SOME ASPECTS OF GEOCHEMICAL EXPLORATION IN HAWAII

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ABSTRACT

The high permeability of the basaltic lavas and the oceanic environment of Hawaii complicate geothermal exploration, and the formation of reservoirs requires the existence of impermeable structures, such as dike systems. These conditions also preclude the widespread formation of features such as hot springs, which are a major source of geochemical information. Although a large number of groundwater wells exist, they do not penetrate deep thermal groundwaters, limiting quantitative interpretation of their chemistry. Prospective areas have consequently been selected for more detailed studies on the basis of geology, qualitative groundwater chemistry (e.g. ratio of Cl/Mg; SiO_2 concentration) and groundwater temperatures. A site specific geochemical approach has consequently been to utilize techniques dependent on ground gas, such as ground radon (Rn) and the mercury (Hg) content and pH of soils. Surveys in three different areas are presented; two in rift zones and one in an extinct caldera.

INTRODUCTION

Geothermal exploration in Hawaii is still in an early stage, and up until 1978 was largely concentrated in the Puna area on the lower east rift of Kilauea volcano (Fig. 1). During 1961, four exploratory wells were drilled within that rift zone, but were unsuccessful due to their shallow depth (54 to 210 m). One produced low-pressure steam and had a maximum downhole temperature of 105°C; two others extended below sea level, but bottom temperatures were only 43° and 93°C (Macdonald, 1973).

Various surveys, largely geophysical, were conducted at Puna from 1972 to 1977, and the chemical and stable isotope compositions of shallow groundwaters were assessed (Druecker and Fan, 1976; McMurtry et al., 1977). The outcome of this work was the drilling of well HGP-A in 1976. The well is 1,953 m in depth and downhole temperatures are on the order of 300° to 320°C below about 1,100 m with a maximum temperature of 358°C.

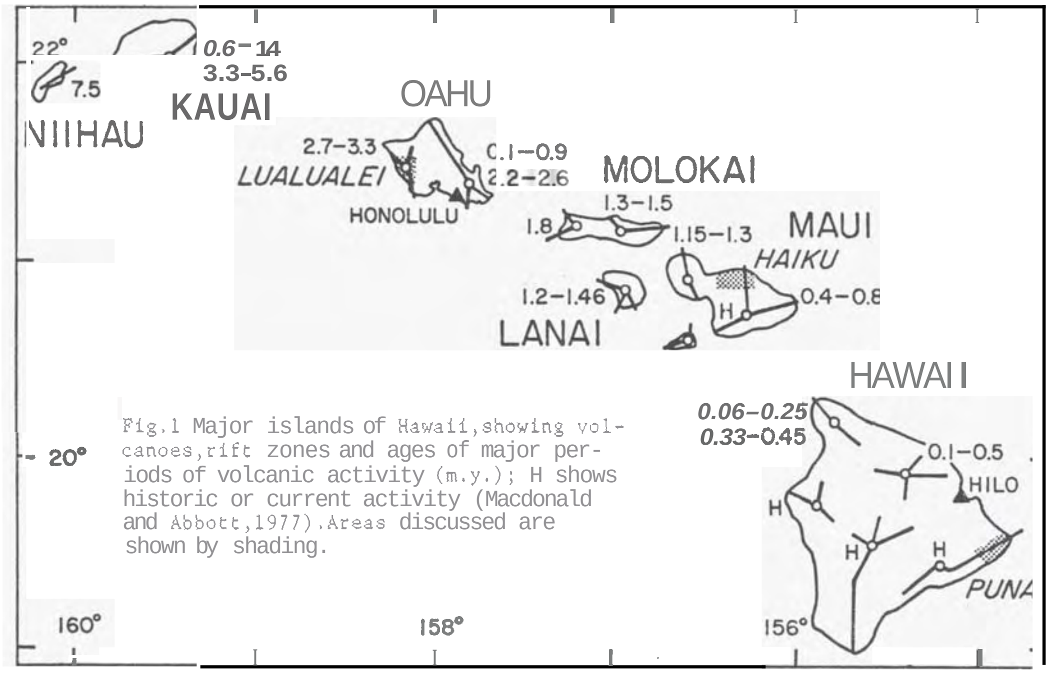

Fig.1 Major islands of Hawaii, showing volcanoes, rift zones and ages of major periods of volcanic activity (m.y.); H shows historic or current activity (Macdonald and Abbott, 1977). Areas discussed are shown by shading.

