently encouraging to warrant an additional well by the Puna Geothermal Venture to identify reservoir and well characteristics for electrical power plant consideration which includes wellfield development costs.

INTRODUCTION

The Puna geothermal system is located within the lower East Rift Zone of Kilauea Volcano on the island of Hawaii (Figure I). Kilauea is one of the world's most active volcanos. The Puna Geothermal Venture (PGV) wells are stepouts to the successful HGP-A well drilled jointly by the US Department of Energy, State of Hawaii and University of Hawaii.

HGP-A was completed in 1976 to a total depth of 6450 feet with a bottomhole temperoture of 676°F. The well has been producing 110,000 lbs/hr at 166 psig wellhead pressure with approximately 43% steam quality (Thomas, 1983) to a 3 MW turbine generator in nearly continuous operation since May, 1982. The well results have been summarized by Kihara et al (1977), Chen et al (1978), Stone and Fan (1978), Thomas (1982), and Waibel (1983). HGP-A demonstrated the feasibility of generating electrical power from a Hawaii volcanic resource. It is the objective of PGV to develop geothermal energy in Howaii for reliable electric power production at a marketable price. PGV consists of Diamond Shamrock Thermal Power Company, Dillingham Geothermal, Inc. and Amfac Energy, Inc. Competitor drilling in the region has reportedly found high bottomhole temperatures but production has not been demonstrated.

Reported herein are some highlights of the PGV wellfield activity. These data are integrated to formulate a conceptual model of the Puna Geothermal System. We hope that this overview will assist the work being done in the development of high temperature, two-phase geothermal systems for electrical production.

GENERAL SETTING

East Rift Zone of Kilauea is one of the conduits for the lateral migration of basaltic magma from the holding chamber beneath the volcano's summit caldera. It is manifested at the surface as a linear belt, 1 - 2 km wide, consisting of linear and open fissures, faults, small grabens, pit craters, cones and vents for numerous eruptions. In the lower portion of the rift zone eruptions have occurred as recently as 1740, 1840, 1955, 1960 and 1961. The rift zone is a constructional ridge some 150 - 1500 feet above the adjoining terrain throughout its length except in its lowermost portion where the ridge disappears into a series of grabens and spatter deposits (Moore, 1983). The successful drilling actitivy to date lies in the transition area from the constructional ridge to the more subdued topography. Underlying the surface expression of the East Rift Zone is a much broader (5-15 mile) dike complex inferred on the basis of gravity and magnetic data (Furumoto, 1978). This complex is thought to consist of an aggregate of closely spaced parallel to sub-parollel, vertical to steeply dipping dikes whose top is in general about 7600 feet below the surface. The dikes intrude a sequence of Mauna Loa and Kilauea lava flows. This complex is reported (Furumoto 1978) to be locally above the Curie Point (1000°F) and in places may even approach the melting point of basalt (about 1900°F). Petrologic studies of lavas in the rift zone indicate the presence of differentiated tholeiite which strongly suggests the existence of subsidiary magma chambers. The Puna geothermal system overlies one such area (Moore, 1983). Sufficient heat to drive a geothermal system is clearly indicated.

The Puna system is considered a blind geothermal prospect because no surface manifestations exist in the area except for several hot springs discharging along the coast some three miles to the south and for isolated steam vents within the rift zone which are associated with recently active fissures. The lack of surface manifestations, in spite of the tremendous heat flux potential created by the dike complex, is attributed to a vigorous, cool groundwater system which "hydraulically masks" the reservoir and to a relatively impermeable seal. Annual rainfall in this area is about 120 inches which immediately infiltrates into the ground; virtually no standing water bodies exist. Groundwater residence time is reported to be on the order of years (Kroopnick et al, 1978). Additionally, very recent lava flows could easily caver any surface evidence of a geothermal system.

