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GEOPHYSICS

Overview. This review consisted of consultation of most of the original geophysical reports from the files of GeothermEx, followed by the examination of ENEL's evaluation of existing data for the KERZ.

Homogeneous coverage of the KERZ is afforded by only three kinds of geophysical data: passive seismic, aeromagnetic, and airborne EM (VLF). Other types of data, including ground-based geoelectrical, gravimetric, microearthquake, and ground noise, have been collected rather intensively in the Lower KERZ, east of Pahoa; however, these data are virtually non-existent for the Middle and Upper parts of the KERZ. Even within the Lower KERZ, however, the distribution of observing points has been very uneven; station positions have apparently been confined to the irregular, mostly sparse, distribution of roads.

Review of Geophysical Findings in the KERZ 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 are devoid of gravimetric stations, and the contours shown in that area are merely inferred. The Lower KERZ has been surveyed in some detail (Furumoto, 1976), and the resulting Bouguer anomaly map reveals a strong, elongate high, parallel to the rift, in the western part of the Lower KERZ. The source of this feature has been modeled as a zone of high-density dikes and flanking sills, in which the top of the dike complex may rise to within 1.5 km of the land surface (Broyles, 1977). The high-density rock is believed to be composed of olivine-rich gabbro with a density of 3.1 g/cc, about 0.5 g/cc greater than the country rock. This density contrast is supported by high P-wave velocities (around 7.0 km/s) interpreted from refraction surveys.

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In the vicinity of Puulena Crater and geothermal well HGP-A, this sharp gravity high appears to be offset along a NNW-trending belt in a left-lateral sense. This subtle offset might not have been noticed and discussed were it not for the existence of several successful geothermal test wells nearby. This and other features of the gravity data are correlated with aeromagnetic anomalies. However, the gravity data of themselves do not exhibit clear or definitive anomalies in the vicinities of proven geothermal targets.

Aeromagnetic Surveys

Aeromagnetic surveys were flown in 1966 and 1978 (Flanigan and others, 1986). The earlier survey was flown too high (4,000 meters a.g.l.) to have resolution useful in characterizing shallow structures of geothermal interest, while the later one was flown at only 300 meters a.g.l., with flight lines separated by 0.8 - 1.6 km. Because the regional (IGRF) field has a very small gradient (not more than 4 nT/km) in the area, it was not subtracted from the data in making the anomaly map. This survey shows steep linear gradients and associated dipolar anomalies alined with most of the length of the KERZ, and positioned along its southern flank. 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 inclination of around 35° N. This implies that the source bodies cooled below the Curie temperature within the current polarity epoch (beginning 20,000 years ago).

Flanigan and others (1986) have modeled the typical anomaly pattern in terms of a 2-dimensional prismatic body which is about 2.5 km wide and 2 km high, with top near the ground surface. This is considered to represent a complex of dikes that have higher magnetic susceptibility than the country rock. The model predicts that the anomaly extrema are approximately over the prism edges, so that the mapped extreme may be taken to locate the

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edges of the source. The magnetic susceptibility (K) contrast of the model is around 0.03 cgs units, with K higher in the source prism than in the country rock. This model agrees well with that put forward for the gravity anomaly prevailing in the Lower KERZ.

In the Puna area, the aeromagnetic data appear more complex than to the west, and some researchers suggest that an "offset" of the anomaly pattern is present, which may be related to and is supported by that of the Bouguer gravity anomaly. However, neither the so- called "offset" nor its relationship to the gravity data are obvious or compelling to the present reviewers. Although the aeromagnetic data appear to be effective in illuminating extensive structures, it seems that they cannot resolve geothermal targets, such as that in the Puna area.

Passive Seismic Data

Since the 1950s, the Hawaiian Volcanic Observatory (HVO) has operated a seismographic network, with stations located primarily in the vicinity of Kilauea and on the southern side of the island of Hawaii. The number and sensitivity of the seismographs have increased steadily since the network's inception: since 1969, virtually all shocks with magnitude 3 or larger on the island have been located; by 1985, the magnitude threshold of complete detection and location had dropped to around 1. Probably tens of thousands of small shocks have been detected and located by the HVO during the past 30 years.