A test generator with a total capacity of around 3 MW has been installed at the wellhead and start-up and testing were initiated in June 1981.

GEOTHERMAL ENVIRONMENT IN HAWAII

HGP-A has confirmed earlier geological reasoning (Macdonald, 1973) that the most likely environments in which geothermal reservoirs could develop in Hawaii are within volcanic structures. The following characteristics are likely:

(a) Main heat source of intrusive bodies: dike swarms within rift zones and intrusive plugs within dormant and extinct caldera structures;

(b) Development of a reservoir would require entrapment of groundwater by impermeable structures (e.g. dike complexes, massive lavas) and so would be structural not lithological (a "caprock" as such is unlikely). Chemical sealing of reservoirs by deposition of secondary minerals (e.g. silica, calcite, anhydrite) may also be possible;

(c) Because of high ground permeability and high recharge, water-dominated systems are the most likely;

(d) Geothermal waters are likely to be basal groundwaters of meteoric origin, with some encroachment of the underlying deep saline groundwater, due to thermal perturbation of the Ghyben-Herzberg interface.

Largely because of the high permeability of the lava flows there are no widespread surface features such as hot springs, fumaroles and steaming ground, and these features are limited to the summits and rift zones of the active volcanoes (Kilauea and Mauna Loa). Some coastal thermal seepages occur on the island of Hawaii, and are apparently the result of thermal groundwaters rising toward sea level along the Ghyben-Herzberg lens (e.g., Fig. 4).

REGIONAL ASSESSMENT FOR POTENTIAL GEOTHERMAL AREAS

From 1978 this Institute began a statewide assessment of geothermal potential, part of which consisted of compiling and reassessing available on-file groundwater chemistry. An appreciable amount of such data was available from local agencies due to the dependence of Hawaii on groundwater supplies.

For these shallow groundwaters it was not possible to use most elements or ratios of elements as geothermal indicators, and they cannot be assessed in the same manner as hot spring discharges. This consequently precludes the use of the standard quantitative chemical geothermometers such as SiO_2, Na-K and Na-K-Ca, by which estimates of "reservoir" temperatures (or that of the last water-rock equilibrium) can be made. Two basic criteria were initially established as indicators of geothermal processes: temperatures $\geq$ 26°C or SiO_2 concentrations $\geq$ 55 ppm for the island of Oahu, and SiO_2 $\geq$ 30 ppm for the other islands (Thomas et al., 1979). [Groundwater data in the known geothermal area of Puna had shown that SiO_2 concentrations of $\geq$ 50 ppm were indicative of zones of high subsurface temperatures. The SiO_2 content of deep water from HGP-A is around 800 ppm (Thomas, 1980)]. Application of the above criteria on a regional basis, however, has shown that many variables exist which lead to ambiguities in interpretation. Of note are the shallow depth of the wells (30 to 300 m), the mixing of different water types and that within one area wells may penetrate different aquifers. Different aquifer types tend to have characteristic values. High-level aquifers (ususally dike-impounded) have SiO_2 concentrations of 15 to 45 ppm and basal aquifers (i.e. non-artesian and "floating" on saline water) 30 to 60 ppm. Sedimentary aquifers (coastal, or deep valleys and largely on the older islands) have SiO_2 values of 25 to 45 ppm, which can increase to 50 to 85 ppm due to recirculation by irrigation and reinjection of industrial water (Davis, 1969). Likewise, aquifers have characteristic temperature ranges: high-level, 18° to 21°C; basal, 20° to 24°C, and sedimentary, 22° to 26°C.