Review of public domain information which has been recently summarized by Thomas 1984, indicated that the Puna system may be localized in the eastnortheast trending rift zone at the structural intersection with a north-northwest trending transverse fault (Figure 1). The successful results of the HGP-A and PGV wells support this hypothesis.

PCV WELL RESULTS

Comments

The PGV stepout wells, Kapoho State-l (KS-l) and Kapoho State-2 (KS-2) were drilled in the rift near the trace of the 1955 fissure eruption (Figure 1). In general, the casing programs, lithologies and mineral alteration suites, lost circulation zones, available temperature/pressure surveys and flow test results are very comparable in both wells. However, the latter two data sets are not complete for each well. The apparent commonality between these wells has allowed as a first approximation, data set interchange for interpretational purposes.

Drilling and Completion

KS-1 was completed on 12 November 1981 to a total depth of 7290 feet after 65 days of drilling operations. The top hole was drilled with mud; water was used as the principal drilling fluid in the reservoir section. KS-2 was drilled almost immediately after KS-l, without any appreciable intervening flow tests. With only 56 days of drilling operations, KS-2 was completed at total depth of 8005 feet on 2 April 1982. The type of drilling fluid used was as in KS-l except that at depths greater than 6800 feet a very light saltgel mud was continuously utilized to lift cuttings to the surface. Other than severe lost circulation problems in the upper portions of both wellbores (in the highly permeable subaerial basalts), no significant drilling problems were encountered. Although not realized until after flow testing, cementing of the casing strings was apparently less than optimum in the shallow lost circulation zones. Both wells are completed with two ANSI 900-series wellhead gates. The 9-5/8 inch production casing in KS-l and KS-2 was run from surface to 4072 and 4209 feet, respectively. An uncemented 7-inch perforated liner was stood in the 8-3/4 inch (KS-1) and 8-1/2 inch (KS-2) wellbores.

Lithology, Mineral Alteration and Lost Circulation Zones

The wells penetrated a sequence of subaerial basalts, subaqueous basalts, basalt tephra and subvolcanic intrusives which increase in frequency with depth. Preliminary minerological alteration studies (Columbia Geoscience, 1982) reveal a variable and complicated section. Three specific types of alteration are recognized: (1) deuteric (vapor phase), (2) contact metamorphic, and (3) hydrothermal. The latter two processes totally overprint the deuteric alteration below 2500 feet. Discrimination between contact metamorphic effects and hydrothermal alteration is difficult since both processes alter the rock to a low grade chlorite-albite greenschist facies. The original rock texture is largely obliterated by alteration below 4500-4700 feet. Barring the deuteric alteration assemblage, the wells can be characterized as follows:

0 - 3000':	Virtually free of alteration
3000-4000':	Localized moderate alteration (30-60% of cuttings altered) with rare highly altered zones (greater than 60% of cuttings altered).
4000'-TD:	Common moderate alteration with localized zones of highly altered rock interspersed with occassional zones of fresh, unaltered rock.

This alteration mineralogy suite is comparable to that reported by Waibel (1983) for HGP-A where it begins a thousand feet shallower. However, unaltered intervals below 4000 feet (reservoir section) in the PGV wells are in marked contrast to the HGP-A which shows fairly complete alteration from 2000 feet to total depth. These zones of fresh rock are thought to represent, at least in part, recent intrusives most likely related to the 1955 fissure eruption (Figure 1) which have not had enough time to became hydrothermally or thermally altered (A. Waibel, pers. dommunication, 1984). They could also represent large blocks of impermeable host racks. Detailed petrological studies of the wellbore cuttings are to be conducted.

Lost circulation as an indicator of permeability can be subdivided into four discrete zones: (1) 0–1500 feet: total loss; (2) 1500 - 2000 feet: intermittent and minor losses; (3) 2500 - 4000 feet: virtually no loss; and (4) 4000 feet - total depth: intermittent and generally minor losses. The only significant lost circulation zone in the reservoir section occurs below 7000 feet.

