HISTORY AND RESULTS OF SURFACE EXPLORATION IN THE KILAUEA EAST RIFT ZONE

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ABSTRACT

Government-funded surveys of the Kilauea East Rift Zone have resulted in a wealth of geophysical and geochemical data from an active volcanic area. All data are clearly of academic interest; Hawaii was used as a testing ground for various geophysical methods in the early days of geothermal exploration. Some surveys, such as gravity and magnetic, are useful from a regional perspective for determining broad structural trends and grossly identifying magmatic intrusions. Seismic data are currently being used for a more site-specific purpose: to determine fault locations and geometries. Only a few methods have been found to be useful for the very specific tasks of identifying and quantifying geothermal resources and siting productive geothermal wells in areas such as the Rift Zone. These are self-potential (SP) surveys, possibly resistivity soundings, and soil gas surveys.

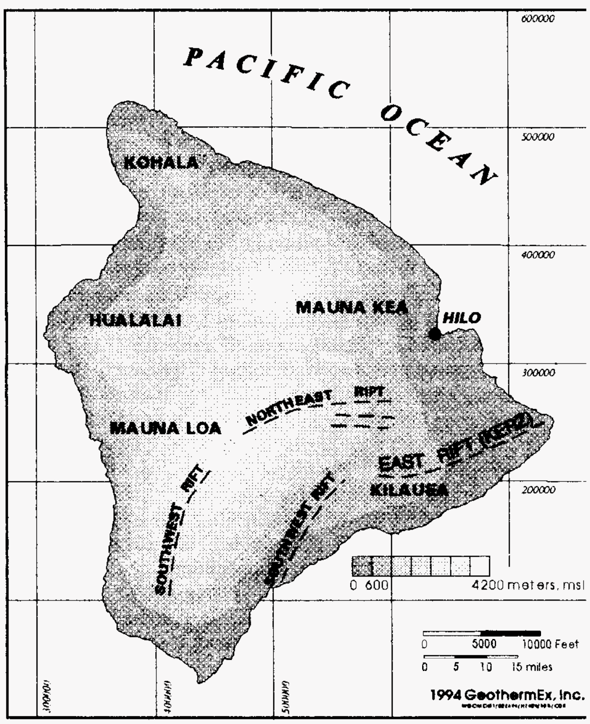

Figure 1: Map of the Island of Hawaii, showing the East Rift Zone of the Kilauea Volcano (KERZ)

1. INTRODUCTION

The Kilauea East Rift Zone (KERZ), a major volcanic feature on the Island of Hawaii (Figure 1), has long been the subject of geophysical and geochemical studies by many investigators, using a wide variety of techniques. These studies have been concerned with such topics as: determination of the physical properties of magma chambers; studies of the hydrologic systems of island volcanoes; evaluation of potable groundwater resources; compilation of regional geological or geophysical maps; research into active volcanic processes; evaluation of the seismicity of an active volcanic rift; identification of pre-emption earthquake signatures; determination of the sequences of hydrothermal mineral deposition in volcanic rock suites; and research into gas emissions from active volcanic systems.

Despite their varied origin and purpose, many of these research-oriented studies have been applied in geothermal exploration or characterization of the KERZ. Not surprisingly, the utility of results has been highly variable, reflecting such factors as the area of coverage, the scale at which work has been done, and the ultimate purpose of the work. For the most part, the anomalies defined by the geophysical and geochemical surveys completed in the KERZ do not coincide with each other in area, and cannot be used with confidence to either delineate the geothermal reservoir or site geothermal wells.

2. GEOPHYSICAL SURVEYS

Government-funded geophysical surveys carried out over the KERZ during the 1970s and 1980s included gravity, magnetic, seismic, and a variety of electrical surveys, including DC resistivity (bipole-dipole and pole-dipole), EM (time domain, variable-frequency inductive soundings and transient soundings), *mise-à-la-masse* and SP (self-potential, detection of electrical streaming potentials).

Homogeneous coverage of the KERZ is afforded by passive seismic, aeromagnetic, and airborne very-low-frequency electromagnetic (EM/VLF) survey data. Ground-based geoelectrical, gravimetric, microearthquake and ground noise data have been collected in the Lower East Rift Zone (LERZ), east of Pahoa (Figure 2); however, these data are virtually non-existent for the middle and upper parts of the KERZ.