Some success was obtained using the Cl/Mg ratio as a qualitative indicator, and it enabled distinguishing between SiO_2 - temperature anomalies most likely due to geothermal processes from those due to other conditions (Cox and Thomas, 1979). Groundwater with Cl/Mg $\geq$ 15 (that of seawater) are strongly indicative of having experienced reactions with rocks at elevated temperatures (Fig. 2). The assumption in using this ratio is that the Cl ion content of seawater and groundwater remain largely unaffected by thermal processes during subsurface migration, or by anionic exchange when seawater infiltrates the island aquifers. The Mg ion, however, is strongly depleted where groundwaters are affected by thermal processes and where aquifer rock chemistry is changed by hydrothermal alteration. Water-rock equilibria studies have shown that Mg can be

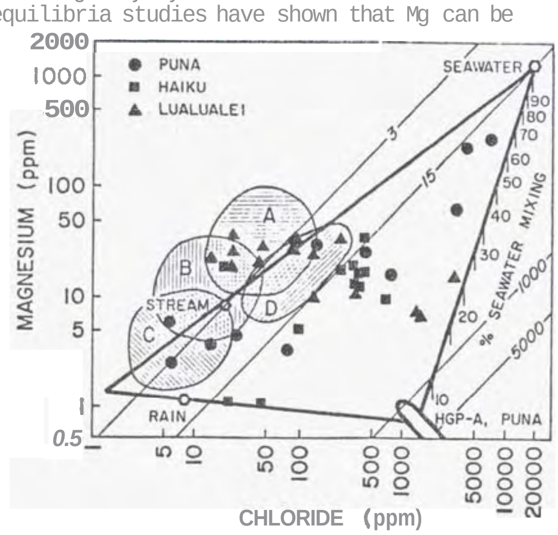

Fig.2 Plot of Cl/Mg concentrations showing parameters for Hawaiian conditions; groupings of non-thermal groundwaters are shown at left (A = unconfined and basal; B = high level; C = high recharge, usually windward areas; D = sedimentary). Waters with Cl/Mg $\geq$ 15 are thermally anomalous; degree of saline water mixing is indicated.

effectively removed from solution hy the formation of alteration products at elevated temperatures (Ellis and Mahon, 1964), e.g. chlorite at high temperatures and illite at lower temperatures. Mg depletion may also be enhanced by heating of saline waters in deep aquifers, which under high temperatures may produce precipitates of magnesium oxysulfate; intermediate temperature reactions (70° to 150°C) can also deplete Mg through the formation of smectite clays (Seyfried and Bischoff, 1979). Figure 2 demonstrates the characteristic Cl/Mg ratios for different aquifer types, the effects due to mixing of different waters and thermal conditions.

SITE SPECIFIC SURVEYS

On the basis of the regional assessment, seven areas were selected for more detailed study (Thomas et al., 1980). Geochemical studies in three areas of different characteristics are presented.

(a) Puna area, lower east rift, Kilauea volcano - formed of tholeiitic basalt lavas erupted from fissures. The area is still active and last experienced eruptions in 1790, 1840, 1955 and 1960. Soil development is generally poor or nonexistent over historic flows, but over older flows organic soils reach a thickness of 0.5 m. The area is presented as an example of a (known) high temperature geothermal system.

(b) Haiku area, lower north rift, Haleakala volcano - this is considered a dormant volcano, having no historic eruptions from the summit or north and east rift zones, but a fissure eruption on the lower southwest rift in about 1790. Radiometric dating indicates an age of 0.8 to 0.4 m.y. for the last flows from the north rift. These flows are predominantly hawaiite with lesser alkalicolivine basalt and overlie the highly permeable tholeiitic basal rocks of east Maui. The surface expression of the rift is of two trends of eroded cinder cones along a broad topographic high (Fig. 5). The area is presented as an example of a (possible) intermediate temperature geothermal location.

