HIG-79-8

INVESTIGATION OF GEOTHERMAL POTENTIAL IN THE WAIANAE CALDERA AREA, WESTERN OAHU, HAWAII

MALCOLM E. COX, JOHN M. SINTON,
DONALD M. THOMAS, MARK D. MATTICE,
JAMES P. KAUAHIKAUA*, DONALD M. HELSTERN,
and POW-FOONG FAN

*U.S. Geological Survey

Assessment of Geothermal Resources in Hawaii:
Number 2

SEPTEMBER 1979

Prepared for
WESTERN STATES COOPERATIVE
DIRECT HEAT RESOURCE ASSESSMENT

under grant no.
DOE/ID/01713-5

HAWAII INSTITUTE OF GEOPHYSICS
UNIVERSITY OF HAWAII

HIG-79-8

INVESTIGATION OF GEOTHERMAL POTENTIAL IN THE WAIANAE CALDERA AREA, WESTERN OAHU, HAWAII

Malcolm E. Cox, John M. Sinton,
Donald M. Thomas, Mark D. Mattice,
James P. Kauahikaua*, Donald M. Helstern,
and Pow-foong Fan

*U.S. Geological Survey

Assessment of Geothermal Resources in Hawaii:
Number 2

September 1979

Prepared for
Western States Cooperative
Direct Heat Resource Assessment
under grant no.
DOE/ID/01713-5

Charles E. Helsley
Director,
Hawaii Institute of Geophysics

ABSTRACT

Studies of Lualualei Valley, Oahu have been conducted to determine whether a thermal anomaly exists in the area and, if so, to identify sites at which subsurface techniques should be utilized to characterize the resource.

Geologic mapping identifies several caldera and rift zone structures in the Valley and provides a tentative outline of their boundaries. Clay mineralogy studies indicate that minor geothermal alteration of near-surface rocks has occurred at some period in the history of the area. Schlumberger resistivity soundings indicate the presence of a low resistivity layer beneath the valley floor, which has been tentatively attributed to warm water-saturated basalt. Soil and groundwater chemistry studies outline several geochemical anomalies around the perimeter and within the inferred caldera boundaries. The observed anomalies strongly suggest a subsurface heat source. Recommendations for further exploratory work to confirm the presence of a geothermal reservoir include more intensive surveys in a few selected areas of the valley as well as the drilling of at least three shallow (1000-m) holes for subsurface geochemical, geological and geophysical studies.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Page

Figure

INTRODUCTION

The present study was undertaken to determine whether residual heat still exists beneath the caldera complex of Waianae volcano and, if so, to locate an exploratory drilling site to determine whether a fluid reservoir exists and what its thermal potential might be. Our exploration efforts have included the compilation and evaluation of currently existing data and published research in this area as well as the present studies by HIG staff members. These studies are as follows:

(1) Field mapping to locate boundaries of the Waianae caldera and to identify faults and structural features in the caldera area with which a geothermal system may be associated.

(2) Clay mineralogy studies to identify the types of clay minerals present and to determine whether they are related to geothermal activity.

(3) Resistivity soundings to assist in defining structure and to determine whether conductive layers exist that may be related to geothermal activity.

(4) Mercury-radon surveys to identify structurally controlled, and potential thermally driven, areas of ground outgassing.

(5) Chemical analyses of groundwaters to identify chemical anomalies that may be associated with thermally altered groundwaters.

Our results and interpretations are presented herein, and recommendations are made in the summary.

also appears to be, to some degree, fault-controlled and air photographs suggest that the seaward side may be slightly downthrown.

Hydrogeology

The hydrology of the area is relatively complex. It is in part controlled by the extensive diking in the caldera-rift zone complex and by the alluvial fill in the valley floor and along the coastal margin. The highly fractured rocks of the middle and lower members are a reservoir for meteoric recharge (760 to 1020 mm annually) in the northeastern rim of the valley. Impermeable dike systems at the higher elevations in the valley and above Kolekole Pass impound a considerable fraction of the incoming meteoric water, so that the net outflow is somewhat lower than the recharge. These high-level impounded waters tend to be compartmentalized and do not conform to the classical Ghyben-Herzberg model (i.e., these waters are not floating above saline water).

Fresh groundwater also occurs in the alluvial valley fill material but is limited in volume because of the lower porosity of this sedimentary material. The groundwaters beneath the valley floor are of basal-type floating on deeper saline water, although some dike impoundment may occur toward the head of the valley (Stearns et al., 1940). The lower permeability of the coastal sediments and coralline material limits seawater encroachment into the basal lens to some extent, but heavy withdrawal of several wells within this aquifer have caused their abandonment because of increasing salinity (Takasaki, 1971).

GEOLOGY OF OAHU AND WAIANAE VOLCANO

Malcolm E. Cox
Donald M. Thomas

The island of Oahu, third largest of the Hawaiian chain, has an area of 1569 sq. km. (Fig. 1). The island was built from two, originally independent, volcanic systems: Waianae volcano, the older of the two, in the central western part of the island, and Koolau volcano, which formed eastern Oahu. Volcanism on the Waianae shield is thought to have terminated about 2.4 million years (m.y.) ago, whereas Koolau post-erosional activity (Honolulu Volcanic Series) has continued until as recently as 30,000 years ago. Subsequent to the periods of most active volcanism of both systems, marine and surface erosion removed nearly half of both volcanic shields.

A complex series of submergences and reemergences since the Pleistocene significantly altered the morphology and hydrology of Oahu. Lower sea levels (during glacial episodes) have allowed stream-cut valleys to be formed to depths considerably below present sea level. Subsequent higher elevation sea levels have silted in many of these valleys to depths of several hundreds of meters. The formation and silting over of extensive reefs at various elevations around the island have provided flat alluvial-filled valleys (e.g., Lualualei) as well as a limestone cap rock around the perimeter of the island that inhibits the outflow of fresh water from the deeper groundwater aquifers.

Part of the Waianae volcano caldera is located in what is now Lualualei Valley. Although subaerial and submarine processes have removed substantial amounts of material from this area, collapse subsidence of the central and western part of the shield also may have occurred. The pre-erosion caldera was no doubt considerably smaller. Evidence suggests that the central vent area was located between Mauna Kuwale and Kolekole Pass (Fig. 2) where extensive dike formation, brecciation, and highly resistive topography are evident.

The geology of this region has been described in detail (Stearns and Vaksvik, 1935; Stearns et al., 1940; Macdonald and Katsura, 1964; Stearns, 1967; Macdonald and Abbott, 1970) and the area has been remapped petrographically (Sinton, this report). Rocks of the area have been classified as the Waianae Volcanic Series and subdivided into lower, middle, and upper members.

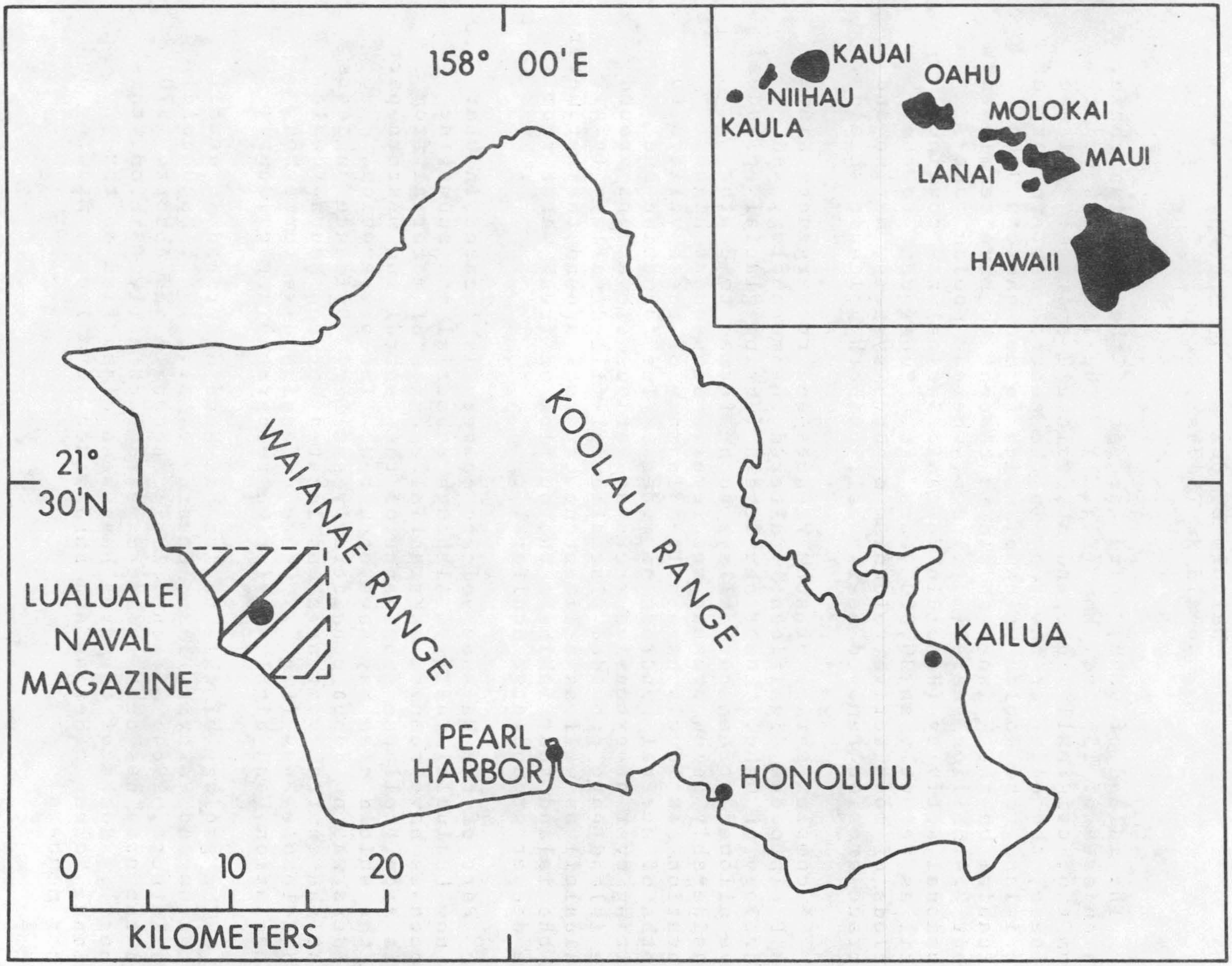


Fig. 1. Map of Oahu, showing area of investigation.

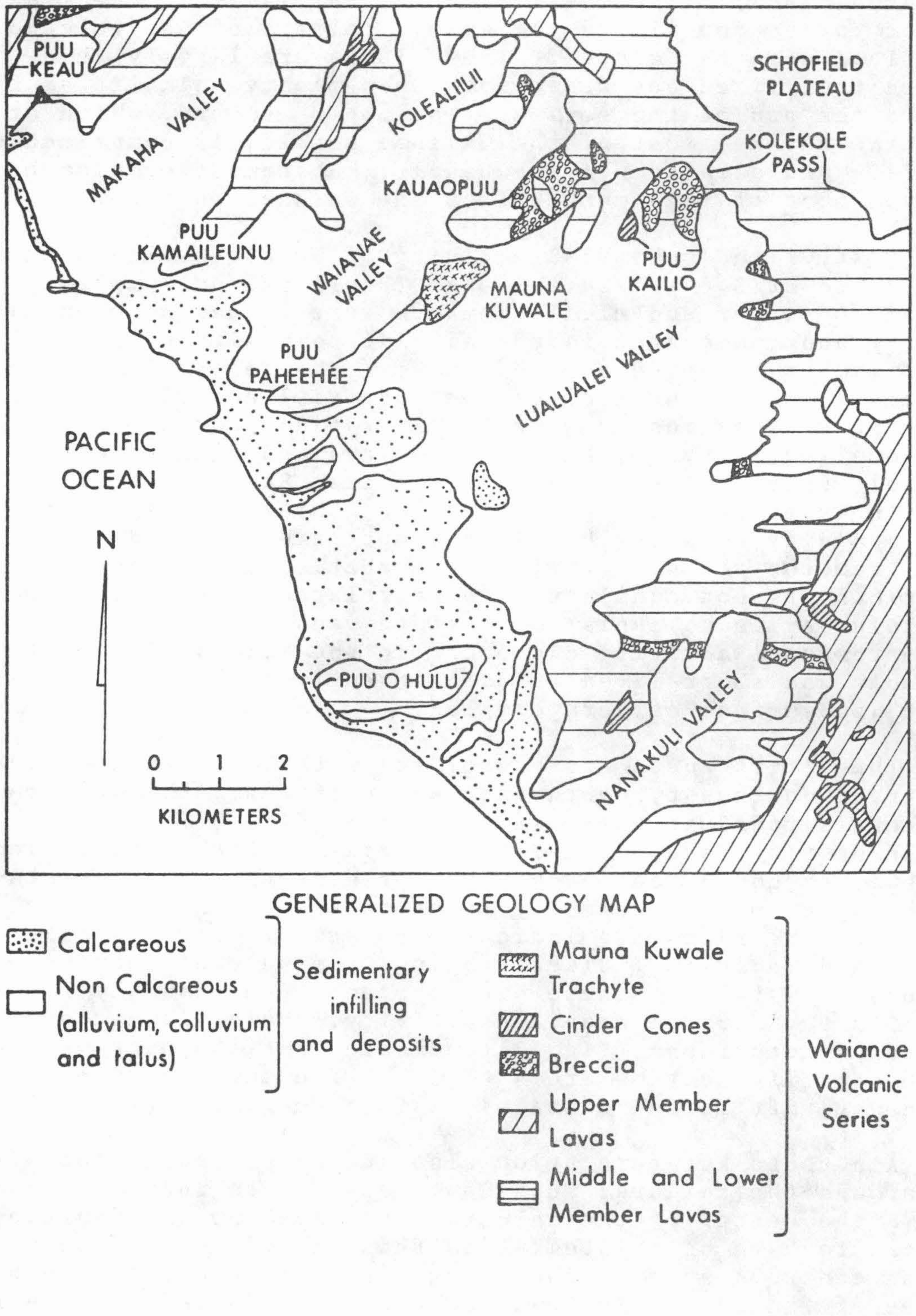


Fig. 2. General geology of the area around Lualualei Valley (after Stearns et al., 1940).