2.1 Gravity Surveys

A Bouguer gravity anomaly map that covers the entire island of Hawaii has been prepared (Kinoshita, 1965), but the upper and middle KERZ were devoid of gravimetric stations, and the contours drawn across that area were merely inferred. The LERZ has been surveyed in some detail (Furumoto, 1976); the resulting Bouguer anomaly map reveals a strong, elongate gravity high, parallel to the rift, in the western part of the LERZ. The source of this feature has been modeled as a complex of high-density dikes and flanking sills, with the top rising to within 5,000 feet of the land surface (Broyles *et al.*, 1979). The density contrast between the dike complex and the surrounding rock is supported by high P-wave velocities (around 7.0 km/s) interpreted from seismic-refraction surveys. In the vicinity of the Puulena Craters and geothermal HGP-A, this gravity high appears to be offset slightly in a left-lateral sense along a NNW-trending belt.

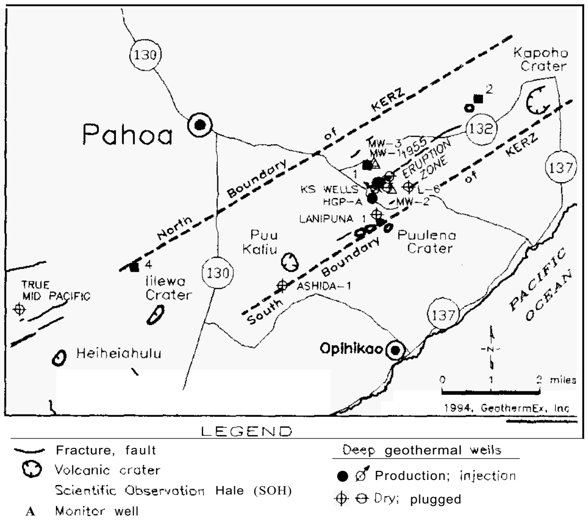

Figure 2: Wells and selected geologic features in the Puna District

Efforts are underway to extend gravity surveys (Kauahikaua, 1993; Cooper, 1993) to the middle and upper KERZ, but large areas SW of the geothermal wells remain unsurveyed. Even within the LERZ, the distribution of observation points has been very uneven; station positions apparently have been confined to the irregular and mostly sparse distribution of roads.

2.2 Aeromagnetic Surveys

An aeromagnetic map of the KERZ, published by the **U.S.** Geological Survey (Flanigan *et al.*, 1986a), was prepared from data collected in 1966 and 1978. This map shows steep linear gradients and associated dipolar anomalies aligned with the southern flank of the KERZ along much of its length. The orientation of the dipoles is in accord with a remanent magnetization of the source bodies, which is close to that of the present geomagnetic field, with an approximate inclination **of** 35° N. This implies that the source bodies had cooled to below the Curie temperature within the current polarity epoch (beginning 20,000 years ago). The map also shows a major discontinuity in magnetic anomalies corresponding to the location of a possible NW-trending fault that cross-cuts the KERZ.

Flanigan *et al.* (1986a) have modeled the magnetic anomaly pattern in terms of a two-dimensional prismatic body which is about 8,200 feet wide and 6,600 feet high, with its top near the ground surface. This is considered to represent a complex of dikes that have higher magnetic susceptibility than the country rock. This model agrees well with that put forward for the gravity anomaly in the lower KERZ. Hildenbrand *et al.* (1993) reanalyzed and modeled the magnetic data, describing a shallow magnetic low zone paralleling a 1.5 mile-wide, highly magnetic zone **(of** dikes) in the active KERZ. The former is likely to "depict rocks chemically altered by hydrothermal Cuids" along the flanks of a rift.

2 3 Passive Seismic Data

Since the 1950s, the Hawaiian Volcano Observatory (HVO) has operated a seismographic network with stations located in the vicinity of Kilauea and near the southern coast of the Island of Hawaii. By 198.5, earthquakes with magnitudes as low as 1.0 could be detected and located in the middle and upper KERZ. The main results of the HVO seismic work may be summarized as follows.