Since identification of hydrothermal alteration is not unequivocal, the degree of alteration rather than a specific mineral or mineral assemblage has been used in conjunction with lost circulation zones, flow test and other data to identify a minimum of three production zones. These production zones can occur in intra-flow boundaries, fractured flows (and dikes) and intrusive contacts. Fracturing is principally fault induced.

Temperature/Pressure Surveys and Shut-in Conditions

Figure 2 illustrates temperature/pressure profiles for the PCV wells and HGP-A. Hydraulic masking is evident from the surface to 1500 - 2000 feet (top of basal water is about 600 feet). Below this zone a relatively impermeable caprock extending to 2250 feet in HGP-A and to 4200 feet in KS-2 is suggested by the extremely high conductive gradient. However, while a caprock is thought to exist above the reservoir based on the absence of significant lost circulation and mineral alteration, close examination of the data strongly suggests that the observed wellbore temperature/pressure profiles are dominated by circulation in the perforated liner interval (i.e., interzonal flow described below).

A maximum temperature and pressure of 648°F and 2120 psig were measured in KS-2 at a depth of 5500 feet where the survey tool was blocked presumably by rock bridges. A pressure gradient of 0.248 psi/ft in the perforated liner interval indicates boiling conditions and a liquid-dominated geothermal system. The open hole interval is essentially at saturation both prior to and immediately after the first series of flow tests. Extrapolation of these data suggests that supercritical fluids could be present at depth in this system. This is consistent with the magmatic heat source postulated to exist in the rift.

KS-1 shows a relatively isothermal gradient in its perforated liner interval. A maximum temperature of 643°F was recorded at 6400 feet where the survey tool was blocked presumably by rock bridges. While pressure data has not been obtained in this well saturation conditions are assumed based on flow test results given below. The elevated temperatures/pressures in KS-2 are attributed to its greater depth and possibly additional production zones beneath the total depth of KS-1. Similarily, the higher temperature/pressure and saturation conditions observed in the PCV wells relative to HCP-A is interpreted to result primarily from a production zone(s) below total depth of HCP-A. Additionally, Rudman and Epp (1983) have shown that proximity to a hot dike can have a significant effect on a well's temperature profile. The greater lateral distance of HGP-A from the recent 1955 fissure eruption may also be a factor.

As stated above, interzonal flow is operative in open-hole interval in both PCV wellbores. Higher temperature/pressure fluids enter the wellbore below 7000 feet and exit through a permeable horizon just below the casing shoe. As this situation proceeds in the shut-in mode, the perforated liner interval is brought to saturation conditions. This upflow disguises the true wellbore temperature/pressure profile in these wells. A gas column collects below the wellhead which drives the liquid level in the wellbore down to the first permeable horizon presumably at the base of the 9-5/8 inch casing. At this point gas does not collect in the wellbore but exits through this permeability zone (Grant, 1979). When this occurs the wellhead pressure is stable and is referred to by us as the equilibrium shut-in wellhead pressure; it attained 1435 psig in KS-1.

Post Completion Problems and Flow Test Results

The drilling and completion of these wells were relatively straightforward. Flow testing proved to be altogether different. Hostile wellbore conditions in the wells led to several different types of wellbore obstructions (e.g., rock bridges, lost survey tools, a 270 foot fish in KS-1). Thermal cycling has occurred with a temperature flux of 475°F, in the shallow wellbore, between shut-in and flow conditions. The accumulated gas column has allowed H_2S stress corrosion in the upper portions of the wellbore where the vigorous groundwater regime is active. Atmospheric venting of the wells to keep the wellbores hot and free of gas was not an environmentally acceptable option because of the high levels of H_2S that would be discharged.