The lower member formed the mass of the volcano and is comprised of thin-bedded tholeiitic lavas and pyroclastics (Stearns, 1967). The massive horizontal lavas of the middle member formed and filled the summit caldera of the volcano and flows down the slopes. These lavas are largely thin-bedded tholeiites but grade into more massive alkalic aa flows toward the end of the series. The upper members, which at one time covered most of the Waianae shield, is comprised of hawaiite and alkalic olivine basalt; subsequent erosion has removed most of this member from the Waianae surface.

Most of the subaerial activity of Waianae volcano has been dated at 3.6 to 2.4 m.y. ago (Doell and Dalrymple, 1973); the lower and middle members were formed penecontemporaneously and the change to the alkalic composition of the upper member occurred over 0.2 m.y. (McDougall, 1964). The relatively short duration of the subaerial activity suggests that rates of extrusion were fairly rapid. Local post-erosional activity may have formed lava and cinder near Kolekole Pass (Kolekole Volcanic Series; Stearns et al., 1940); however, recent mapping (Sinton, this report) has shown this activity to be of hawaiite composition and indistinguishable from the rocks of the upper member. Consequently, these eruptions are not considered to be related to the Pleistocene Honolulu Series volcanism of eastern Oahu. If such post-erosional activity did occur in the Waianae Range it probably was short-lived and consequently added little heat to the subsurface caldera complex.

Three rift zones are associated with the Waianae volcano and trend northwest, southeast, and northeast; the caldera complex is found at their intersection (Fig. 3). The southeast rift is evidenced by a series of later stage cinder and spatter cones that probably represent the latest vents of the upper member activity (Stearns et al., 1940). The traces of the rifts are indicated by steeply dipping dike swarms and individual dikes ranging from several centimeters to about 2 m thick. These dike systems were probably feeder conduits for surface eruptive activity. Major lineations from air photographs (Fig. 3) indicate that the northwest and southeast rift systems are 4 to 5 km wide and the minor northeast rift is approximately 2 to 3 km wide.

Air photo interpretation also indicates fracturing within and around the caldera; subsidence appears to increase inward toward the center of the caldera. Vertical normal faulting appears to have been integral in this subsidence and in places controls some of the topographic features; a higher degree of fracturing is found around the inferred caldera rim and along the major rift systems. In addition, the coastline

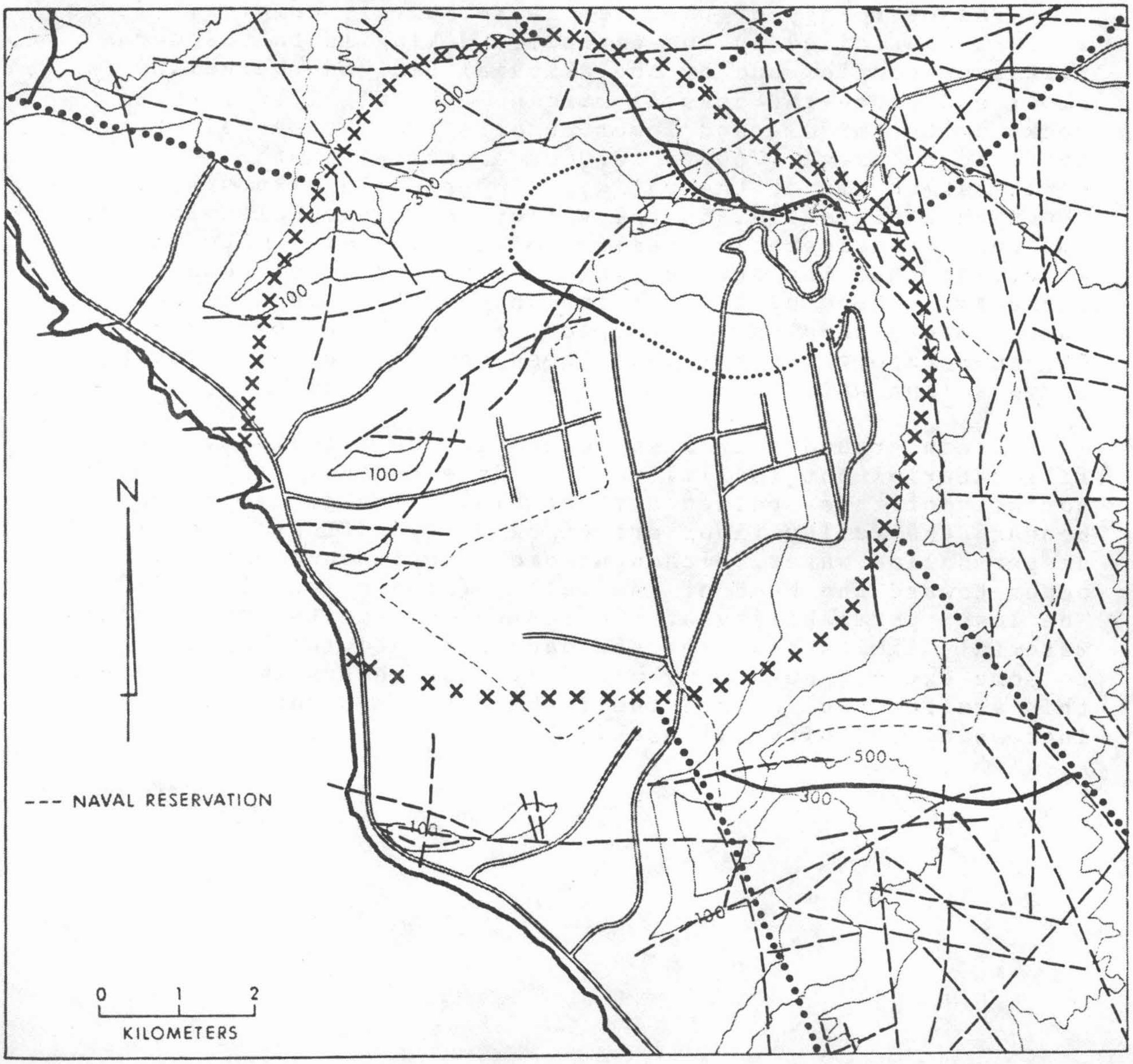


Fig. 3. Structural features of the Lualualei Valley area. Air photo lineations are shown by broken lines; faults mapped by Stearns et al. (1940) by unbroken lines; crosses indicate the inferred outline of the eroded caldera; dots outline the main eruptive zone; closed circles outline the indicated extent and trend of the rift zones. The 100-, 300-, and 500-m contours are shown.

also appears to be, to some degree, fault-controlled and air photographs suggest that the seaward side may be slightly downthrown.

Hydrogeology

The hydrology of the area is relatively complex. It is in part controlled by the extensive diking in the caldera-rift zone complex and by the alluvial fill in the valley floor and along the coastal margin. The highly fractured rocks of the middle and lower members are a reservoir for meteoric recharge (760 to 1020 mm annually) in the northeastern rim of the valley. Impermeable dike systems at the higher elevations in the valley and above Kolekole Pass impound a considerable fraction of the incoming meteoric water, so that the net outflow is somewhat lower than the recharge. These high-level impounded waters tend to be compartmentalized and do not conform to the classical Ghyben-Herzberg model (i.e., these waters are not floating above saline water).

Fresh groundwater also occurs in the alluvial valley fill material but is limited in volume because of the lower porosity of this sedimentary material. The groundwaters beneath the valley floor are of basal-type floating on deeper saline water, although some dike impoundment may occur toward the head of the valley (Stearns et al., 1940). The lower permeability of the coastal sediments and coralline material limits seawater encroachment into the basal lens to some extent, but heavy withdrawal of several wells within this aquifer have caused their abandonment because of increasing salinity (Takasaki, 1971).

DETAILED GEOLOGIC MAPPING

John M. Sinton

Introduction and Objectives

Background

Previous geologic mapping in and around Lualualei Valley, Oahu was undertaken by Stearns as part of a survey of the geology and groundwater of the island of Oahu (Stearns and Vaksvik, 1935; Stearns, 1939). Except for minor field checking by Macdonald (1940), Stearns' mapping has stood as the definitive field-based work in this region to the present. This earlier work defined three members in the Waianae Volcanic Series; the distinctions between individual members were largely based on field orientation. These members were defined as follows (Stearns and Vaksvik, 1935):

> A lower member is comprised of mainly olivine-rich basalts; these lava flows generally dip away from Puu Kailio (Fig. 4) at angles of 10 to 20°.
>
> The middle member consists of olivine and plagioclase-rich flows, generally with sub-horizontal dips. The middle member overlies the lower member with angular unconformity.
>
> An upper member unconformably overlies the middle member; the contact is commonly marked by a reddened soil horizon. Upper member flows consist mainly of feldspar-rich alkalic differentiates.

The above work, along with subsequent studies by Stearns and Macdonald (e.g., 1942), allowed those authors to formulate a four-stage generalized model for Hawaiian volcanism as follows (see Macdonald and Abbott, 1970):

1. A shield-building stage is dominated by tholeiitic basaltic volcanism. This stage probably constitutes 95% of the volume of most Hawaiian volcanoes.

2. Most Hawaiian volcanoes apparently undergo partial collapse near the summit regions late in the shield-building stage. This collapse gives rise to caldera structures. Locally it is possible to distinguish precaldera or extra-caldera flows from post- or intra-caldera flows. Such flows were respectively considered by Stearns to be represented by the lower and middle members of the Waianae Volcanic Series.