The positions, source mechanisms, and rates of occurrence of earthquakes in relation to magmatic activity associated with Kilauea volcano and its rift zones, and with reference to the tectonics of the surrounding region, have been studied in great detail by a number of investigators. Scientific articles concerning these phenomena probably number several

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hundred, and this work cannot be totally characterized here. However, a few important features are considered: since 1960, many tens of thousands of small earthquakes have been detected and located beneath Kilauea as well as the KERZ and Southwest Rift, at depths from nearly 0 to more than 60 km; earthquakes associated with eruptive and intrusive magmatism occur in rather tight space-time clusters known as "swarms"; swarms shocks are small, with magnitudes that rarely exceed 4; shocks related to magmatism are caused by the fracturing that takes place when magma forces its way into and through brittle rock.

A recent review article (Klein and Koyanagi, 1989) presents an excellent, concise summary of the current understanding of seismicity in the southern part of the island of Hawaii. This includes a presentation of the spatial distribution of earthquake foci in a number of maps and cross sections, for the period 1970-1984. The report and map by ENEL (1990) does not adequately present this kind of information. A cluster of shallow shocks (depths of 0-5 km) is easily distinguished around Puulena Crater and geothermal wells, such as HGP-A. Shallow and deeper (depths of 5-13 km) clusters of shocks are centered north of Ka Lae Apuki, about 2 km east of a resistivity low shown by the airborne VLF survey discussed below. Other, less distinct, clusters seem to be present within the KERZ, but additional spatial analysis would be required to demonstrate or disprove their existence.

Microearthquake surveys have been carried out in the Lower KERZ, and one of the two reported by Suyenaga and others (1978) indicated clustering of small shocks near well HGP-A, predominantly at depths of 1-5 km. These workers conducted another survey, which indicated a cluster centered about 4 km north of Kehena, near wells GTW-1 and GTW-2. This is in the same area as a pronounced SP anomaly discussed below.

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Based on the experience outlined above, it is fair to say that passive seismic data are potentially useful in the delineation of geothermal targets in the KERZ.

Geoelectrical Surveys

Only one geoelectrical survey provides homogeneous coverage of the entire KERZ, and this is the very low frequency electromagnetic (VLF EM) mapping reported by Flanigan and others (1986). Ground-based geoelectrical soundings and surveys have been carried out in the Lower KERZ and are of the following types: bipole-dipole, pole-dipole and time domain electromagnetic (TDEM) or EM transient surveys (Skokan, 1974; Keller and others, 1977); vertical electrical soundings (VES or Schlumberger) and EM soundings (Kauahikaua and Klein, 1977; Kauahikaua and Mattice, 1981); a mise-al-a-masse survey (Kauahikaua and others, 1980); and a self-potential (SP) survey (Zablocki, 1977). By far, most of the ground-based work has been conducted in the area extending easterly from the road between Pahoa and Kalapana to Kapoho Crater. A small number of bipole sources and VES spreads were located north of Pahoa, to near Kurtistown, and three bipole sources were positioned near Kilauea Crater.

The ENEL report (1990) makes a useful contribution in its compilation of a map showing transmitter sites for the various active geoelectrical surveys and soundings; however, receiver sites are shown only for the TDEM work, and not for the direct-current surveys. Also, the ENEL report includes a map compilation showing major results of the geoelectrical work, although it appears to oversimplify data which show great variability in electrical structure over distances of a few kilometers.

Most of the soundings (both direct-current and EM) have indicated a dry, highly resistive (100s to 1,000s of ohm-m) surficial layer above the

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water table, underlain by a saturated, more conductive layer (1 to 600 ohm-m) with variable thickness; this is underlain by more resistive (electrical "basement") material. The most significant variability is in the depth, thickness, and resistivity of this second, conductive layer. These factors appear to be controlled by the salinity and temperature of the ground water, possible lenses of meteoric water over sea water (brine), and, to a lesser degree, by clay alteration. Except for the Puna area, the spatial density of sounding points has been insufficient to permit resistivity mapping with really useful resolution.