(c) Lualualei valley, Waianae volcano - this valley roughly corresponds to the location of the caldera of the extinct Waianae volcano (bulk of activity from 3.6 to 2.4 m.y.). The western part of the edifice has been removed by erosion, and its eastern part is formed by the western boundary of the central plateau of Oahu. Resistant E-W ridges have formed several valleys, the largest of which is Lualualei, and significant sedimentary infilling has occured within them. The central vent system is believed to be located in the northeast of the caldera (Fig. *6)*, where there is extensive dike formation and brecciation. Flows are largely tholeiitic basalts, although alkalic flows overlie parts of the area, mainly in the southeast. A post-erosional period of renewed activity may have taken place during the Pleistocene, forming lava and cinder near the vent area. Lualualei is presented as an example of a low-temperature geothermal locality.

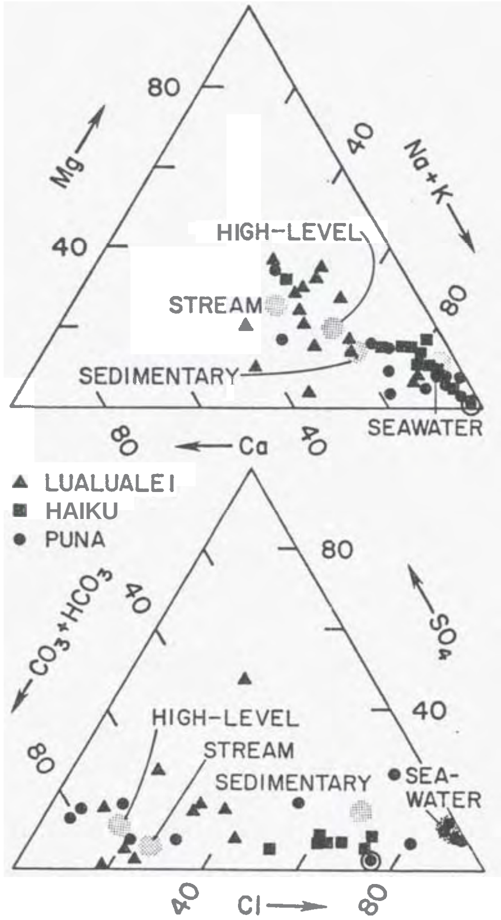

Fig.3 Piper diagrams for major cations and anions demonstrating chemical types of groundwaters in survey areas. Shaded areas show averages of a large number of samples of different water types. Double circle is HGP-A water.

Description of Water Chemistry in Example Areas

In each area groundwater wells were relocated and where possible, resampled. The chemical types of the waters are demonstrated in Figure 3; obvious is the distribution from very saline groundwater to fresh water from high-level aquifers. Most groundwaters are slightly alkaline, and pH is commonly 6.9 to 7.8 (deep water in HGP-A has a pH of around 4). Averages of a large number of water analyses from throughout Hawaii show characteristic chemistry for different types: sedimentary aquifers, NaCl; high-level aquifers, $CaNaHCO_3$ and streams, $CaMgNaHCO_3$. At Puna, because of its low elevation, proximity to the coast and high temperatures at depth, groundwaters within the rift are of NaCl type; cooler, shallow waters adjacent to the rift are $NaHCO_3Cl$ types and those further inland $NaHCO_3$ and $CaMgNaHCO_3$ types. Groundwaters at Haiku are largely NaCl types, grading to $NaHCO_3Cl$ for warmer waters. This suggests the possibility of mixing of deeper (?warmer) water with water from further up-flank. In Lualualei valley most groundwaters are CaNaHCO$_3$Cl $\pm$ Mg $\pm$ Cl reflecting the sedimentary aquifers and shallow saline water intrusion; one well had anomalously high SO_4.