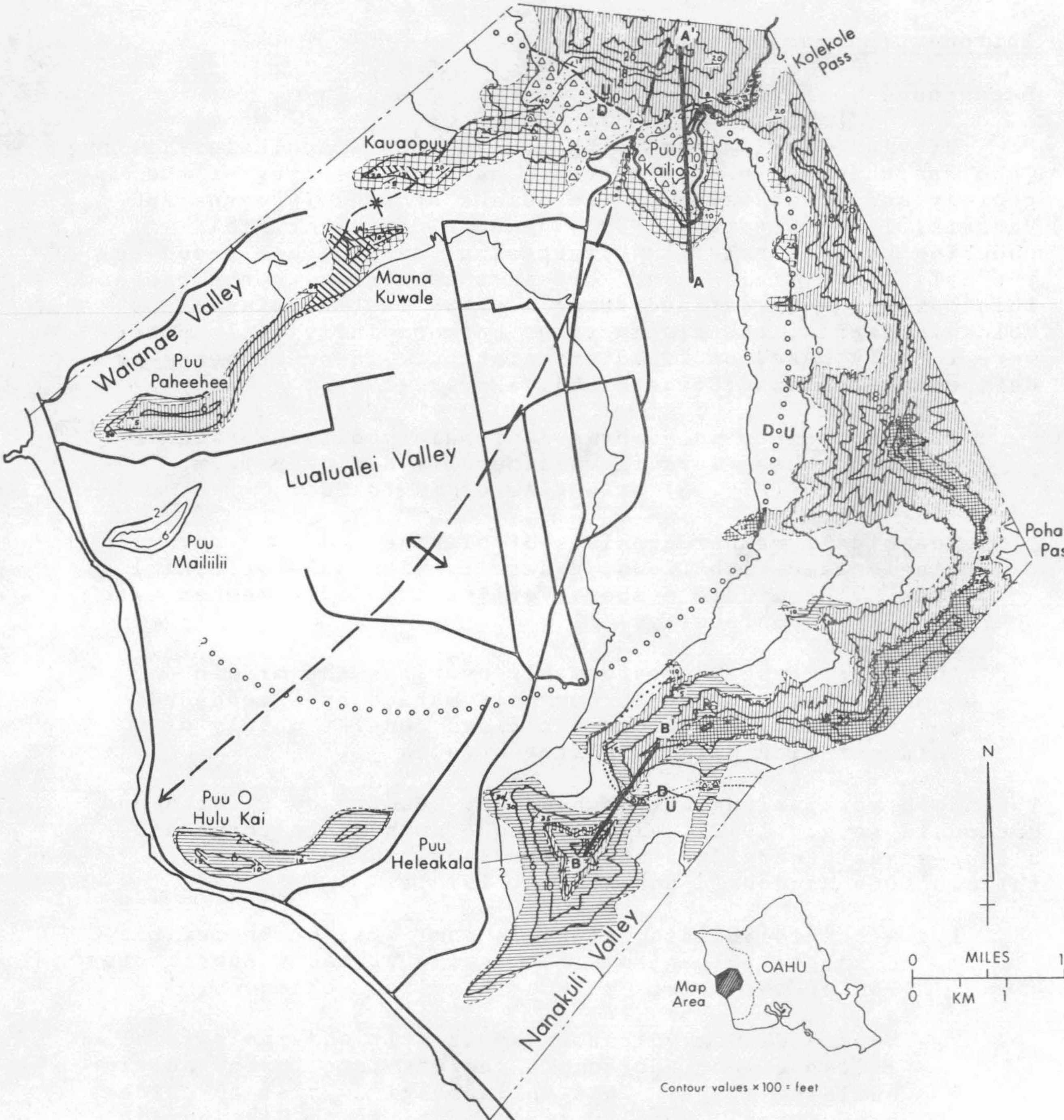
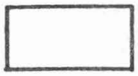
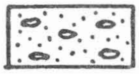


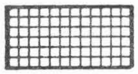
Fig. 4. Detailed geology of the Lualualei Valley area.

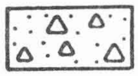
LEGEND

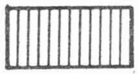
Lithologies


unpatterned areas include alluvial and colluvial sediments, marine sediments and unmapped basalts (Puu Mailiilii)

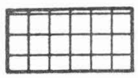

Kolekole Pass Conglomerate - deeply weathered, poorly-bedded volcanigenic conglomerate/breccia, devoid of dikes and probably post-volcanic in origin


hawaiite - massive thick-bedded flows of hawaiite, locally with olivine microphenocrysts


polymict vent and talus breccias, cut by dikes at Puu Kailio


plagioclase-phyric basalt, locally with olivine, hypersthene and/or augite phenocrysts; pahoehoe and aa lava flows


hornblende ± biotite ± hypersthene - phyric glassy rhyodacite; contains gabbroic and peridotitic xenoliths at Mauna Kuwale


pyroxene basalts, mainly sparsely phyric augite - hypersthene ± olivine ± plagioclase pahoehoe and aa basaltic lava flows


olivine - phyric basalts ± hypersthene ± plagioclase; mainly pahoehoe with minor aa lava flows

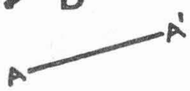
Symbols

strike and dip of flow planes in lava flows, bedding in breccias


syncline


anticline showing direction(s) of plunge

faults, dotted where covered



lines of cross-sections (see text)

Geology by John M. Sinton, 1978

Fig. 4. (continued)

3. Alkalic volcanism produces a thin cap on more advanced Hawaiian volcanoes. The alkalic flows may show a wide range of lithologies but generally overlie the tholeiitic shield-building and caldera-fill lavas with a marked discontinuity. In some cases, (e.g. East Maui, Stearns and Macdonald, 1942) tholeiitic and alkalic flows may be interbedded. The upper member of the Waianae Volcanic Series represents stage 3 alkalic volcanism.

4. Following a period of well-developed erosion on several islands, volcanism briefly resumes with the eruption of highly silica undersaturated basanites and/or nephelinites. Such post-erosional volcanism is represented on Oahu by the Honolulu Volcanic Series (Stearns and Vaksvik, 1935) but is apparently restricted to areas outside the limits of the Waianae volcano.

This generalized model of Hawaiian volcanism has gained wide acceptance and has come to be regarded as a model for oceanic island formation and evolution.

Geochronologic studies of Waianae volcanic rocks (McDougall, 1964; Funkhouser et al, 1968; Doell and Dalrymple, 1973) indicate that the subaerial eruptions took place from about 2.4 to 3.6 m.y. ago. These authors also found that there is no systematic age variation between the lower and middle members; both members accumulated about 3.0 to 3.6 m.y. before present (B.P.). The upper member formed 3.0 to 2.4 m.y.B.P. Any unconformity between the upper member and the lower or middle member is not discernible by geochronology. Thus it appears that the lower and middle members of the Waianae Volcanic Series, as defined by Stearns and Vaksvik (1935) and utilized by Macdonald (e.g. 1940, 1968; Macdonald and Katsura, 1964; Macdonald and Abbott, 1970) do not have time-stratigraphic significance. It was therefore necessary to re-map this area in order to better define age relationships, as well as structural effects, that might be important in the present study.

Current work: method and objectives

The prime objective of the current work was to investigate structual or petrological controls, or both, that might affect geothermal potential in the Lualualei region. In order to determine structural features, however, it is necessary to first define the lithologic stratigraphy. In contrast to the member mapping of Stearns, I have mapped individual lithologies in order to define the stratigraphic relationships within the volcano. The results of this mapping are presented in Figure 4. It is clear that individual lithologies also do not have regional time-stratigraphic significance. Individual lithologic sections, along with structural criteria, however, do help define the evolution of the volcano in terms of the rock types produced. Since individual lava flows have restricted areal extent, lithologic sections are not expected to be similar in different areas, even over the same time interval; however, the present mapping shows that certain characteristics can be ascribed to certain evolutionary stages of the volcano.

Lithologic Units

Olivine-phyric basalts. The oldest units mapped in the area consist mainly of tholeiitic basalts with olivine phenocrysts. Such olivine-phyric basalts occur at Puu O Hulu Kai, Puu Heleakala, Puu Paheehee and interbedded with other lithologies between Puu Heleakala and Pohakea Pass (Fig. 4). This lithology is defined by rocks where olivine is the dominant phenocryst phase; plagioclase, augite and/or hypersthene may locally form less abundant phenocrysts. Interbedded with the olivine-phyric basalts are thin flows of other lithologies, too thin to show in Figure 4.

At Puu O Hulu Kai, olivine-phyric basalts dominate the 200-m-thick section. In most of this section, olivine is the only phenocryst phase and locally constitutes 30% of the rock. Some rocks contain subsidiary plagioclase and augite or hypersthene phenocrysts or both. Thin interbeds of plagioclase-rich basalts locally occur. One flow contains phenocrysts of olivine, plagioclase, and augite in sub-equal proportions with lesser hypersthene. Plagioclase-free olivine basalts at Puu Paheehee contain minor augite and hypersthene phenocrysts.

The section at Puu Heleakala is more diverse. Again, olivine-phyric lavas dominate the section and most of these are plagioclase-free rocks. Hypersthene is an abundant phenocryst phase in some samples. One interbed of olivine-free, plagioclase-augite-phyric lava occurs in the lower part of the section but is too thin to be shown in Figure 4.

Pyroxene basalts. Pyroxene-rich basalts are exposed below rhyodacite at Mauna Kuwale and at Kauaopuu, below breccia at Puu Kailio and west of the fault line south of Kolekole Pass (Fig. 4). These rocks tend to be sparsely phyric, but porphyritic rocks of this unit all contain significant amounts of the pyroxene minerals augite and/or hypersthene. Aphyric lavas are locally abundant, particularly along the Kolekole Pass road.

Pyroxene basalts, exposed below rhyodacite at Mauna Kuwale and at Kauaopuu, range from aphyric to hypersthene-augite-olivine-phyric to olivine-free, hypersthene-augite-plagioclase-phyric variants. Lavas exposed below breccia at Puu Kailio are sparsely phyric augite-plagioclase ± olivine basalts. They are notably fine grained and most samples contain interstitial glass. A sample from 1.5-km southeast of Puu Kailio contains small augite and hypersthene grains as the only phenocrysts.

Plagioclase-phyric basalts. Plagioclase-phyric basalt is the most abundant rock type encountered in this study. It is also petrographically quite diverse. The distribution of plagioclase-phyric basalts is shown in Figure 4. In this lithology, the phenocryst assemblage is dominated by plagioclase feldspar, generally of composition An 55-65. Accessory phases are quite variable; however, the second most abundant phenocryst is generally olivine with lesser augite, hypersthene and/or pigeonite. Locally, rocks mapped as plagioclase-phyric basalt contain plagioclase, olivine, and pyroxene in sub-equal proportions. Such three-phenocryst basalts are common at Puu Paheehee, both sides of Kolekole Pass and interbedded with olivine basalts between Puu Heleakala and Pohakea Pass.

Plagioclase locally attains phenocryst size up to 4 cm in length and accounts for 40 to 50% of some rocks. Highly plagioclase-phyric lavas are exposed above rhyodacite at Mauna Kuwale, at Puu Paheehee, southeast of Kolekole Pass, and at Pohakea Pass. At Pohakea Pass, plagioclase-phyric lavas may be mildly alkalic. At this locality, hawaiite overlies weathered plagioclase-phyric lavas, separated by several centimeters of red ashy soil. The lower plagioclase-phyric lava contains microphenocrysts of olivine and groundmass andesine and alkali feldspar. This groundmass mineralogy may indicate that the upper plagioclase-phyric lavas of the Waianae Volcano are transitional to alkalic hawaiites. Where mapped, the hawaiites exclusively overlie plagioclase-phyric lavas.

Rhyodacite. A hornblende ± biotite ± hypersthene, glassy rhyodacite occurs at Mauna Kuwale and at Kauaopuu. This lithology is about 100 m thick at Mauna Kuwale where it apparently consists of a single flow. It locally contains small inclusions of dunite, wehrlite, and gabbro, and discrete rounded crystals of augite. Near the top of the unit, tuffaceous inclusions are also abundant, and this flow may have been associated with a partly explosive eruption.

Hawaiites. Alkalic cap lavas occur as hawaiites, mainly along the ridge running from Kolekole Pass, south to Pohakea Pass and then southwest toward Puu Heleakala (Fig. 4). In addition, hawaiites occur 2.5 km west of Pohakea Pass. Hawaiites in this area are not strongly porphyritic; plagioclase, olivine, and rare augite locally form microphenocrysts. Na-plagioclase, augite, oxides and alkali feldspar comprise the groundmass.

Breccias. A variety are present in the area. These include monolithic aa flow breccias that have not been distinguished from the other lithologic units that characterize the flows. Polymict breccias occur at several localities in the area however and are important stratigraphic horizons. Well-bedded polymict breccias are exposed at Puu Kailio and on the next ridge to the west (Fig. 4). These breccia beds have dips up to 40° and are mainly composed of poorly sorted talus debris including clasts of several flow and dike lithologies. Breccias at Puu Kailio also include some ash and may be partly vent breccias. The Puu Kailio breccia beds are cut by numerous dikes of several lithologic types. Polymict breccias also occur in small outcrops west and southwest of Pohakea Pass, in the saddle north of Puu Heleakala, and cut through the ridge that projects south into Nanakuli Valley (Fig. 4). These breccias appear to have accumulated along scarps and therefore are important structural markers (see Structure).

Kolekole Pass conglomerate. A deeply weathered volcanigenic conglomerate fills the saddle at Kolekole Pass. The fine silt matrix includes subangular to sub-rounded clasts from about 10 cm up to several meters of volcanic fragments. These fragments show marked spheroidal weathering. Compared to the Puu Kailio breccia, this unit is poorly bedded, probably quite thin and not cut by dikes. It also has more rounded clasts and is more deeply weathered. This unit may be a mudflow deposit. One thin hawaiite flow overlies this unit, just north of Kolekole Pass.