Because of their very uneven and frequently non-coincident spatial distribution, it is difficult to compare or synthesize results of the many ground-based geoelectrical surveys and soundings. Only the EM transient (TDEM) survey, with 24 soundings in the Puna district, had sufficient spatial density of observation points to allow a useful mapping (that is, with horizontal resolution better than about 5-10 km) of shallow, second-layer resistivity; this is shown in ENEL report (1990, Plate 7). Of the 24 soundings, 17 were interpreted in terms of a layered model. The data indicate an ENE-trending low, some 3 km wide, extending from the vicinity of well Ashida 1 to Kapoho Crater (ENEL, 1990, Plate 7). This has resistivity of about 2-4 ohm-m for a second layer with a thickness of 500-1,000 m.

The various surveys (bipole-dipole, pole-dipole, mise-a-la-masse) using fixed current sources and distributed receiver sites portray surficial resistivities at close range and second-layer resistivities at greater distance, making it quite difficult to combine the data. Only two bipoles were close enough to HGP-A to illuminate that area; they indicated apparent resistivities of around 10 ohm-m at HGP-A, and that the well is positioned away from the lowest apparent resistivities (2 to 5 ohm-m); the depth of current penetration and true resistivities are unknown. The mise-a-la-masse survey, which used the casing of well HGP-A as one current electrode, showed a

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similar situation. The investigators speculated that these high apparent resistivities at HGP-A are the result of fresh water impounded upgradient of dikes.

The most interesting of the geoelectrical investigations is the self-potential (SP) survey carried out in the Puna district (Zablocki, 1977). The survey revealed four anomalies, of which at least two appear to be significant in relation to geothermal targets. One is a narrow monopolar (positive) anomaly centered near well HGP-A, with amplitude of 450 mV, and long axis alined with a 1790 fissure. Another is bipolar, with peak-to-trough amplitude of nearly 800 mV, with positive peak directly over steaming vents formed during the 1955 eruption; wells GTW-1 and GTW-2 are on this anomaly. It is modeled as the result of an asymmetric convective plume, buttressed on its south side by an impervious dike. A third anomaly is located about one kilometer to the northeast of HGP-A, and strikes northwest, cross-cutting fissures. It is noted that the ENEL (1990) report (Plate 7) does not completely represent the SP data. For example, closed positive and negative anomalies are associated with GT1 and GT2 and should be discussed.

Each of the data reports listed above included speculations on the depth, temperature, and geothermal significance of circulating ground waters. In our view, these remain simply speculations.

The airborne VLF EM survey had flight lines draped at 100 m a.g.l. and spaced at 1-2 km, trending NNW, transverse to the trend of the KERZ. An apparent resistivity map was prepared for a transmitter frequency of 18.6 kHz, with attendant skin depth of 30-400 m, depending on actual shallow resistivity. This map reveals three major lows which appear as troughs, about 2-6 km in width, that cross-cut the KERZ. The most easterly of these runs northerly from Opihikao through the Puna area to a point about 5 km north of HGP-A, and has apparent resistivities of 25-600 ohm-m. It is thought that this trough reflects shallow circulation of ground water, and perhaps clay alteration, enhanced by faults and fractures which cross-cut the KERZ, and along which several productive geothermal wells are found. The middle and western troughs run northerly from Kupapau Point and Ka Lai Apuki, respectively, and no other geophysical or structural geologic features appear to be correlated with their positions.

Reiterating, it appears that the self-potential method, and perhaps resistivity soundings, are useful in selection of geothermal targets in Hawaii.