Flow testing was interrupted by wellhead noise levels approaching 120 decibels, high H_2S concentrations and particulate matter eroding surface equipment. To reduce the noise levels a rockfilled, pit muffler (15 x 15 x 15 feet) was constructed to lower effluent venting velocity. An H_2S abatement system was integrated into the surface test equipment to lower emitted H_2S levels to within regulatory standards and permit conditions. Continuous flaw eliminated the particulate matter problem.

Initial short term (hours) vertical venting of KS-2 indicated saturated to super heated steam production in less than one hour flow time. The well displayed the following general characteristics upon opening: (1) gas cap is discharged; (2) discharge of the liquid column accompanied by a high temperature/pressure transient (maximum levels were 546°F and 1454 psig on a 4 inch line) and abundant iron-sulfide (pyrite?) and other particulate matter; and (3) discharge of saturated steam followed by superheated steam.

Each well underwent four flow tests. The initial three tests conducted on a 10" blooie line, pit-muffler and H_2S abatement system yielded conflicting results. A steel vessel separator was brought in to accurately ,measure the steam and liquid phases. A five day test on KS-2 indicated

100% steam saturated flow at a rate of 33000 lbs/hr and 173 psig wellhead pressure. At lower wellhead pressures liquid from an identified leok in the 9-5/8 inch casing became entrained in the flow. This leak developed some time after the initial vertical venting. A thirteen day test of KS-I indicated essentially 100% saturated steam at a flow rate of 72000 lbs/hr and 120 psig wellhead pressure (H. Dykstro, written communication, 1983). Total non-condensible gas concentration is about 0.2% by weight comparable to HGP-A (Thomas, 1982). H_2S concentrations are about 1100 ppm by weight. Flashing in the reservior is clearly taking place.

Figure 3 illustrates some of the KS-I data obtained during the last 200 hours of almost uninterrupted flow. Cyclic flow is generally present at all wellhead pressures but is most prominent at well-head pressures greater than 170 psig, where steam quality drops from about 100% to about 55%. Liquid flow rate increases but steam flow rate does not change appreciably. Cyclic flow with a much shorter period and zero to trace liquid occurs at wellhead pressures less than 170 psig. This phenomenon was olso visually observed by one of the authors while the well was discharging to atmosphere. The flow went from being slightly wet to dry to superheated an undefined number of times during a one minute interval. For all practical purposes, however, the well flowed dry saturated steam at this time.

Grant et al (1979) has attributed cyclic flow in wells to communication between multiple producing zones significantly separated in depth from each other. The authors agree with this interpretation but the above data would also suggest another. During the KS-I test a 270 foot fish was present in its 7-inch liner. It would seem that the fish would be o significant obstacle to flow from production zones below it. Qualitatively, while flow in the annulus area is taking place, it is not considered sufficient to account for the liquid flow rate observed. Only one productive zone is thought to exist above the fish. Either on additional unrecognized production zone(s) is present above the fish or varying wellhead pressure can cause changes in the flashing characteristics in a single producing zone. Further work is needed to resolve this point. Another phenomenon indicated by the KS-I data is that initial total steam flow rate is somewhat proportional to shut-in time. This is interpreted as indicating that the fluid producing permeable zones around the wellbore are larger than the smallest conduit feeding them. Thus, when the well is shut-in, the high permeabiltity zone around the wellbore undergoes recharge.

Both PGV wells have been suspended with deep drillable cement plugs placed in the 1700-2500 foot interval of the production casing. This is a safety precaution to avoid high shut-in wellhead pressures and H_2S stress corrosion.