- Since 1960, many tens of thousands of small earthquakes have been detected and located beneath Kilauea as well as beneath the KERZ and the Southwest Rift, at depths ranging from 0 (near-surface events) to more than 35 miles.
- Earthquakes associated with eruptive and intrusive magmatism have been found to occur in tight spatial and temporal clusters known as "swarms".
- Swarm shocks are small; earthquake magnitudes rarely exceed 4.0.
- Shocks related to magmatism are caused by the fracturing that takes place when magma forces its way into and through brittle rock.

Geophysicists from the University of Hawaii are attempting to locate faults and refine the velocity model in the Puna section of the KERZ (Cooper, 1993). To date, Dr. Cooper's group has reviewed HVO data, set out 37 portable seismic stations for a microearthquake survey and collected data from 371 earthquakes from January 29, 1992 to March 29, 1993 in the magnitude range of 0.0 to <3.0. The earthquake locations showed two linear trends: one parallel to the KERZ, and **a** second nearly perpendicular to the KERZ, parallel to the NW-trending magnetic discontinuity discussed above, located SW of well HGP-A. The most seismogenic region within the array is close to HGP-A. Some 675 mapped events are tightly concentrated along the southern boundary of the KERZ in the vicinity of well KS-8 and extending WSW for about 3 km. Profiles **of** these events are being used to determine the geometry of faults, and calibration shots have been used to improve the velocity model of the region.

Microearthquake surveys have been carried out in the lower KERZ one of the **two** surveys reported by Suyenaga *et al.* (1978) indicated clustering of small shocks near HGP-A, predominantly at depths of 3,000 to 15,000 feet. Another survey indicated **a** cluster centered near KS-1 and KS-2. This is the same area as a pronounced SP anomaly discussed below.

2.4 Geoelectrical Surveys

Geoelectrical surveys have been carried out primarily in the LERZ between Pahoa and Kapoho Crater (Figure 2). The following surveys have been undertaken:

- bipole-dipole, pole-dipole and TDEM or EM transient surveys (Skokan, 1974; Keller *et al.*, 1977);
- vertical electrical soundings (VES or Schlumberger) and EM soundings (Kauahikaua and Klein, 1978; Kauahikaua and Mattice, 1981);
- **a** *mise-a-la-mum* survey (Kauahikaua *et al.*, 1980);
- an SP survey (Zablocki, 1977);
- an airborne EM/VLF survey (Flanigan *et al.*, 1986b); and
- **a** CSMAT survey for the Puna Geothermal Venture **(PGV)**

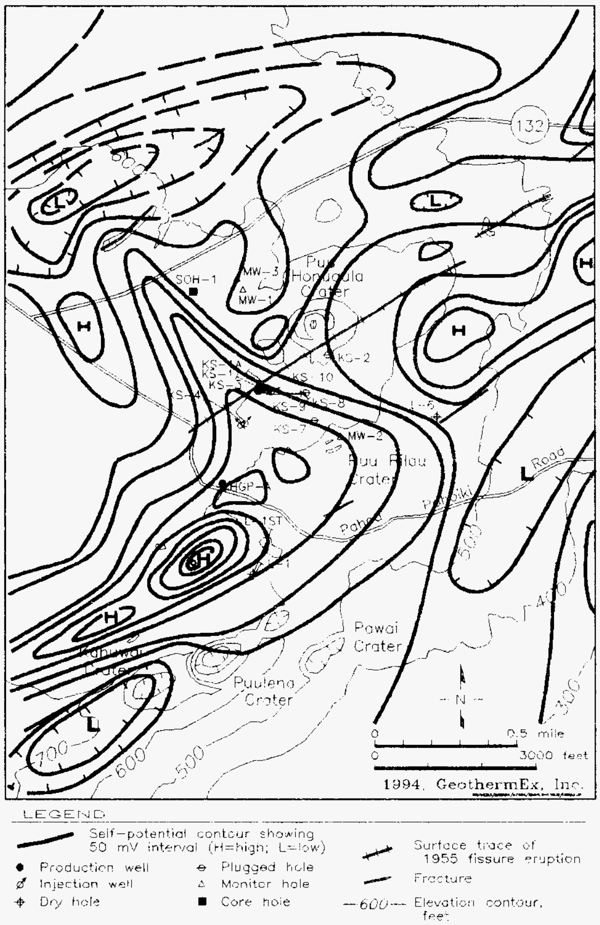

Figure 3: Local self–potential anomaly map

Most of the resistivity soundings (both direct-current and EM) indicate a three-layer structure with a dry, highly resistive (hundreds to thousands of ohm-m) surficial layer above the water table. This is underlain by a saturated, more conductive layer (1 to 600 ohm-m) with variable thickness and a deeper, more resistive ("electrical basement") material.