Structure

Unconformities. Several important unconformities provide evidence relating to the eruptive history of the volcano. Evidence for breaks in the eruptive activity are rare in the older olivine basalts of Puu O Hulu Kai and of Puu Heleakala and these flows probably accumulated fairly rapidly. Thin reddened soil horizons are locally present at Puu Paheehee and north of the saddle north of Puu Heleakala. Apparently, middle stage post-caldera eruptions were somewhat less continuous than older eruptions.

The tops of the pyroxene basalt flows that underlie breccia at Puu Kailio are notably weathered and probably indicate an important period of quiescence during accumulation of the lower beds of breccias.

A red soil horizon up to 1 meter thick underlies hawaiites at Pohakea Pass at Kolekole Pass, and also on the ridge, 2 km northeast of Puu Heleakala. This horizon indicates a significant period of relative inactivity before the onset of differentiated alkalic volcanism in the Waianae volcano.

Folds. Hawaiian volcanoes are not folded in the sense of having undergone major deformational folding; however, shield volcanoes have the form of constructional anticlines. In addition, small synforms or antiforms can commonly be found in Hawaiian volcanoes. These are mainly constructional features where lava has flowed over uneven topography. Some may form from slight post-depositional warping as the volcanic edifice grows and deforms.

The orientation of lava beds in and around Lualualei Valley defines a large dome or doubly plunging anticline (Fig. 4). This dome reflects the original shield volcano structure, with lava flows dipping (flowing) away from the central axis. The orientation of lava flows on the ridges indicates that the dome axis runs approximately through Puu Kailio (Fig. 4). More important than the orientation of this feature is its age. Lava flows underlying breccia at Puu Kailio and the breccias themselves do not show attitudes reflecting this structure. Indeed, their orientations were gained despite the development of the domal structure of the volcano, and probably formed in a caldera.

A small syncline is present along Mauna Kuwale and Kauaopuu ridges (Fig. 4). It probably is constructional in origin, and reflects flow of lavas over a topographic trough.

Faults. Two important faults are designated in Figure 4, both probably normal faults produced during the collapse or caldera stage of the volcano. A large fault, partly buried by breccia between Puu Kailio and Kolekole Pass, marks the boundary between plagioclase-phyric basalts and breccia or pyroxene basalts. Breccias in the vicinity of Puu Kailio apparently accumulated at the base of the south-facing scarp of this fault (Fig. 5).

Another fault cuts the saddle north of Puu Heleakala. Here breccias accumulated at the base of a northeast-facing scarp; subsequent flows from the north ponded against these breccias (Fig. 5).

These faults and talus breccias provide important evidence for the morphology and structural control of the evolving Waianae volcano. Lava flows on the downthrown side of the Kailio fault have shallow dips and generally do not show the domal structure of the beds outside the fault. In addition, the fault strike largely parallels the strikes of flows on the ridges around Lualualei Valley. Such data are strong evidence that this major fault marks the boundary of a large depression centered along the domal axis of the volcano; hence the fault is interpreted as a caldera boundary. Structural relations near to and around this caldera are analogous to those of the active calderas of Mokuaweoweo (Mauna Loa) and Kilauea. The maximum dimension of the Waianae caldera, as presently mapped, is about 7 km, or just slightly larger than Kilauea or Mokuaweoweo calderas. The Waianae caldera walls appear to be eroded away, or buried by younger flows to the southwest and west. The western boundary apparently lies outside the map area. Flows of Puu Paheehee are caldera-fill lavas.

The small depression boundary indicated by the saddle fault north of Puu Heleakala may be continuous with breccia exposed 2 km northeast of Puu Heleakala (Fig. 4), which is consistent with a small pit crater 1.5 to 2 km in diameter. This crater was filled by lavas flowing from the northeast and north. The northern walls have been buried and thus are not exposed. This depression apparently continues to the east, outside the present map area.

Vents and rifts. The breccia at Puu Kailio contains significant amounts of ash and is cut by a complex of dikes ranging in lithology from tholeiitic picrite to hawaiite. This region probably marks the site of pronounced post-caldera activity and is interpreted as a vent. Flows that must have once covered breccia in this region have been removed by

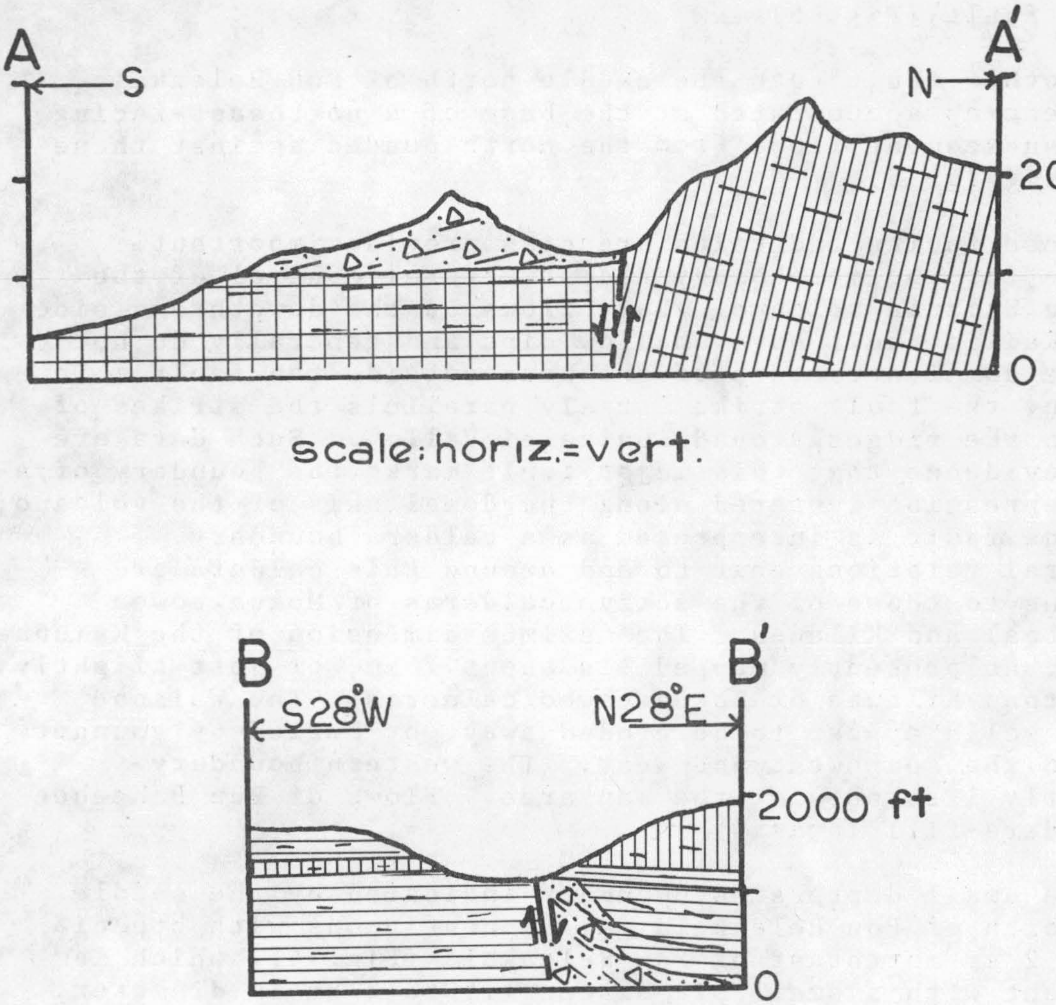


Fig. 5. Cross sections along A-A' and B-B' section lines as shown in Fig. 4. Lithologic patterns as in Fig. 4. Dashed lines indicate dips of beds. Arrows along faults indicate relative movements. Subsurface geology on section B-B' after Stearns and Vaksvik (1935).

erosion. This interpretation is consistent with that of Stearns and Vaksvik (1935), who suggested that Puu Kailio represents the center of Waianae volcanic activity.

By analogy with the active rift systems of Mauna Loa and Kilauea, rift zones should show an anticlinal structure cut by abundant dikes. Dikes cut many of the lithologies of the area but are especially abundant at Kolekole Pass, Puu Kailio, Mauna Kuwale and Puu O Hulu Kai. Dikes are significantly fewer along the Puu Heleakala - Pohakea Pass ridge; in fact, the present mapping has not documented well-defined rift zones in this area. The dike abundance at Puu Kailio and Puu O Hulu Kai is consistent with a zone roughly aligned along the dome axis (Fig. 4), and possibly with a second zone running approximately northwest through Mauna Kuwale.

Age Relations

The oldest rock units exposed in the area are olivine basalts of Puu O Hulu Kai and Puu Heleakala. These units correlate with the "lower member" of Stearns and Vaksvik (1935). The intra-caldera pyroxene basalt, olivine basalt, rhyodacite and plagioclase-phyric basalt flows are of intermediate age and may approximately correlate in time with crater-fill flows north of the Heleakala saddle. These in turn unconformably underlie summit and flank eruptive flows of hawaiite. One intra-caldera hawaiite flow occurs about 2 km west of Pohakea Pass. Its source was probably to the southwest, within the caldera. Plagioclase-phyric basaltic flows in the vicinity of Kolekole Pass are of unknown age. They are extra-caldera flows but are probably continuous with hawaiite north of Pohakea Pass, and therefore are likely to be fairly late-stage tholeiitic flank eruptions.

Discussion and Recommendations

A generalized geologic history of the area in and around Lualualei Valley can be drawn from the present and earlier studies. Of particular importance to the exploration for geothermal potential is an analysis of structural features delineated in this study. Identification of caldera-related structures and possible subsidiary pit craters provides evidence for zones of weakness in the volcanic edifice. These zones may have extended to depths great enough for deep-level water circulation. A comparison of the structural features identified in this section with geochemical anomalies shows that they can be generally correlated. Such correlation implies that the structural zones are still open to circulation and may be important zones for thermal upwelling.

Since these studies indicate that structures associated with 2- to 3-m.y.-old volcanism may be important for present-day geothermal activity, it is important to better define these structures. Recommendations for further field mapping include:

1. Extend mapping to the west and northwest in order to find the main caldera boundary in this region. Presumably it lies somewhere in Waianae Valley or near the ridge separating Waianae and Makaha Valleys.

2. Extend mapping east of Nanakuli Valley to trace the extension of the pit crater boundary identified north of Puu Heleakala.

3. Undertake a detailed study of dike populations and orientations. This study should give a good indication of structural features of the volcano, and possibly of how such features have evolved through time. Furthermore, this study should allow definition of Waianae rift zones; such zones have proven geothermal potential on the island of Hawaii.

Thin section support is needed for control on the lithologic mapping, as many lithologies are not macroscopically distinct. Whole-rock chemical analyses would provide even better control on the field mapping.

In summary, the principal results of this study indicate that:

1. Lithologic mapping is possible in an eroded Hawaiian volcano. This type of mapping makes no age-genetic assumptions, but allows for definition of lithologic stratigraphy that can, in turn, help define structural elements.

2. The ancient Waianae caldera boundary is exposed along the north and east walls of Lualualei Valley. Despite significant post-caldera volcanism, this fault boundary may be still open to deep-level circulation. Other similar features may also be important.

3. Rift zones are poorly delineated near Lualualei Valley. Such features may well be better developed away from the caldera region.

4. Further field studies are warranted in order to better define structural elements of the Waianae volcano, and to extend our lithological-structural data over a greater area.

MINERAL ASSEMBLAGES OF BASALT AND SOIL SAMPLES

Donald M. Helstern
Pow-foong Fan

A study of clay and rock mineral assemblages was undertaken in the Lualualei Valley to identify zones of hydrothermal alteration and mineralization and the probable temperature and pressure conditions under which such alteration may have taken place.

Sampling and Analysis Methods

Eight rock samples were collected around the rim of the Waianae caldera, and 23 soil samples were taken from the adjacent valleys (Fig. 6): 12 samples from Lualualei Valley, 5 from Waianae Valley, and 6 from Kolekole Pass. The soil samples were collected within 10-cm depth of the surface and from a diverse topographic selection. The rock specimens collected and analyzed were only those that showed a significant degree of weathering or hydrothermal alteration at each site.

All 31 samples were ground to a 4-µm clay size by a combination of mechanical and hand grinding techniques. The <4-µm clay sizes were obtained by decantation from a water medium. Bulk samples were then X-rayed with a Norelco diffractometer by using copper Kα radiation (run at 30 kv and 15 mA). Semiquantitative peak-height analysis was used to determine the relative abundance of minerals identified by major peaks. The results are presented in Tables 1, 2, and 3.