These data suggest that it is reasonable to assume that a geothermal reservoir of any potential would contain NaCl or NaHCO$_3$Cl waters, representing basal groundwaters that have been mixed with the underlying saline water due to thermal perturbation.

Geochemical Mapping Surveys

To aid in assessing the areas in more detail, areal mapping surveys were conducted which measured the concentration of the radioactive gas (Rn) at shallow depth, and the concentration of mercury (Hg) in soil and the pH of the soil. It was believed that the measurement of these parameters which are associated with migrating ground gas would be suitable in the Hawaiian environment largely because of the high permeability of the lavas. Further, elevated concentrations of both Rn and Hg are known to occur in association with hydrothermal fluids in both terrestrial and marine environments. It was hoped that soil pH may indicate zones in which there was a component of hydrothermal "acid" gases within ground gas.

The methods used are described elsewhere (e.g. Cox, 1980; Cox, 1981); in summary, the concentration of Rn is measured at ≈ 30 cm depth by alpha-particle sensitive film, exposed for about four weeks. After development alpha tracks appear on the film as perforations and are counted under 100 x magnification, Rn emanation from representative soil samples was similarly determined in the laboratory for use as background values. Soil samples were also analyzed for Hg by gold film mercury analyzer (McNerney et al., 1972) and for pH by meter (soil sieved to < 1.0 mm and mixed into a slurry of 2:1 distilled water to sample by volume). Rn stations were set up at intervals of 0.6 to 1 km and soil samples were collected at about twice this density.

Relative variations of values within each survey area are most important, but because of differing environments of survey areas comparisons to local backgrounds may be needed to compare results between areas. This is especially so for the Rn surveys because of differences in concentration of the parent nuclides within different lava types. To enable this comparison the Rn data are presented as "x background". Based on the above, values of 5-6 x background are believed to indicate increased permeability and, low order heat, and values of ≥ 10 x, high permeability and "significant" heat. Determination of Hg backgrounds for different soil types was found necessary in areas of historic volcanism where there is high variability in soil development. This approach was not used in the older areas of more uniform soil cover and Hg concentrations were assessed relative to the apparent background for the whole area. Values of soil pH were assessed relative to the mean pH for each area.

EXAMPLES OF MAPPING SURVEYS

Puna

Anomalies for both Rn and Hg occur in association with cracks and fissures along the rift structure (Fig. 4). The Rn anomaly outlined shows values of 5 x and 10 x background, and contains values up to 43 x background, which is believed indicative of high subsurface temperatures. The variable outline of the Rn anomaly apparently shows changes in near-surface Permeability. The Hg anomaly outlined is 2 x background, and concentrations were commonly 20 to 200 ppb with the highest value of 1,250 ppb near a low-temperature fumarole. The overall correlation between Rn and Hg is significant, as is the location of HGP-A within these anomalies. Soil pH was highly variable, with an average of 6.5; small zones of low pH (to 5.0) did occur over the rift structure and associated with minor steam discharges, but larger areas of low pH also occurred peripheral to the rift structure, and thus soil pH data were not conclusive.

Haiku

Rn and Hg anomalies are associated with the western boundary of the rift zone as inferred from cinder cone locations (Fig, 5). The Rn anomaly shows 5 x and 10 x background; the highest values (to 36 x) occur within a well-developed linear N-S zone, which strongly indicates the presence of a highly permeable structure continuous with elevated subsurface temperatures. The Hg anomalies shown are 200 and 800 ppb; the highest value was 3,160 ppb in the northeast. The zone of anomalous Hg in part overlaps the Rn anomaly, but also continues over the rift. Soil pH generally decreased west to east, from 8.0 to < 5.5 over the rift; mean pH was 6.5. The Rn values are believed to indicate the existence of geothermal conditions; the overall high Hg values are partly in response to the thick organic soils in the area, but the zones of very high values (≥ 4 x background) are of significance.