Because of their vely uneven and frequently non-coincident spatial distribution, it is difficult to compare oı synthesize results of the many ground-based geoelectncal surveys and soundings. Only the TDEM survey, with 24 soundings in the Puna district, has a sufficient spatial density of observation points to allow useful mapping (that is, with horizontal resolution better than about 3 to 6 miles) of the second-layer zone; this is shown in ENEL (1990). Of the 24 soundings, 17 were interpreted in terms of a layered model. The data indicate an ENE-trending resistivity low, some two miles wide, extending from the vicinity of well Ashida 1 to Kapoho Crater (ENEL, 1990). Resistivity is about 2 to 4 ohm-m in a second layer with a thickness of 1,500 to 3,500 feet.

The various surveys using' fixed current sources and distributed receiver sites (bipole-dipole, pole-dipole and *mire-8-la-masse)* are capable of determining surficial resistivities at close range and second-layer resistivities at greater distance, making it quite difficult to combine the data. Although the depth of current penetration and true resistivities are unknown, there were two results of interest for geothermal evaluation. Two bipoles near well HGP-A indicated apparent resistivities of around 10 ohm-m in that area, and also showed that well HGP-A is positioned at some distance from the lowest apparent resistivities (2 to 5 ohm-m). Lanipuna 1, which encountered high temperatures (>685°F) but low permeability, was drilled in an area with the lowest apparent resistivity. The *mire-8-la-masse* survey, which used the casing of HGP-A as one current electrode, gave similar results.

The most interesting of the geoelectrical investigations is the SP survey carried out in the Puna district (Zablocki, 1977). The survey revealed four anomalies, of which at least twc appear to be significant in relation to geothermal targets (Figure 3). One is a narrow, positive, monopolar anomaly centered near HGP-A, with an amplitude of 450 mV. This anomaly is aligned with a 1790 eruption fissure. The other is bipolar, with peak-to-trough amplitude of nearly 800 mV, having its positive peak directly over steaming vents formed during the 1955 eruption. As shown on Figure 4, wells KS-1 and KS-2 are located on this anomaly, which is modeled as being the result of an asymmetric convective plume, buttressed on its south side by an impervious dike.

A third SP anomaly is located about one-half mile to the northeast of HGP-A, and strikes northwest, cross-cutting fissures. A re-survey of the area by Kauahikaua in 1992 (personal communication) revealed that the SP anomalies had shifted in location and intensity since Zablocki completed his work.

Of the many geophysical anomalies defined by these surveys, SP anomalies appear to be most closely associated with geothermal features, both in the Kilauea crater area, and in the KERZ. Indeed, the discovery well of the Puna field (HGP-A) was sited in part on the basis of the first SP anomaly described above (Figure 3).

One geoelectrical survey provides homogeneous coverage of the entire KERZ: the airborne EM/VLF mapping reported by Flanigan *et al.* (1986b). The survey was flown at about 350 feet above ground level, with NNW-trending flight lines (transverse to the KERZ), spaced at 3,000 to 6,500 feet. An apparent resistivity map was prepared for a transmitter frequency of 18.6 kHz, with attendant skin depth of 100 to 1,300 feet, depending on actual shallow resistivity. This map reveals three major lows which appear as troughs, about one to three miles in width, that cross-cut the KERZ

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Figure 4:

The easternmost trough runs N from Opihikao (Figure *2)* through the Puna area to a point about 3 miles north of HGP-A, and has apparent resistivities of 25 to 600 ohm-m. It is thought that this trough reflects shallow circulation of groundwater, and perhaps clay alteration, enhanced by faults and fractures which cross-cut the KERZ, and along which several productive geothermal wells are found.