Results

The bulk rock samples consist mostly of feldspar, pyroxene, olivine with minor amounts of magnetite, hematite, quartz, calcite, kaolinite, montmorillonite, and gibbsite. Trace amounts of cristobalite and pyrite also were found in many rock samples. The mineral assemblages of the samples from Kolekole Pass and Waianae Valley were similar. Average compositions of each of the four main sample divisions are presented in Table 3 along with an average soil composition derived from a combination of Lualualei Valley, Waianae Valley, and Kolekole Pass soil samples. As evidenced by the mineral assemblages given, these samples represent unstable soil and rock types.

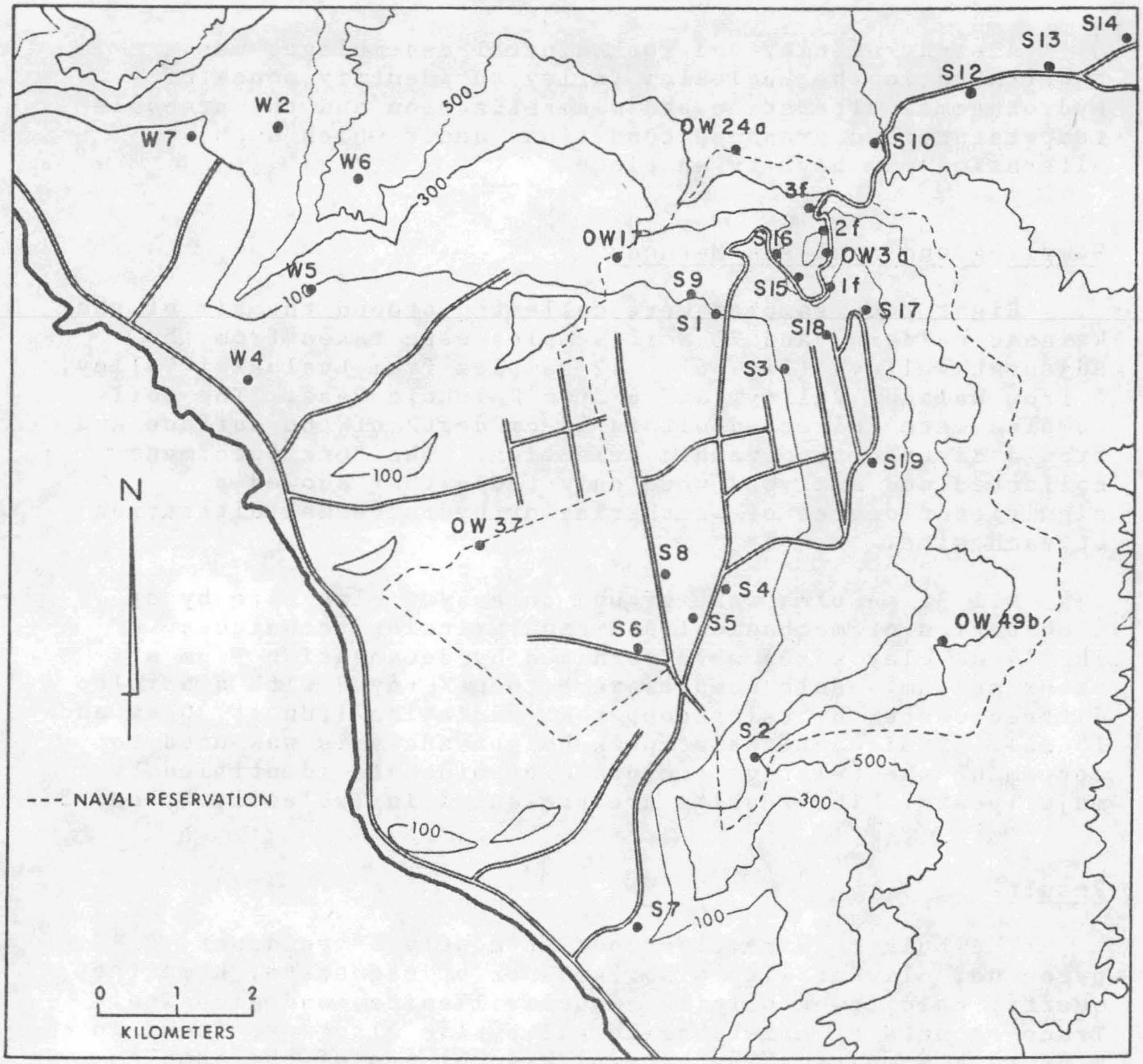


Fig. 6. Locations of samples studied for clay and rock mineralogy.

Table 1. Mineral composition of rock samples from Lualualei Valley, Oahu, Hawaii

Sample No.	Minerals (wt %)											
	Kaol.	Mont.	Plag.	Hema.	Mag.	Qtz.	Gibb.	Cal.	Pyrox.	Oliv.	Crist.	Pyrite
1F	2.8	5.3	40.7	5.0	9.5	2.8	1.0	2.5	23.8	6.8	TR	--
2F	3.0	13.5	47.1	2.7	8.7	7.7	0.9	1.2	7.5	7.7	--	TR
3F	3.4	7.7	39.6	5.0	10.8	2.6	0.8	0.7	23.6	5.8	TR	--
OW-3a	1.5	3.5	40.3	15.1	4.6	1.7	0.5	1.1	28.3	3.4	TR	--
OW-17	2.6	11.4	32.5	22.9	12.9	1.2	0.6	1.4	6.6	7.9	TR	--
OW-24a	3.6	15.9	34.8	7.7	6.8	3.0	0.9	1.2	20.7	5.4	TR	TR
OW-37	2.6	3.4	45.3	3.2	7.2	3.6	0.9	1.6	23.8	8.4	TR	TR
OW-49b	2.2	7.6	38.0	6.0	10.2	2.3	1.2	1.5	24.3	6.7	TR	TR

Table 2. Mineral composition of soil samples (<4 μm) from Lualualei Valley, Oahu, Hawaii

Sample No.	Minerals (wt %)								
	Kaol.	Mont.	Feld.	Hem.	Mag.	Qtz.	Gibb.	Cal.	Crist.
S-1	4.7	6.2	64.9	13.2	7.3	1.2	--	2.5	TR
S-2	3.2	7.8	78.2	6.5	2.5	0.8	0.8	0.6	TR
S-3	19.8	4.6	64.3	5.1	3.2	1.0	1.2	0.8	--
S-4	9.9	3.3	75.3	2.5	5.6	1.7	0.7	1.0	TR
S-5	6.7	6.4	68.3	7.4	6.3	2.8	0.8	1.3	TR
S-6	3.8	2.3	76.4	10.1	4.7	0.9	0.9	0.9	--
S-7	2.3	17.7	70.1	3.5	2.9	1.0	1.3	1.2	TR
S-8	9.1	8.7	51.9	11.6	11.0	2.6	1.8	3.3	--
S-9	4.8	19.1	52.3	13.0	5.2	2.5	2.0	1.1	TR
S-10	5.1	4.1	82.1	3.0	2.4	1.1	1.3	0.9	TR
S-12	4.3	2.9	76.2	9.5	4.0	1.2	0.7	1.2	TR
S-13	5.2	3.5	69.7	10.6	5.5	2.9	1.7	0.9	--
S-14	5.6	8.2	68.4	8.3	5.2	2.0	1.1	1.2	TR
S-15	3.0	23.7	57.1	6.6	5.5	1.3	1.5	1.3	--
S-16	6.3	21.9	34.5	9.3	14.1	4.5	3.2	6.2	TR
S-17	7.8	6.7	70.6	3.3	5.2	2.5	1.4	2.5	TR
S-18	9.4	12.6	56.6	5.8	8.8	3.1	2.0	1.7	TR
S-19	10.1	17.9	48.0	9.9	7.1	2.6	2.5	1.9	--
W-2	4.6	3.9	79.0	5.3	3.3	0.9	1.4	1.6	--
W-4	5.5	5.9	54.0	8.9	5.6	1.4	1.7	17.0	TR
W-5	5.8	2.6	78.6	5.8	5.5	1.7	--	--	--
W-6	9.8	5.2	66.5	8.2	6.6	2.4	1.3	--	TR
W-7	5.1	7.5	67.8	9.8	4.3	0.9	1.0	3.6	TR

S-10, 12, 13, 14--Northeast of Kolekole Pass
W--Waianae Valley

Table 3. Average mineral compositions of soil and rock samples

Sample Location	Minerals (wt %)									
	Kaol.	Mont.	Feld.	Hem.	Mag.	Qtz.	Gibb.	Cal.	Pyx.	Ol.
Lualualei Valley (soil)	7.2	11.4	62.0	7.7	6.4	2.0	1.4	1.9	--	--
Kolekole Pass (soil)	5.1	4.7	74.1	7.9	4.3	1.8	1.2	1.1	--	--
Waianae Valley (soil)	6.2	5.0	69.2	7.6	5.1	1.5	1.1	4.4	--	--
Average (soil)	6.2	7.2	68.4	7.7	5.3	1.8	1.2	2.5	--	--
Lualualei Valley (rock)	2.7	8.5	39.8	8.5	8.8	3.1	0.9	1.4	19.8	6.5

The mineral assemblages of the rock samples can be grouped according to three types: (1) Waianae basalt -- feldspar, olivine, pyroxene, and magnetite; (2) hydrothermal alteration products -- quartz, cristobalite, calcite, and montmorillonite; (3) weathering products -- kaolinite, montmorillonite, hematite, and gibbsite. The small range in degree of alteration can be seen in the rock samples as evidenced by the relative abundances of stable versus unstable minerals present. Rocks of the Waianae basalt series described in Figure 4 represent the parent material of the area and source for the soils. The four hydrothermal alteration products listed above were identified in varying amounts by X-ray analysis in all but one rock sample. Veinlets of calcite and montmorillonite were also observed (John M. Sinton, per. comm., 1978) under petrographic microscope studies in samples collected northwest of Kolekole Pass. The weathering products are those normally expected for the aforementioned parent material and environmental conditions typical of the area.

Minor trends and the distinction of lateral zones can be described from the observed mineralogical distribution of the area. In general, feldspar predominates in all of the soil samples. This abundance is possibly due to a slow weathering process caused by locally arid climatic conditions (mean annual rainfall 400 mm) yielding sparse vegetation, coupled with a fairly rapid rate of erosion of the surrounding range. The average feldspar percentages for Lualualei Valley samples are lower than those calculated for the adjacent areas; the amount of clay mineral, especially montmorillonite, is higher here than for either Waianae Valley or Kolekole Pass. Increasing concentrations of montmorillonite are found in the brownish soils in the vicinity of the dike-dissected structure of Puu Kailio; isolated concentrations are also found in lowland areas at the base of the mountain range. Local variations in clay concentrations can be attributed to the effects of both topographic and temperature conditions. The percentage of quartz in these samples is substantially higher than would be expected for basaltic parent material (Fig. 7); a noticeable increase in these concentrations is also observed within the inferred caldera boundary.

On the basis of the identification of the above mineral assemblages, the study area has been classified as being in the montmorillonite phase of hydrothermal alteration (Fan, 1978a, 1978b). The absence of zeolite minerals in the samples suggests classification of the area below the low temperature/low pressure zeolite facies. No great lateral variations of mineral assemblages exist to point to a facies change from one sample location to another (Fig. 8).