The Kilauea Southwest Rift Zone (KSWRZ). The data available for this review were quite incomplete for the KSWRZ, and so this very brief evaluation is subject to revision. Gravity and aeromagnetic data for this area exist but were not reviewed. The HVO seismographic network has revealed abundant seismicity in the KERZ. The VLF EM mapping (Flanigan and others, 1986) reveals no low-resistivity features along the KERZ. Further review of data available for the KERZ is underway for these tasks (1 and 3).

Utility Ranking and Recommendations for Obtaining Additional Geophysical Data. A utility ranking is presented, which considers the logistical problems (physical access to land areas), expense, and ability to resolve a geothermal target. The geophysical methods are listed in order of decreasing utility, and explanations are given below:

1. Self potential (SP) surveys over selected areas
2. Detailed spatial analysis of existing HVO seismicity data
3. Airborne VLF EM surveys in selected areas
4. Resistivity soundings (VES/Schlumberger or TDEM)
5. Resistivity surveys, gravimetry, aeromagnetics

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1. Self Potential Surveys

Self potential surveys in selected areas, not larger than approximately 50 km^2, have a good likelihood of identifying geothermal resources, should they exist, with a precision better than 1 km. SP surveys, including that in the KERZ, have shown a good capability of resolving geothermal targets, because they can detect the streaming potentials often associated with shallow hydrothermal plumes. Among the geoelectrical methods, SP surveys are probably the easiest to conduct on foot, as one man can backpack the required receiver, porous pots, and a small reel of wire for short spread lengths. Portable global positioning receivers are now available, making it easy to establish precise coordinates for remote observing stations. Off-road portability of equipment and locatability are critical considerations for ground-based exploration in the KERZ, as most of the area has no road access, and land surveying is quite inconvenient in the dense tropical forest. Selection of new areas in which to make SP surveys can be based on several other types of available data, including passive seismic (HVO data), VLF EM mapping, surficial geologic structure, locations of historically formed fissures and steam vents, and results from recently drilled SOH and exploration wells.

2. HVO Seismicity Data (Passive Seismic)

Detailed spatial analysis of the enormously large set of earthquake locations available for the Kilauea East and Southwest Rifts offers a relatively inexpensive means of identifying shallow (0 - 5 km deep) seismicity that may be linked to significant, ongoing hydrothermal activity in the upper crust. No field work is required to conduct this study. Analysis would rely primarily on preparation of maps and cross sections of earthquake hypocenters within selected rectangular crustal blocks; it would be useful to apply moving time-of-occurrence windows to identify swarms, which appear to be

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more related to geothermal activity than non-swarm events. Location of targets may have a precision of about 1 km. Detonation of a few "calibration shots" in the KERZ (and perhaps also in the Southwest Rift) could be used to significantly improve the accuracy of hypocentral locations (by appropriate reprocessing of hypocenters already located). The USGS might cooperate in such a venture; some of the analyses and indeed calibration shots may have been done and maps and cross sections may be available to inspection by interested scientists at The Volcano Observatory.

3 , Airborne VLF EM Surveys

The existing airborne VLF EM mapping reveals three interesting low-resistivity troughs that cross-cut the KERZ. The easternmost of these transects the Puna area and includes the geothermal resource in the vicinity of Puulena Crater. It is obvious that parts of the troughs also extend outside of the areas of the geothermal reservoir, but geology and other geophysical methods enable exclusion of these parts of the troughs from consideration for geothermal exploration. It would probably be worthwhile to conduct additional VLF EM surveys, with higher resolution (using closer-spaced flight lines) and incorporating lower frequencies (to provide deeper penetration) than the existing survey, in selected areas. Selection of areas for future exploration may be guided by the locations of the two resistivity troughs lying west of the Puna area, by locations of seismicity clusters, and, of course, by surficial geologic features.

4. Resistivity Soundings. Resistivity soundings are rather cumbersome to make, and are not practical without road access. It may be worthwhile to fill-in some gaps left by previous sounding efforts (TDEM and VES) in the Puna geothermal area, where there is relatively good road access. Such work could help to better define extent of the Puna geothermal reservoir. Additional data review would be required to specify worthy locations.