The results of an aeromagnetic survey near well HGP-A suggested that a controlled source audiomagnetotelluric (CSAMT) survey would be able to delineate the reservoir. Thermal Power commissioned a such a survey in 1984(?); however, it was not possible to complete the survey according to specifications because electrode-contact resistance was much higher than the contractor had anticipated. Based on the limited data that the contractor was able to gather, it appeared that the CSAMT method would not be able to delineate the limits **of** the reservoir precisely and unequivocally. In view of these problems, the survey was abandoned.

A second CSMAT survey consisting of four profiles was commissioned in 1992 by the successors-in-interest to Thermal Power, the new owners of PGV. The survey appeared to show strong anomalies when the data were plotted in vertical sections along the profile lines. After smoothing the data, the geophysical contractor generated contour maps at several depths.

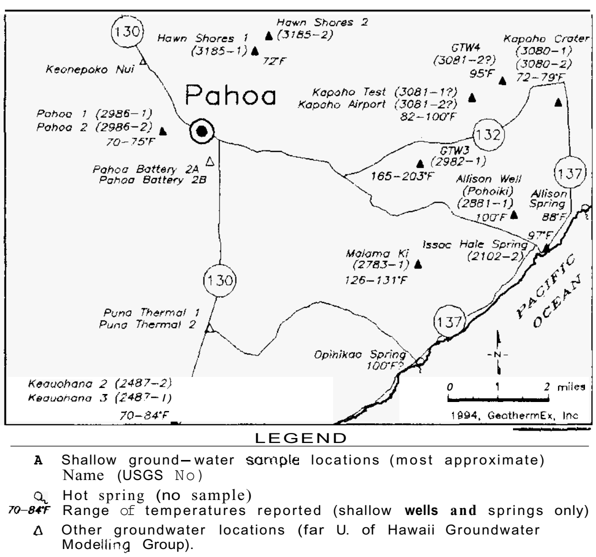

Figure 5: Water **sample** locations in the Puna District

3. GEOCHEMICAL SURVEYS

3.1 Work Underway

State and Federal government agencies are currently conducting fluid chemistry surveys and monitoring programs (Figure 5) in the KERZ region which include:

- routine to occasional groundwater sampling and analysis of shallow wells (MW-1, MW-3, MW-2, GTW-3, Malama Ki, Kapoho Shaft, Allison Water Well, Kapoho Airstrip), by the University of Hawaii Groundwater Monitoring Group;
- installation and use of downhole monitoring systems (temperature, water level, conductivity) and sampling pumps at several wells (Malama Ki, MW-2, GTW-3) by the University of Hawaii Groundwater Monitoring Group;
- sampling of steam, gases and liquids produced by PGV wells KS-4, KS-9, and KS-10, by the University of Hawaii; and
- hydrologic studies by the **U.S.** Geological Survey, including the isotope hydrology of meteoric waters and groundwaters in the vicinity of Kilauea's rift zones.

3.2 Groundwater Evolution and Thermal Effects

A review of the available data (Cox, 1980; Cox, 1981; Thomas, 1986; Thomas, 1987; Thomas, 1989; ENEL, 1990; and Iovenitti, 1990) reveals that groundwater compositions in the Puna area are determined by various factors:

- low-temperature reactions between meteoric water and volcanic rock minerals;
- the marine origin of the meteoric component (presence of sea salts);
- mixing of meteoric water and seawater in the subsurface;
- hydrothermal alteration of meteoric water;
- hydrothermal alteration **of** seawater; and
- mixing of the various components.

The coolest, most-dilute waters in the area, with less than about 100 mg/l chloride (Cl), also have low levels of alkalinity and sulfates, and mixed cation concentrations which reflect the mineral composition of the volcanic rocks. Mixing with cool seawater, which has about 19,000 mg/l Cl, raises the Cl concentration and adds considerable amounts of other cations and anions.