DISCUSSION

The PGV well dato ore complicated by a variety of factors. The wellbore temperature/pressure profiles do not provide any detail on the in-situ reservoir section. However, saturation is considered to be the general reservoir thermodynamic state. Upon opening the well to flow, the ensuing pressure drop in the wellbore in 'this very high temperature environment allows flashing in the reservoir. Production of superheated steam, 100% saturated steam, or two-phase flow can take place as a function of wellhead pressure. A dry steam flow has been observed in a very short period of time in these wells. Comparable behavior has not been previously reported in any other two-phase liquid-dominated system. A possible explonation for this phenomenon may be found in Dunn and Hardee (1981). They hove shown that the heot transfer rates dramatically increase in a permeable medium in the vicinity of the critical point. The role (if any) of interzonal flow on production of 100% saturated steam flow at the surface along with impact of a fish on the KS-I test data is not clearly identified. Unreported data suggests the shallowest production zone in KS-I may produce a high quality fluid in the absence of interzonal flow.

The producing behavior of the PGV wells varies from HGP-A located some ¼ to ½ mile to the south-southwest (Figure 2). While the production characteristics of KS-I are markedly different from HGP-A at wellhead pressures lower than 170 psig, they become comparable at higher wellhead pressures (Figure 4). The 57% liquid fraction produced in HGP-A is attributed to: (1) its perforated liner interval between 4000 and 2900 feet allowing shollower lower temperature and pressure fluid production; (2) its completion near the edge of the field; (3) its shallower total depth; *(4)* the natural variability in a two-phase geothermal system (discussed below); (5) its lateral distance from the 1955 fissure; or (6) some combination of the above.

Figure 5 presents a conceptual model of the Puna Geothermal system. The Puna reservoir tapped by three productive wells is considered to be a very high temperature, two-phase liquid-dominated system with a varying steam fraktion confined within the rift. The reservoir is kepi in this state by the very high heat flow within the rift zone, by an effective impermeable rock seal, and the lack of significant venting to the surface. There is no evidence of a vapor cap. Consequently, vertical permeability is thought to be small relative to horizontal permeability. A condensate layer does not seem to be present. Heat flow is thought to be primarily in the vertical direction but lateral contributions from dike swarms ore also possible. The vigorous, cool groundwater system acts in conjunction with the caprock to keep the system effectively hidden at the surface. Where the cap is locally broken by structure leakage would be relatively minor and transient in nature as the leaking structure self-seals due to hydrothermal alteration. This system is significantly overpressurized relative to conventional boiling point curve versus depth relationships (J. Hebein, personal communication, 1984) for reasons cited above. The impact of a supercritical fluid (if it does exist) on the system is not treated.

CONCLUSIONS

The PGV wells show many of the characteristics described by Stefansson and Steingrimsson (1982) for wells tapping two-phase reservoirs. It is not un common to find wells in high temperature, volcanic systems (e.g. Krafla, Tongonan, etc.) to exhibit enthaplies above that for hot liquid water. The PGV welldata are the first we are aware of in the literature that indicates early, dry steam production from such a reservoir. These data provide some definition of the factors that influence steam quality at the wellhead in two-phase geothermal reservoir: (1) well completion interval (e.g. total depth and casing geometry); (2) number of producing zones opened to the wellbore; (3) the thermodynamic state of these producing zones (temperature, pressure and steam fraction); (4) the permeability of these zones; and (5) the relative permeabilities to steam and water of these zones.

The high steam quality of the produced fluids in the PGV wells has enhanced the feasibility of geothermal electrical power production in the East Rift Zone of Kilaueo Volcano. If the proposed system model is verified by future well results we would then expect the reservoir under exploitation to become in a very short period of time a typical vapor-dominated system not unlike The Geyers in the U.S. and Kamojang in Indonesia. We speculate that the Puna system may be analogous to the paleo "Geysers" geothermal system (two-phase liquid-dominated) before it became the vapor-dominated system observed today.

Wellbore complications (e.g. hostile environment, obstructions, interzonal flow, etc) have prohibited complete definition of the wells and reservoir performance both with time and varying wellhead pressures. Technical challenges and higher costs are indicated both for exploration and development wells. A revised well program with upgraded casing, cementing and completion procedures has been prepared to best fit the unique characteristics of the Puna geothermal system. An improved well test program to minimize flow interruptions and maximize data recovery has been similarly designed. A third well will be drilled before mid-1985.