5. Resistivity Surveys, Gravimetry, Aeromagnetics. Based on experience to date, none of these methods is considered capable of providing sufficient resolution of geologic structure in all-volcanic terrain, or in detection of hydrothermal plumes, to be clearly useful in geothermal exploration on Hawaii. However, gravity data in the Puna area are confined to a few roads, and the available Bouguer gravity map (Furumoto and others, 1976) interpolates these data. Several gravity stations were located along an approximate east-west traverse through the geothermal district. It may be useful to make several or many more observations (fill gaps) along this traverse and to model all data (old and new). Otherwise no further work is recommended.

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GEOCHEMISTRY

Overview. Geothermal resource assessments may be undertaken with the focused goals of resource exploration, exploitation and management, the broad objectives of scientific research, or some combination such as doing basic science to assist developing tools for technology.

This review of geochemistry mainly concerns assessments to locate, define and, if possible, utilize the resource, from the viewpoint of cost effectiveness and the broad objective of economic assessment.

Methods and technologies which are most likely to give direct and useful information about the resource are therefore favored over methods which tend to give indirect information. For example, temperature and pressure logs and fluid samples from a drillhole, correctly obtained and analyzed, give direct knowledge of current rock temperatures in a hydrothermal system. By comparison, fluid inclusion homogenization temperatures may reflect current rock temperatures, or otherwise represent conditions at some time in the past. While data concerning historic temperatures are interesting from a scientific viewpoint, they contribute less to the type of assessment addressed herein, than to an understanding of system evolution over geologic time.

Geochemical studies in an economic assessment may have various immediate objectives:

A. detecting "hidden" reservoirs (exploration targets) which are not connected to known hot springs, steam or gas vents and wells, but which release trace amounts of certain substances, such as ^{222}Rn (radon isotope 222), Hg (mercury), NH_3 (ammonia), and/or CO_2 (carbon dioxide)) into shallow groundwaters and soils;

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B. classifying and ranking exploration targets by fluid type and geochemical temperature, at locations where thermal manifestations are known to exist and water, steam/gas and solids samples can be collected;

C. defining the hydrogeologic model of the reservoir, for example its zone(s) of upflow, internal circulation and outflow, by classifying and showing relationships between the fluids and solids compositions at various wells and springs which tap into the hydrothermal system;

D. predicting and allowing design-stage engineering to manage: scaling, corrosion, fluids releases to the environment and/or fluids behavior upon injection back underground;

E. assisting long-term reservoir and production engineering by monitoring changes in fluids chemistry which have been caused by production and injection;

F. classifying the background chemistry of the natural environment in the vicinity of the resource, and monitoring changes caused by production.

These studies typically are coupled with parallel geological, hydrological and/or geophysical studies, which are desirable/necessary to aid the interpretation of the data and avoid errors resulting from single-discipline conclusions.

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Review of Prior Geochemical Work and Possibilities for Additional Surveys.

Several reviews of geochemical studies in the Kiluaea East Rift Zone (KERZ) and its surroundings have been published (e.g. Cox, 1980; Cox, 1981; ENEL, 1990; Iovanetti, 1990; Thomas, 1986; Thomas, 1987; Thomas, 1989). These, along with discussions with scientists and private operators recently active in the area, form the basis for the following observations and conclusions.

Soil Surveys (Objective A)

Exploration to detect trace chemical emissions from "hidden" reservoirs (objective A, above) has been reported by Cox (1980, 1981), who conducted soil surveys for Hg and ^{222}Rn with reconnaissance-level sample spacings of about 0.5 to 0.8 km (Hg) and 1 to 1.5 km (^{222}Rn), in the lower KERZ (lower Puna area). Reducing the Hg data to remove strong background effects of soil chemistry was particularly difficult; the reduced data presented "a pattern of anomalous Hg overall (which) indicates Hg leakage in ground gas from fractures within the rift zone and tends to reinforce the model of a rift-controlled reservoir" (Cox, 1981, p.70). There were localized variations some of which may be related to the influence of specific fractures, but most of which appeared to be a function of the problems with data reduction. The major anomaly included the location of well HGP-A.