Lualualei

Results in this area are believed to represent anomalous, but low subsurface temperatures, and suggest warm groundwater in association with the rim of the old caldera. Rn anomalies (Fig. 6) are 5 x background (the highest within the caldera structure being 8.2 x). Hg values were commonly 30 to 180 ppb, and ≥ 100 ppb is considered anomalous. Soil pH was relatively uniform from 5.9 to 7.3, averaging 6.7. and appears to reflect changes in soil properties only. Some limited correlation between Rn and Hg exists, but anomalies are of low order.

CONCLUSIONS

The geochemical investigations described are believed to have been successful in assisting delineation of potential geothermal areas in Hawaii, but have certain limitations. The use of groundwater data is restricted to those locations in

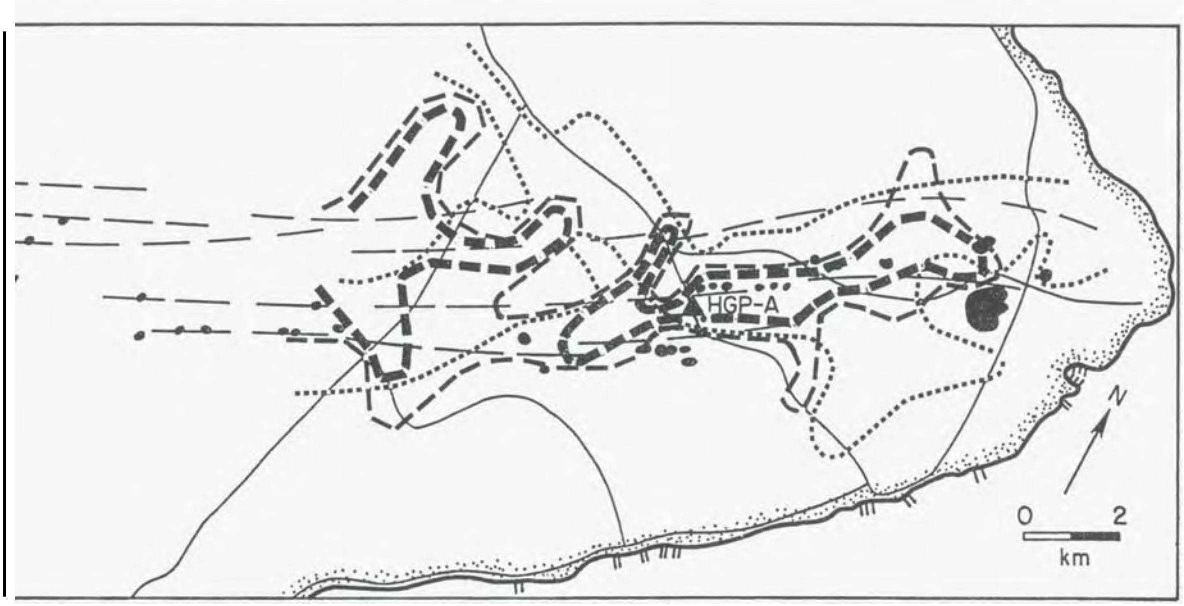

Fig.4 Puna survey area showing main roads, trends of major fractures along the rift and eruptive features. Rn anomalies are shown by broken lines (5 x and 10 x background); Hg anomaly by dotted line (2 x background). Dashes along south coast show locations of thermal water seepages and infra-red anomalies.