Acknowledgements

We thank the Puna Geothermal Venture for allowing the release of this paper. A special thanks is extended to two recent employees of Thermal Power Company: Messrs. J. Hebein and K. Goyal, whose helpful commentaries and critiques have assisted the preparation of this document.

REFERENCES CITED

Chen, B.H., Kihara, D.H., Yuen, P.C., and Takahaski, P. K., 1978, Well test results from HGP-A: CRC Trans., 2, p. 99-102.

Columbia Geoscience, 1982, Lithology and alteration of drill holes Kapoha State #1 and #2, Puna District, Hawaii: Unpublished report prepared for Thermal Power Company.

Dunn, J.C. and Hardee, H.C., 1981, Superconvecting geothermal zones, J. Volcanol. Geotherm Res., 11, p. 189-201

Furumoto, S. D., 1978, Nature of the magma conduit under the East Rift Zone of Kilauea Volcano, Hawaii: Bull Volcanol, 41-4, p. 435-453.

Grant, M. A., 1979, Interpretation of downhole measurements in geothermal wells: Report 88, Applied Mathematics Division, Department Scientific & Industrial Research, Wellington, New Zealand.

Grant, M.A., 1982, On the existence of two-phase fluid in good communication with liquid water. Proceedings of the sixth workshop on geothermal reservoir engineering, Stanford University.

Grant, M A., Bixley, P. F. and Syms, M. C., 1979, Instability in well performance: CRC Trans., 3, p. 275-278.

Kihura, D.; Chen, B.; Yuen, P. and Takahashi, P., 1977, Summary of HCPA well testing: Proceedings of third workshop on geothermal reservoir engineering, Stanford University, p. 138-144.

Kroopnick, P. M., Buddemeier, R. W. and Thomas, D., 1978 Hydrology and geo chemistry of a Hawaiian geothermal system: HGP-A: Hawaii Institute of Geophysics Report HIG-78-6.

Moore, R., 1983, Distribution of differentiated tholeiitic basalts on the lower East Rift Zone of Kilauea Volcano, Hawaii: A passiblt guide to geothermal exploration: Geology.

Rudman, A. J. and Epp, D., 1983, Conduction models of the temperature distribution in the East Rift Zone of Kilauea Volcano; J. Volcanol Geotherm. Res., 16, p. 189-204.

Stefansson, V. and Steingrimsson, B., 1982, Production characteristics of wells tapping two phase reservoirs at Krafla and Namafjall: Proceedings of the sixth workshop on geothermal reservoir engineering, Stanford University.

Stone, C. and Fan, P., 1978, Hydrothermal alteration of basalt from Hawaii Geothermal Project Well-A, Kilauea, Hawaii: Geology, 6, p. 401-404.

Thomas, D., 1982, A summary of the chemical characteristics of the HGP-A well, Puna, Hawaii: Proceeding of the eighth workshop on geothermal reservoir engineering, Stanford University, p 209-313.

Thomas, D., 1983, Status summary of the HGP-A generation facility: 1983: GRC Trans., 7, p. 75-80.

Thomas, D., 1984, Geothermal resources assessment in Hawaii, final report: U.S.D.O.E. Report DOE/SF/I081-1-T1.

Waibel, A., 1983, A review of the hydrothermal mineralology of Hawaii Geothermal Project Well-A, Kilauea, Hawaii: CRC Tranb, 7, p. 205-210.