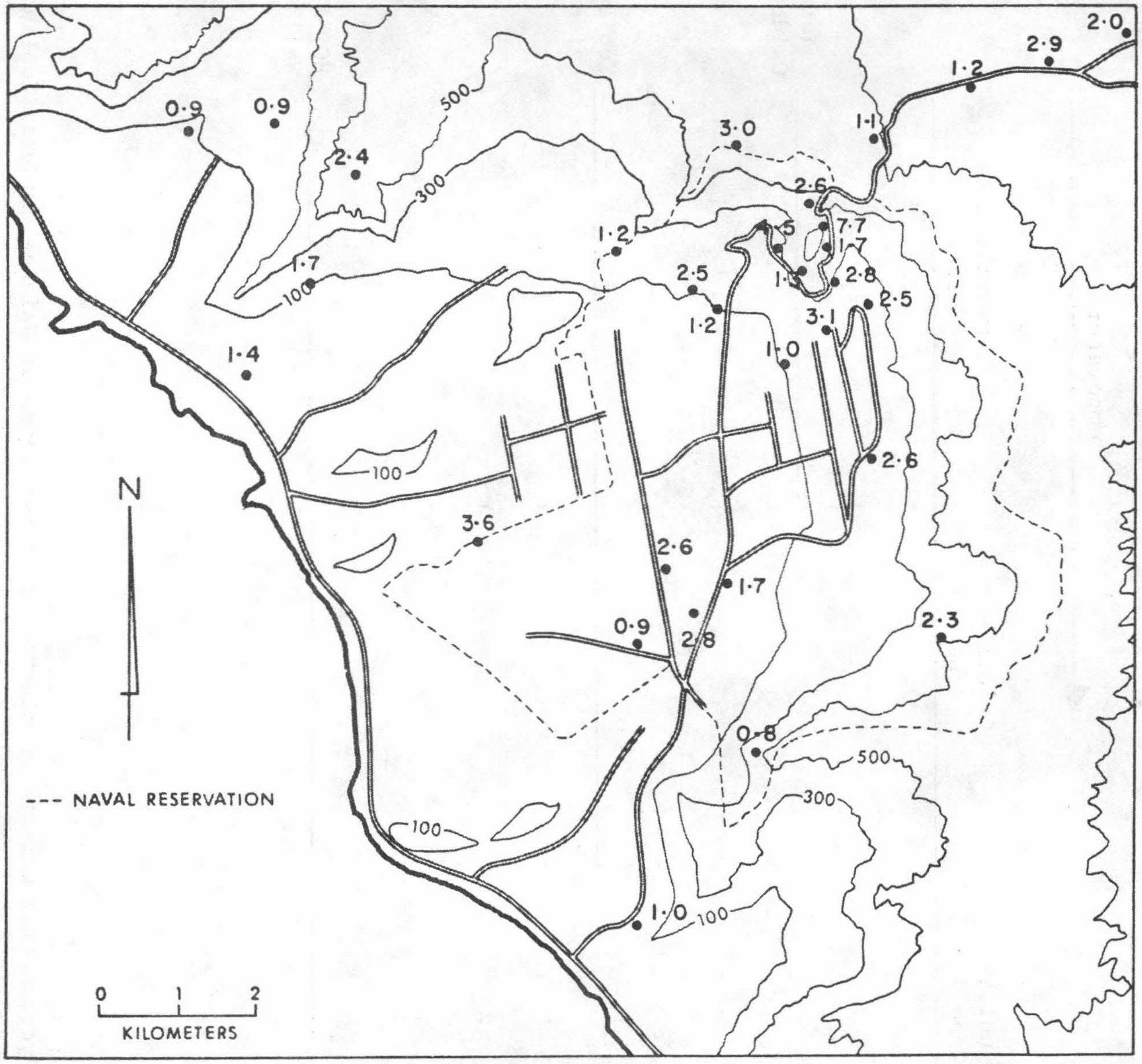


Fig. 7. Percentages of quartz in rock and soil samples.

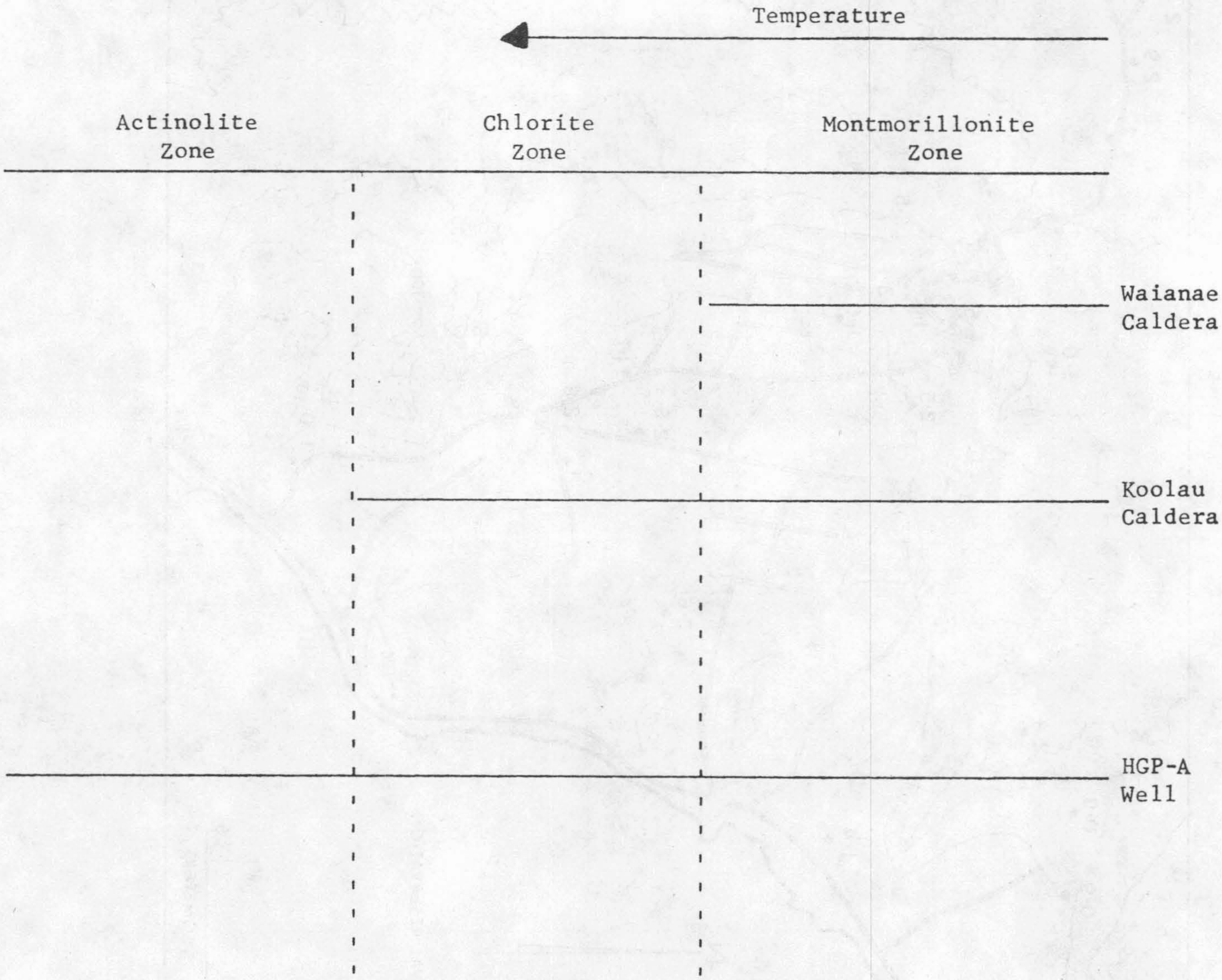


Fig. 8. Hydrothermal alteration mineral groupings found at Waianae caldera, Koolau caldera and in geothermal well HGP-A (island of Hawaii).

SUMMARY OF REGIONAL GEOPHYSICS

Malcolm E. Cox

Airborne Magnetics

A regional, total field magnetic survey was flown over Oahu at a mean altitude of about 3045 m (Malahoff and Woollard, 1965, 1966). Although the relatively high flight elevation of these surveys tended to emphasize the deeper structure (5- to 10- km depth) beneath the island, some near-surface information can be obtained from their data.

The magnetic contours over the Waianae shield (Fig. 9) show a curved, elongate dipolar anomaly (normally polarized), probably related to intruded dike systems in a crustal rift beneath the Waianae caldera. The magnetic anomalies are thought to arise from differences in magnetic susceptibility of mantle material intruded into zones of weakness in the overlying crust (Malahoff and Woollard, 1965). These authors use the inflection point between the elongate dipolar anomalies to indicate the trace of the primary rift zone (NW-SE); the anomalies have a peak-to-peak value of about 650 gammas (γ) with normal polarity. The inflection point at the dipole centers (at approximately 36,100 γ) indicates the approximate location of the main vent system. The primary vent zone is indicated to be centered between Kolekole Pass and Mauna Kuwale, and to have an average diameter of 9 km at a depth of 800 m and to extend to a depth of 5 km. The trend of the main rift complex is similar to that indicated by structural lineations.

Gravity Surveys

Onshore gravity measurements plotted as a Bouguer anomaly map (Strange et al, 1965) indicate a dense mass below and north of the central eroded caldera (Fig. 10). The highest gravity values are centered between Mauna Kuwale and Kolekole Pass, probably indicating a dense intrusive mass below this area. The peak value here, in excess of 310 mgal, is abnormally high -- 110 mgal greater than the regional value (Woollard, 1951). The location and outline of the gravity anomaly suggest that the mass causing it is within the intersection of the rift systems. The boundary of the rim of the eroded caldera is probably between the 290- and 300-mgal contours; some elongation of the contours to the northeast and northwest further substantiates the proposed trends of intrusive dike systems in the rift zones.

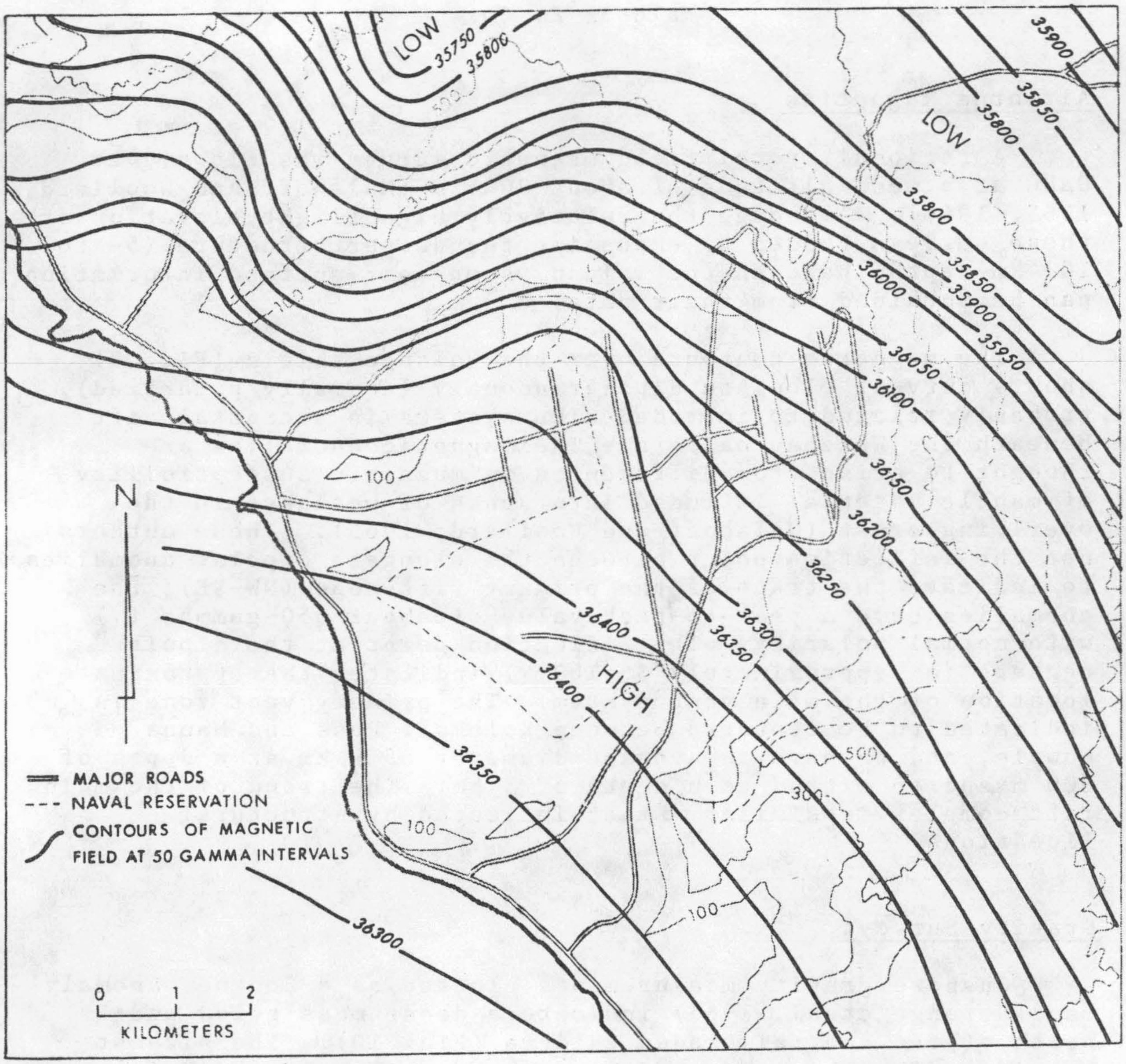


Fig. 9. Airborne total magnetic field contours at flight elevation of 3045 m. Normally polarized elongate dipolar anomalies approximately outline trace of NW-SE rift zones. Inflection point (≈36,100γ) between centers of anomalies indicates main zone of intrusion. (From Malahoff and Woollard, 1965.)