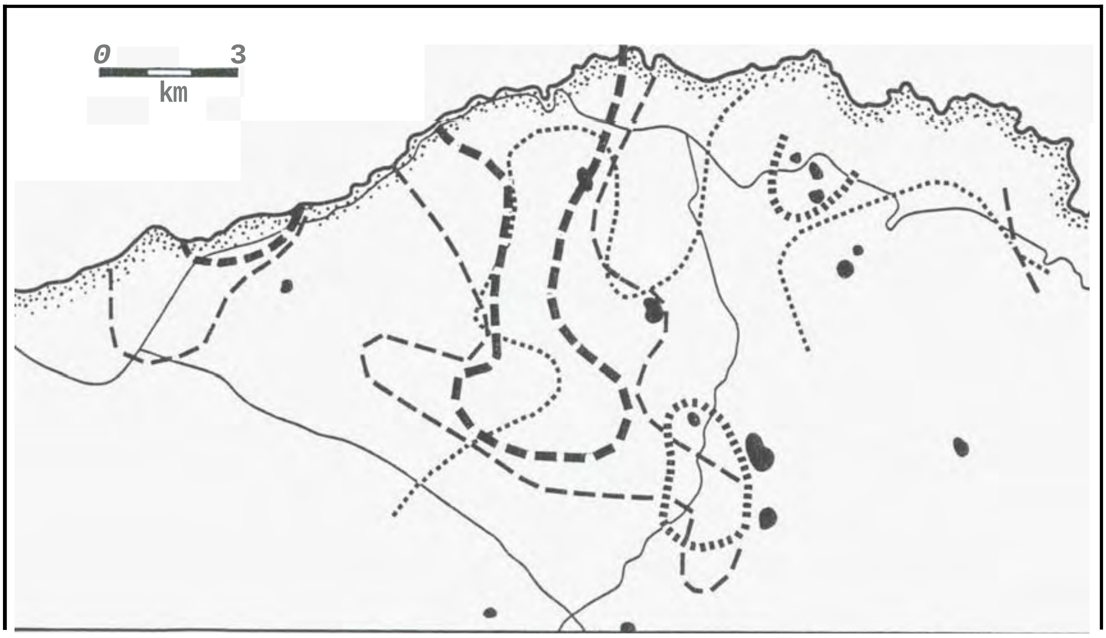

Fig.5 Haiku survey area showing main roads and eroded cinder cones; the trend of the rift is shown by the parallel lines of cones. Rn anomalies are shown by broken lines (5 x and 10 x background) and Hg anomalies by dotted lines (200 and 800 ppb).

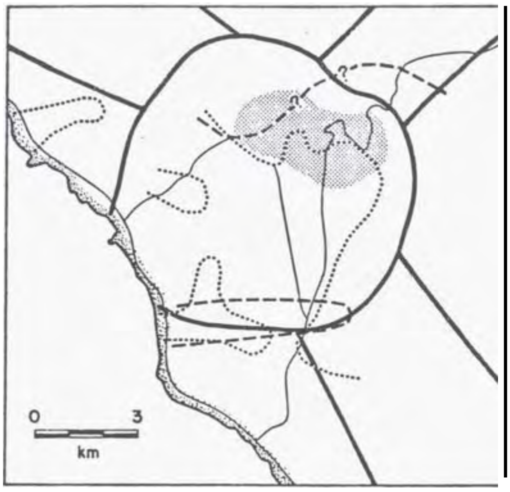

Fig. 5 Lualualei survey area showing main roads, inferred outline of caldera structure, locations of NW, SE and NE rift zones and vent area (shaded). Rn anomalies (5 x background) are broken lines and Hg anomalies (100 ppb), dotted lines.

which wells have been drilled; several other areas with limited or no groundwater data do have initial potential based on geological criteria, Results of many of the surveys may not be confirmed as the areas may not be drilled for a considerable time, if at all. This difficulty is increased as future drilling is likely to be by private enterprise and release of data will probably be limited, Some idea of the suitability of different techniques was, however, gained by conducting them retrospectively around HGP-A. The three areas discussed indicate that the geochemical techniques utilized can provide some indication of the potential as well as assist in understanding the form of the system and in the selection of possible drill sites. A final assessment of the success of such surveys can, however, only be determined by deep drilling.

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