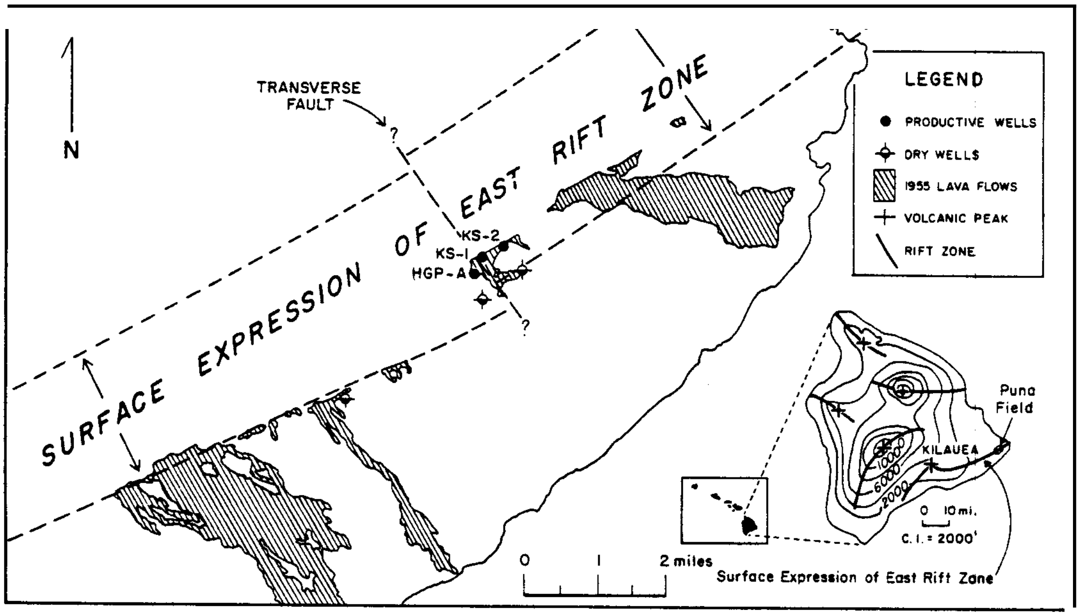

Figure 1: Location map for the Puna geothermal field.

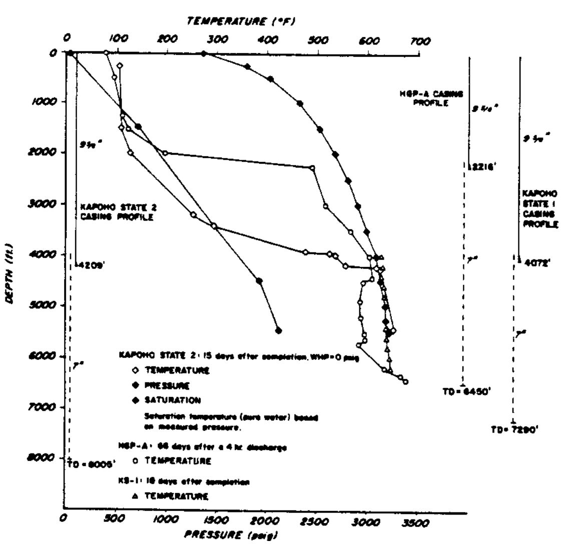

Figure 2: Temperature/pressure profile for KS-1, KS-2, and HGP-A. Production casing and linear profile for each well are shown. All data were measured prior to any significant flow testing. In December, 1974, the upper portion of the HGP-A 7 inch slotted liner was replaced with solid 7 inch casing to 2900 feet.

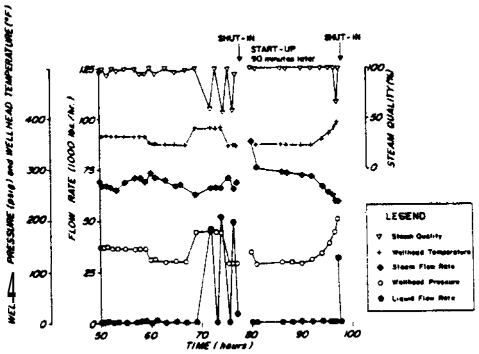

Figure 3: Kapoho State 1 separator flow test data for the period 50 to 100 hours. Note periods of cyclic flow.