The ^{222}Rn survey was regarded as somewhat more successful in defining zones of possible deep permeability and thermal activity. There is an anomaly which encompasses the locations of well HGP-A and the Puna Geothermal Venture (PGV) well, and several other anomalies, all within the KERZ. The anomalies are interpreted as defining zones of both high temperature and structural permeability, allowing ground gas movement (outgassing of deep vapor bearing ^{222}Rn) which is detectable near the surface

(Cox, 1980). However, Don Thomas (oral communication, 1991) suspects that the anomalies are created by variations in local shallow subsurface permeability, and do not necessarily indicate good exploration targets.

Both surveys have established correlations between soil anomalies and the KERZ, and show that an anomaly exists at the proven HGP-A and PGV wellfield. The HGP-A discovery was made without the benefit of these data, and the PGV discovery wells probably also were sited using other criteria. The unproductive deep holes just south and southeast of the wellfield are at the edge or outside of the anomaly. This encourages siting exploration wells within the Rn anomalies, the Hg data being too uncertain. However, the actual utility of the soil chemistry data as a tool for siting wells and proving deep, productive reservoir(s) remains to be established. Data from drilling into the other Rn anomalies are needed.

From reviews of the prior work, it appears that additional Hg surveys would be of little benefit for exploration and scientific values.

Regarding Rn, we recommend considering:

1) a reconnaissance level Rn survey in the middle and upper parts of the KERZ, even though only indirect evidence for deep exploration targets can be expected at this time. The rationale for this work is eventual integration of existing Rn data with further exploration data from the lower KERZ, allowing (possible) use of data from the middle and upper areas;

2) detailed surveys around SOH holes or any other exploration step-outs which discover high temperature and/or high permeability, to investigate whether anomalies exist at these locations. This work

also merges into the realm of research, but may have practical applications at a future time.

This additional survey work at this time is a low priority. It should again be considered if future deep drilling in some way confirms the anomalies already discovered.

These are other techniques intended to detect "hidden" reservoirs, such as sampling and analyses to find anomalies of NH_3 and CO_2. These depend upon the presence of shallow groundwater to concentrate and carry the specie being analyzed, and would not apply to the rift zone environment.

Classifying and Ranking Targets, Defining the Hydrogeologic Model (Objectives B and C)

Thermal springs and fumaroles are absent from the KERZ, so this method of exploration to classify and rank targets (objective B) is impossible. Furthermore, the small number of deep exploration holes and data therefrom in the public domain, except from HGP-A, limits possibilities for more than a sketchy definition of the hydrogeologic model (objective C).

Groundwater studies have identified thermal fluids at shallow (<300m) and cool to warm (<100°C) boreholes and wells, and at coastal springs, in and south of the lower east rift zone (ENEL, 1990; Iovanetti, 1990; Thomas, 1986). The number of shallow boreholes and wells in the area is quite small. ENEL (1990, pl.2) reported 15 locations, but only 6 with temperatures above 30°C. OESI has since drilled two monitor holes and two water wells (one recently completed; 29 Aug. 1991).

Only one sample from a coastal warm spring was tabulated by ENEL (1990, annex A table 1, Isaac Hale Spring). The same report (pl.2) shows the

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temperatures and approximate locations of 10 springs along the coast south of the rift, and one to the north. Temperatures exceed 30°C only at Allison, Isaac Hale and Opihikau springs. Don Thomas (oral communication, 1991) reports that Isaac Hale and Opihikau are the only locations where hot water discharge can be sampled before it mixes with seawater.

Fluids compositions at several of the holes indicate mixtures of dilute shallow groundwater with heated seawater and/or with deep thermal reservoir water. ENEL (1990) tends to view the warm waters as mixtures of dilute groundwater with heated seawater, whereas Iovanetti (1990) has interpreted the same samples as mixtures of dilute groundwater with thermal reservoir outflow.