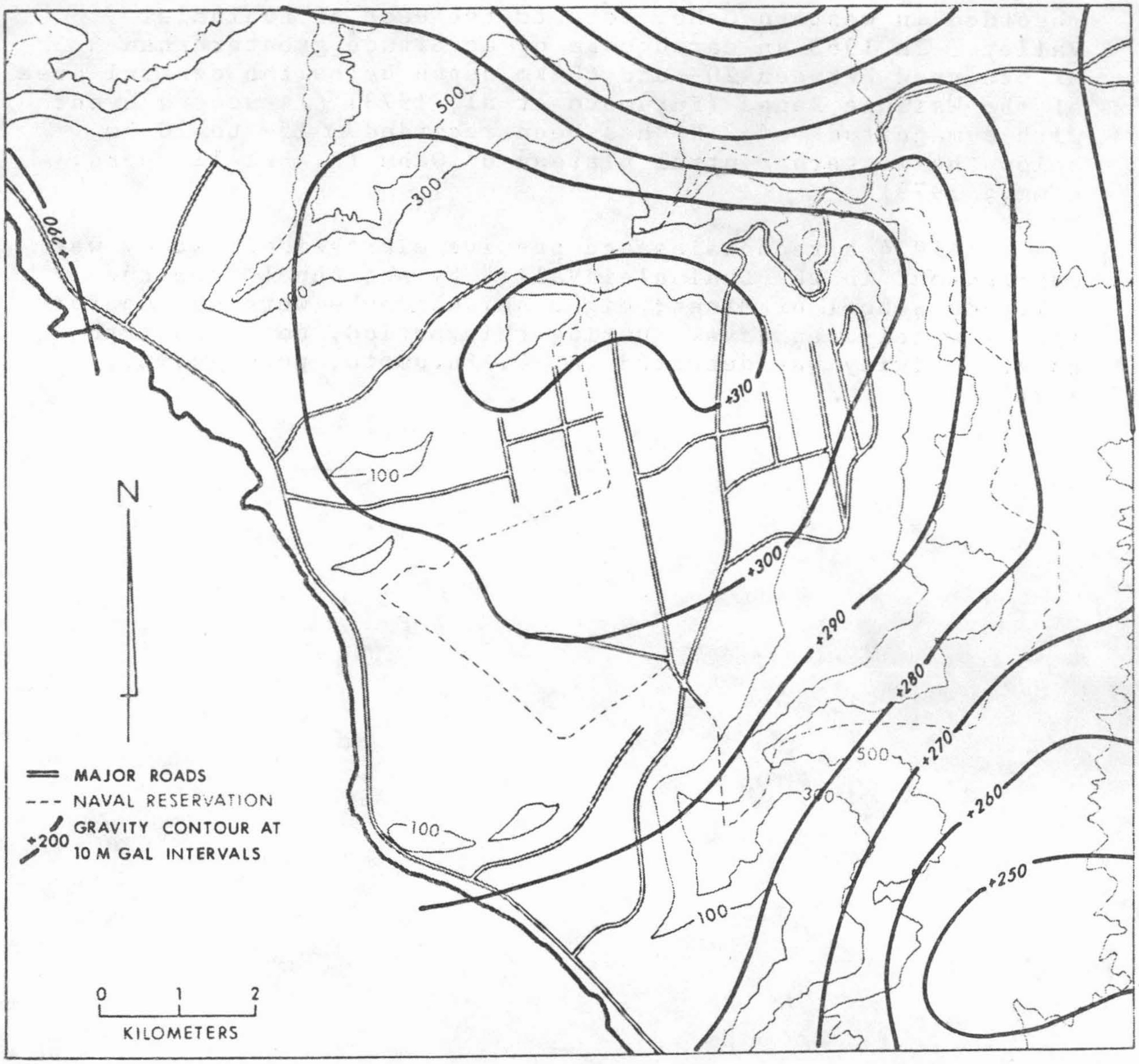


Fig. 10. Gravity Bouguer anomaly map. The gravity high indicates the central eruptive zone of the Waianae volcano. The rim of the volcano is inferred to occur between +290 and +300 contours. (From Woollard, 1965).

Seismic Surveys

Little data regarding natural seismic activity in the Waianae region are available. Two large events have been recorded in western Oahu, both to the east of Lualualei Valley. In 1963 an earthquake of magnitude greater than 3.5 $M\ell$ occurred between 20- and 60-km depth below the central area of the Waianae Range (Furumoto et al, 1973). A second event with a magnitude of 2 $M\ell$ has been recorded at 15- to 20-km below the western central plateau of Oahu (R. Estill, pers. comm., 1979).

In 1974 a reconnaissance passive microseismic study was carried out in the Lualualei Valley by personnel from the Colorado School of Mines; eight seismographs were set up for approximately ten days. During this period, no microearthquake activity was detected (A. S. Furumoto, pers. comm., 1978).

GEOELECTRIC SURVEYS

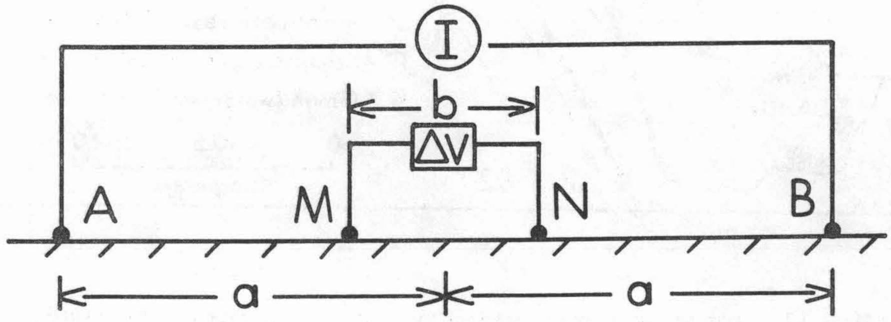
Mark D. Mattice
James P. Kauahikaua

Introduction

Tasci (1975) reported a limited survey of Lualualei Valley in which the rotating quadripole electrical resistivity method (Fig. 11) was used. In that survey several anomalies were observed, and he interpreted the electrically resistive region to the north as the effect of a resistive basement, possibly the volcanic plug of Waianae volcano. The elongated region of apparent resistivities lower than 35 ohm-m to the southwest was interpreted to be a conductive body at depth. Questions arising from this study prompted a second resistivity survey by HIG staff, using the Schlumberger sounding method, to obtain a better idea of the vertical resistivity variations within the valley. The Schlumberger sounding results together with the quadripole resistivity mapping results, the latter of which are sensitive to both vertical and lateral resistivity variations, can give a more complete picture, with emphasis on geothermal potential, of the geologic structure and hydrology of Lualualei Valley.

Methods and Equipment

Three Schlumberger soundings were completed near the northern and eastern edges of the valley floor (Fig. 11). The maximum AB/2 distance used was 762 m (2500 ft). In the Schlumberger array, two closely spaced potential electrodes are centered between two current electrodes, as shown below.



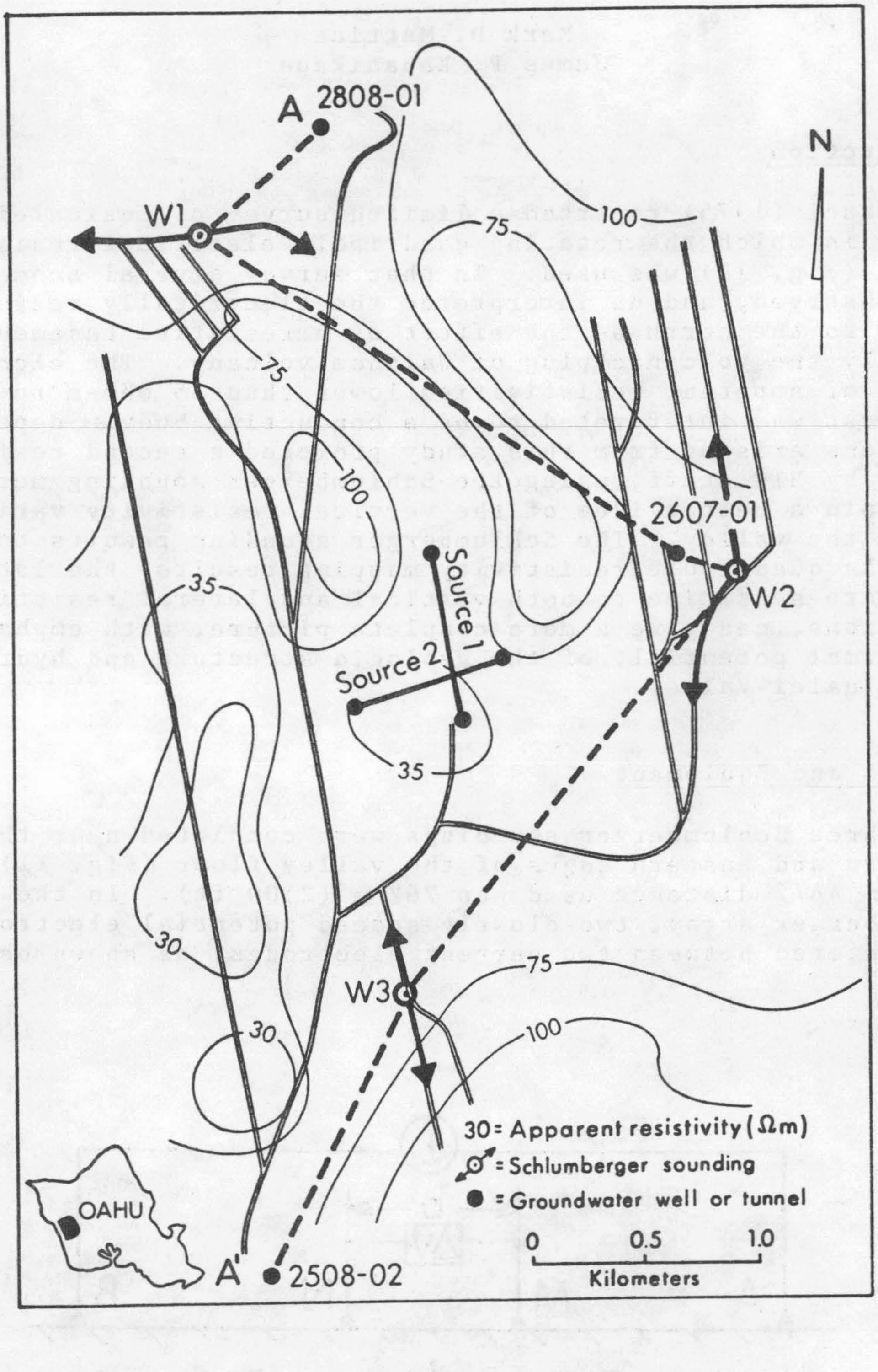


Fig. 11. Apparent resistivity map from rotating quadripole survey (Tasci, 1975) and location of Schlumberger soundings interpreted in this report. AA' is a cross section shown schematically in Fig. 13. This area is within the Lualualei Naval Reservation.

Apparent resistivity is given by:

$$\rho a = \frac{\Delta V \pi}{I} \left(\frac{a^2}{b} - \frac{b}{4}\right) \quad \text{[Keller and Frischknecht, 1966]}$$

where ΔV is the measured potential difference, I is the input current and a = AB/2. Depth of penetration for a homogeneous half space is approximately equal to one-half the maximum current electrode separation, AB/2.

A 1.5-kW portable generator was used for power supply and a Fluke 800A digital multimeter for potential difference measurements. A pair of nonpolarizing copper sulfate porous pots was used for potential electrodes and stainless steel rods for current electrodes. All connections were made through single-conductor insulated cable.

Apparent resistivities versus AB/2 were plotted bi-logarithmically in the field. First the sounding curves were interpreted by curve matching techiques with three-layer master curves (Compagnie Generale de Geophysique, 1955). The interpreted geoelectric sections were used as input for a computer inversion program (Anderson, 1979). Best-fit model parameters (in the least squares sense) and their standard errors are given as output.

Note that these types of electrical studies were not possible in the western part of Lualualei Valley because of cultural features such as grounded fences and the Naval communications ground antenna arrays.

Results and Interpretation

The Schlumberger sounding data, best-fit model curves, and interpreted resistivity sections are presented in Figure 12. Lualualei Valley subsurface structure inferred from these soundings is composed of many layers but can be simplified to four basic units (shown schematically in Figure 13). The surface unit is composed of a number of thin layers whose resistivities range from 2 to 339 ohm-m and whose total thickness does not exceed 40 meters. The second unit is one of high resistivity whose thickness cannot be uniquely resolved. The third unit is well resolved and has a resistivity of 20 to 28 ohm-m and a thickness of 136 to at least 471 meters. The bottom unit (absent in sounding W3 and questionably resolved in W2; Fig. 13) is highly resistive, for which only a minimum resistivity can be determined.