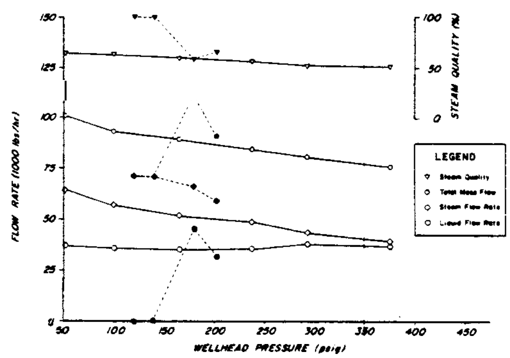

Figure 4: Comparative flow test result plot for HGP-A (open symbol) and KS-1 (closed symbol).

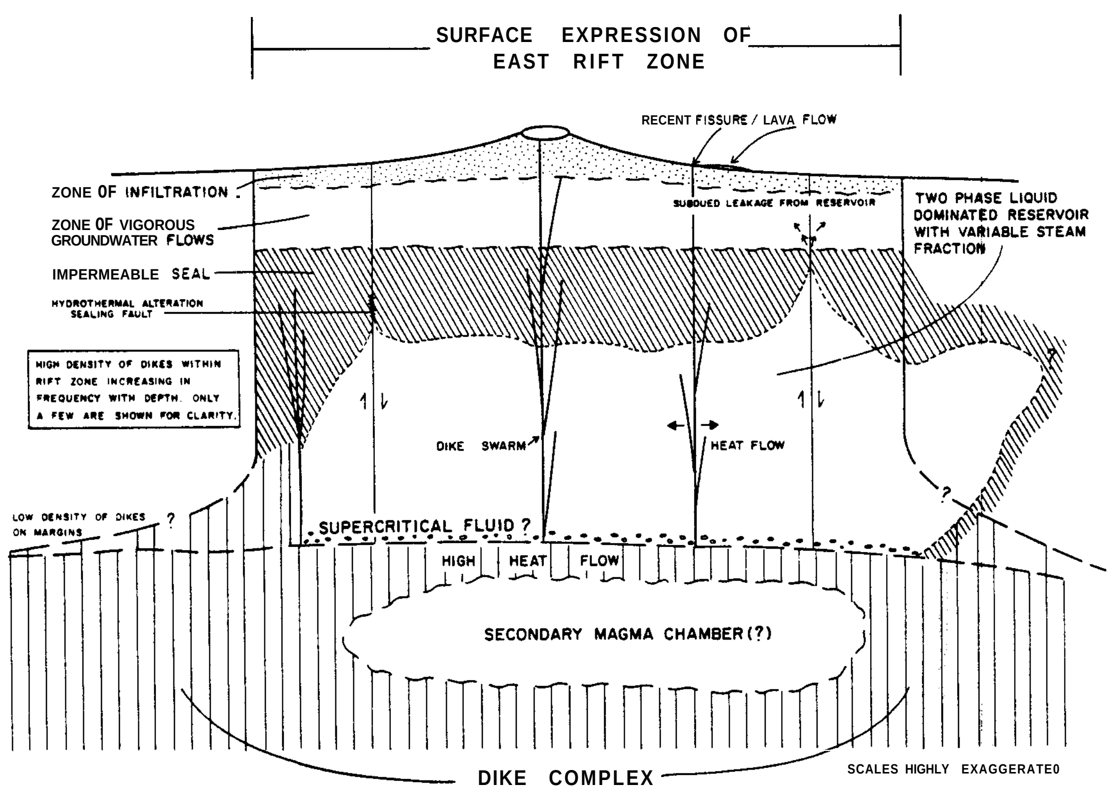

Figure 5: Conceptual model of the Puna geothermal system. Section is normal to the trend of the rift zone. The geothermal system is rift confined except in areas of cross-faulting. Impermeable seal is thought to be due to lithology and hydrothermal alteration.