As ENEL (1990) has pointed out, much of the chemical data that ENEL examined are fragmentary, incomplete, and often marginal in quality. Sample locations are often ambiguous and samples from single locations collected years apart sometimes differ. Most analyses lack trace elements such as Li, Rb, Br and Cs, and the stable isotopes of oxygen and hydrogen. One-half of 94 major element analyses reported by ENEL (1990; annex A, table 1) show major element ion imbalances of more than 10%. ENEL may not have obtained all available information from the USGS and State of Hawaii.

Major ion balances of analyses from well HGP-A, tabulated by ENEL (1990) and also published elsewhere, are quite satisfactory. The HGP-A chemical data include numerous weir samples, and liquid, steam and gas samples collected at the same pressure, but do not include stable isotope analyses. The well was not precisely flow metered, so total flow enthalpy and relative steam-water flow rates are not well-known.

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Discussion and Recommendations for Obtaining Additional Fluids Geochemical Data.

Considering the work already accomplished and the results we recommend:

1) collect new samples where necessary at all of the shallow wells and coastal springs in and south of the east rift zone, at the newer water wells and monitor holes drilled by OESI, at the SOH program holes, and at any other new holes which become available. At a minimum, the older locations should include the GW-3 hole, the Allison well, the Malamam Ki well, and the Kapoho hole (if accessible). Downhole samples can be collected at holes which cannot be flowed.

   Temperature-spinner logs of shut in holes sampled downhole are also recommended, to detect interzonal flow. Sample analyses should include major and trace elements, and stable isotopes. It would be best for the samples from all sources to be analyzed at the same laboratory, with very careful quality controls.

This work should be done to help define the hydrogeologic model of the thermal system, and in particular the patterns and causes of heating in the shallow groundwater system in and south of the rift. Results should be integrated with data from well HGP-A and private deep exploration holes, as such data become available. This work also should be done in connection with long-term monitoring of the environmental background, which is discussed below.

At least some of the recommended locations were sampled in August 1991, by personnel of the U.S. Geological Survey, but a list of locations is

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not yet available (R. Mariner, oral communication, 19 August 1991). The U.S. Geological Survey recently started a 3 to 5 year long project to study the entire hydrologic and hydrogeologic system of Kilauea volcano, from the summit of Mauna Loa, to Hilo, to South Point. The study team includes a hydrologist, two geologists, a geophysicist, and two hydrogeochemists; the project chief is J. Kauahikaua of the HVO. The work is described as a regional hydrogeology project. Project work started in mid 1991 with meetings at the HVO to define the scope of work. The project geochemists then spent two weeks in the field, collecting samples of rainwater, surface water, spring and wellwater, from throughout the project area, for chemical and isotopic analysis. The U.S.G.S. also obtained, in late 1989, samples from some of the hot groundwater sources in the rift zone, including well GW-3. (C. Janek, oral communication, 30 August 1991).

Our recommendations do not include detailed studies of solids chemistry. It is assumed, however, that the basic mineralogy of cores and cuttings will be determined, to distinguish rock types and major alteration patterns such as the presence of hydrothermal calcite, quartz and anhydrite.

Engineering Design and Production Engineering (Objectives D and E)

Public-domain studies related to these objectives have not been done, except for reports on corrosion and scaling at well HGP-A. This work is largely the domain of field developers and operators, except to the extent that failure to manage corrosion can be a matter of public safety, and failure to select appropriate location, depths, composition and pressure may lead to injection problems such as undesired contamination of non-thermal aquifers, gas break-through and thermal degradation.

With respect to corrosion, it may be assumed that the current operators are well aware of the potential corrosivity of the fluid (high H_2S, Cl)

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produced by the existing wells. Some wells have shown a tendency to produce only steam, which presents a very severe corrosion potential if the steam carries HCl. This corrosion can be managed using existing technology. To our knowledge, adequate analyses to detect HCl corrosion potential still do not exist. Steam sampling to monitor for HCl can require special techniques of sample collection and analysis, which are not routinely applied.