In a review **of** about 400 groundwater samples from the State of Hawaii, Cox and Thomas (1979) decided that three parameters could be considered diagnostic of "geothermal water": 1) temperature > 84°F 2) Cl/Mg ratio equal to or greater than 15; and 3) SiO_2 concentration >30 to 85 mg/l, depending upon location. ENEL (1990) also used the Cl/Mg ratio as a diagnostic tool, because the ratio Cl/Mg = 15 is that of seawater, and a higher ratio will result from heating.

Thermal effects are strongly indicated in groundwaters with Cl > 100 mg/l and Cl/Mg > 30. These include samples from MW-2 (temperature not reported), GTW-3 (165 to 203°F), and single samples each from tests KS-1 (113°F), KS-1A (>100°F), and KS-2 (<100°F), all described by Iovenitti (1990) as "top of dike-impounded water". The geothermal signature of these groundwaters is suggested also by SiO_2 concentrations in the range 80 to 180 mg/l, except at MW-2. The signature is not surprising, given that the sites are all within the KERZ.

The ongoing hydrologic study of the Kilauea area by the USGS includes evaluation of stable isotope and tritium to trace the movement of groundwater (Scholl *et al.*, 1993). In particular, an effort is being made to quantify the effects of dikes in the rift zones as impermeable or leaky barriers to regional groundwater flow, **or** possibly as conduits for dike-confined groundwater flow. Scholl *et al.* (1993) have found that water from recharge zones at elevations of 1,300 to 2,800 feet (msl) discharges within and south of the KERZ in 10 to 20 years; this equates to an average flow rate of slightly in excess of one mile per year.

3 3 Trace-Emissions Surveys

In the KERZ, there is neither a shallow water table nor any surface manifestations of hydrothermal activity (*e.g.*, hot springs or fumaroles), except for fumaroles and steaming ground at the "View Area" along the chain of Craters (Highway 130) Road.. Therefore, exploration to detect trace-level emissions of volatile species has been done in the form of soil surveys for mercury (Hg) and radon (^{222}Rn). Cox (1980 and 1981) conducted reconnaissance-level sampling at spacings of about 1,500 to 2,500 feet (Hg) and 3,000 to 5,000 feet (^{222}Rn), in the lower KERZ.

The ^{222}Rn survey was regarded by Cox (1980) as somewhat more successful than the Hg survey in defining zones of possible deep permeability and thermal activity. There are several ^{222}Rn anomalies, all within the KERZ, encompassing the locations of the HGP-A and PGV wells. The Hg survey shows an anomaly closely associated with the surface trace of the main eruptive fissure. As with the aeromagnetic data, the Hg survey shows the NW-trending discontinuity near HGP-A, presumed to be caused by a fault offsetting the rift trend. The highest concentrations of soil mercury, however, are not in the area of offset, but over the NE-trending fissure just to the northeast of the presently drilled area.

4. SUMMARY

Gravity data reveal the geometry of the dike swarm which is thought to represent the principal heat source for the geothermal system. As such, it is useful in a general sense by outlining potentially productive areas. Repeat gravity measurements may allow recognition of new dike emplacements through changes in mass (density) at previously measured stations. Magnetic surveys clearly identify recent intrusions; however, the resolution of both gravity and magnetic surveys is insufficient for selecting specific drilling targets.

The results from geoelectric surveys indicate that the SP method may be more useful in selection of geothermal targets in the KERZ. It is possible that resistivity soundings could also be used; however, the present data distribution is insufficient to allow more definite conclusions. Further drilling and testing of deep wells is required to confirm the tentative findings from resistivity soundings. The relationship between CSAMT anomalies and geothermal production zones remains unclear.

Sampling of Hawaiian water wells may lead to identification of areas with significant geothermal potential by testing for the three geothermal parameters of Cox and Thomas (1979): temperature; Cl/Mg ratio; and SiO_2 concentration.

Radon and mercury soil surveys have revealed correlations between gas anomalies and the KERZ, an anomaly was clearly identified at the proven HGP-A and PGV wellfield. It should be noted that the HGP-A discovery was made without the benefit of these data, and the PGV discovery wells were probably sited on the basis of other criteria. However, the unproductive, deep Lanipuna wells just S and SE of the wellfield are at the edge or outside of the soil gas anomalies. This indicates that gas surveys, particularly **^{222}Rn,** may be useful for siting future exploration wells. The Hg data is probably too uncertain for such use.

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