With respect to injection, we propose~~d~~ that strategies and actual injection must be monitored. We are not aware of locations where deep geothermal injection has mixed into shallow aquifers. However, the relatively unique hydrologic environment of the rift zone will need to be considered, as well as possible effects of injecting large amounts of non-condensible gases, as proposed by OESI. Gas injection in excess of solubility may result in breakout and vertical travel if unconfined zones exist. Injection is a subject of study which will require integrated modeling, which also considers production from the geothermal reservoir, and will be further investigated as part of task 3 of the technical advisory agreement. It may be that the work can be coupled to SOH/EPRI studies.

Chemistry of the Environment and Production Effects (objective F)

As discussed above, the chemistry of the cool to hot shallow groundwater system in and south of the lower east rift zone is not well-documented. For this reason, a re-sampling has been recommended. We further recommend that this work be carried out on a regular, routine basis for 2 or 3 years, to allow establishing solid background data and detecting any seasonal changes in shallow groundwater chemistry which may be occurring. Such changes are not common, but if they occur, they would interfere with detecting and analyzing injection effects. Shallow groundwater sources close to the northern edge of the rift zone should also be included. Samples should be collected about 6 times/year the first year, and 4 times/year or less thereafter, depending upon variability. Species to be analyzed can be limited somewhat to avoid excessive costs, but should include trace elements and isotopes at least at the start.

Summary of Recommendations. The following techniques are proposed as the highest priority items for future work.

1. Resample (or obtain information from the U.S.G.S.) cool to warm shallow groundwater sources in the lower east rift and to the south, and sample new sources, to obtain analyses of trace elements and isotopes along with better analyses of the major elements. Collect downhole samples at wells which cannot be flowed; obtain temperature-spinner logs at these same holes.

2. Continue sample collection at the same locations on a periodic basis for about 2 years, to establish solid environmental background data, and document seasonal changes, if any.

3. Carefully monitor plans of location, depth, pressure, chemistry and volume proposed by operators for water and gas injection from the production areas, the rational for choice of injection locations, and precise injection plans.

4. Consider Rn surveys at reconnaissance scale in the middle and upper east rift zones, and detailed scale in the lower rift, if future drilling in the lower rift shows that existing anomalies correlate with producible deep thermal aquifers.

References - Geochemistry

Cox, M.E., 1980, Ground radon survey of a geothermal area in Hawaii. Geophysical Research Letters, vol.7, no.4, pp.283-286.

Cox, M.E., 1981, An approach to problems of a geothermal mercury survey, Puna, Hawaii. Geothermal Resources Council Transactions, vol.5, pp.67-70.

ENEL, 1990, The Kilauea East Rift Zone: geothermal evaluation of the existing data, draft report (June 1990). *By* Ente Nazionale per L'Energia Elettrica - Italy, *for* State of Hawaii, Department of Business and Economic Development, contract n. 27272, Agreement for Advisory Services for the Geothermal/Cable Project.

Iovanetti, J.L., 1990, Shallow ground water mapping the Lower East Rift Zone Kilauea Volcano, Hawaii. Geothermal Resources Council Transactions, vol.14, part I, pp.699-703.

Iovanetti, J.L. and D'Olier, W.L., 1985, Preliminary results of drilling and testing in the Puna geothermal system, Hawaii. PROCEEDINGS, Tenth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 22-24, 1985, SGP-TR-84, pp.65-72.

Thomas, D.M., 1986, Geothermal resources assessment in Hawaii. Geothermics, vol.15, no.4, pp.435-514.

Thomas, D.M., 1987, A geochemical model of the Kilauea East Rift Zone, *in* Volcanism in Hawaii. U.S. Geological Survey Professional Paper 1350, pp.1507-1525 (ch.56).

Thomas, D.M., 1989, Hydrothermal systems in Hawaii, *in* The Geology of North America, Vol.N, The Eastern Pacific Ocean and Hawaii, Ch.12, The Hawaii-Emperor Chain, pp.271-287. The Geological Society of America.