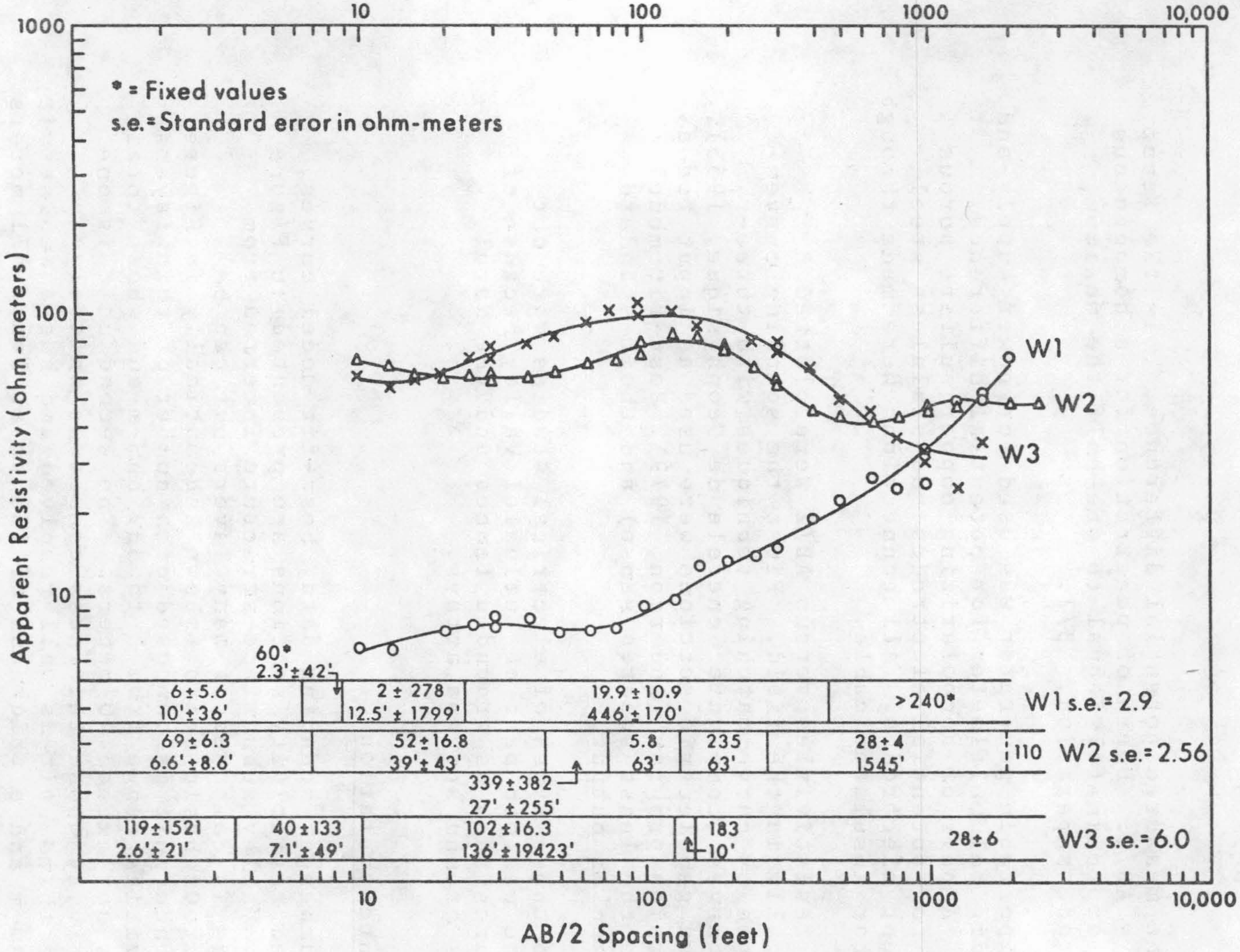


Fig. 12. Schlumberger sounding data for soundings W1, W2, and W3 in Lualualei Valley. Individual points are observed values: open circles for W1, open triangles for W2, and X's for W3. Solid vertical lines are the calculated values for the interpreted models summarized in bar form at the bottom of the figure. Each pair of numbers is the resistivity, in ohm-meters, and thickness, in feet, for each of the layers. Along with some parameters, errors determined by inversion are given. Those parameters without errors are poorly resolved. The dashed line in sounding W2 represents the minimum depth of the basement layer apparent in W1; however, removal of the resistive basement does not significantly increase the standard error.

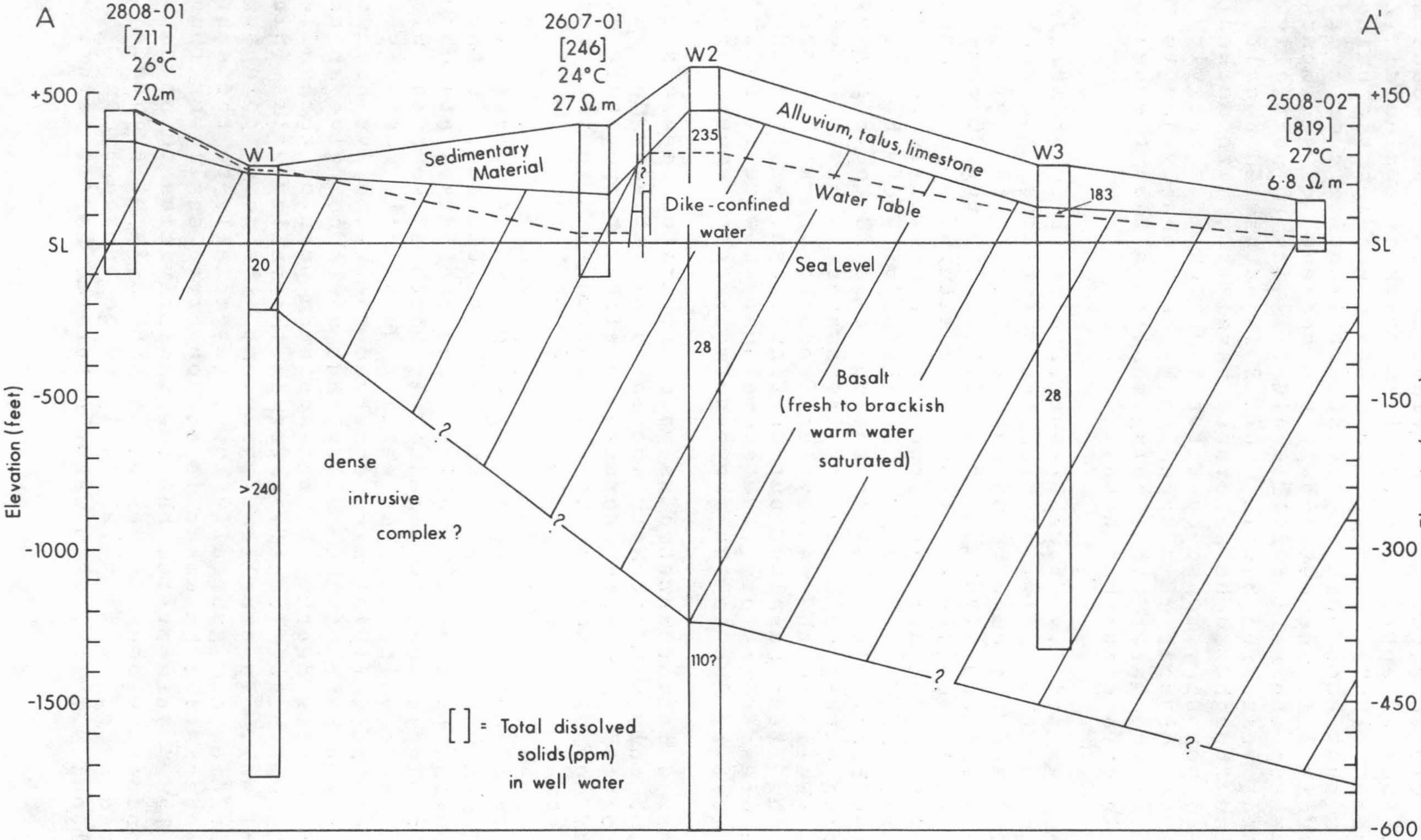


Fig. 13. Geoelectric cross section AA' parallel to inferred caldera rim (see Fig. 11). The elevation of the water table in sounding W2 is possibly the result of dike confinement.

Correlation of available groundwater well logs (U.S.G.S., 1979), geologic maps, and a previous Schlumberger sounding survey, located approximatley 11 km north of Lualualei (Zohdy and Jackson, 1969), with the four basic geoelectric units suggests that each unit is a distinct lithologic or hydrologic type. Unit 1 is unquestionably the sequence of sediments that make up the valley fill; unit 2 is dry to partially saturated, weathered basalt; unit 3 is saturated basalt; unit 4 is also thought to be saturated basalt but with markedly decreased porosity to account for its higher resistivity. The absence of unit 2 in sounding W1 is probably due to the surface of the water table being shallower than the sediment-basalt interface in that area.

The resistivity of water-saturated rock is primarily dependent on the resistivity of the porefluids, the rock porosity, and the amount and nature of weathering of the rock. Zohdy and Jackson (1969) concluded that 300 to 700 ohm-m are typical resistivities for freshwater saturated young basalts. The resistivities are much lower if the basalt is weathered or if the porewaters are warm. The resistivity of the water-saturated basalt (unit 3) in Lualualei is 20 to 28 ohm-m, suggesting either saltwater or freshwater in unweathered basalt. Wells in the valley tap fresh to brackish water, saturating fresh basalts, but at significantly elevated temperatures; therefore, the anomalously low resistivity of unit 3 must be due to the above-normal water temperatures.

Unit 4 is interpreted as water-saturated basalt similar to unit 3 only with greatly increased resistivity caused by low porosity. A marked decrease in either temperature or salinity may also account for the increase in resistivity at depth; however, this is geologically unlikely.

Unit 4 could represent a dike complex associated with the Waianae volcanic plug that is about 100m deep in the northernmost part of the valley. Abundant dikes are observed in the geologic section immediately north of sounding W1 (Sinton, this volume). The earlier quadripole resistivity survey be Tacsi (1975) also observed the resistive basement in the northern part of the valley, but would not give an accurate estimate of its depth. In the southern part of the valley, dikes become significantly rarer in the valley walls (Sinton, this volume). In excellent agreement, the quadripole apparent resistivities are generally lower (especially to the southwest) and the resistive basement is not observed shallower than 800m. Tasci interpreted the low resistivities to be caused by a conductive body at depth; on the basis of evidence presented here, it is more likely to be caused by an exceptionally thick, warm water saturated basalt layer.

Geothermal Assessment and Recommendations

A dense volcanic intrusive complex beneath Lualualei Valley, which was initially located by gravity and aeromagnetic surveys, has been identified as a high resistivity basement; it is shallowest toward the north, in the region of sounding W1.

This survey indicates that the basalt above this intrusive complex is saturated with warm, fresh to brackish water ranging in thickness from 136 to a minimum of 471 m. From temperature measurements in the three wells shown in Figures 11 and 13, water in the shallowest portion of this saturated zone is between 24°C and 27°C throughout the whole valley. The most probable source of heat is the buried volcanic plug. Further work should concentrate on the northern portion of Lualualei because the proposed source of heat is shallowest there.

GEOCHEMICAL SURVEYS

Malcolm E. Cox
Donald M. Thomas

Prior to the present studies, no geochemical surveys directed toward goethermal assessment have been conducted in Lualualei Valley. Our surveys have included several standard geothermal exploration techniques as well as some that are relatively new. In all cases, the techniques have been adapted to the unique geologic environment in Lualualei Valley.

Radon Emanometry

Introduction

Radon is a gaseous radioactive daughter product in the uranium decay series. Its two major alpha-emitting isotopes are ^{222}Rn with a 3.8-day half-life and ^{220}Rn with a 54.5-sec half-life. Radon is produced in soil and rock by naturally occurring concentrations of uranium- and thorium-derived radium. Radon anomalies in other localities have been found to be associated with volcanic eruptions and with increased seismic activity (Gasparini and Mantovani, 1978). Radon has also had limited use as a tracer to define hydrologic parameters within producing geothermal fields (Kruger et al, 1977).

Although uranium concentrations of the basaltic rocks of the survey area are low relative to concentrations in continental rocks, the relatively high permeability caused by the common fracturing of Hawaiian lavas allows for efficient transport to the ground surface of the radon that is produced. Radon surveys on the lower east rift of Kilauea volcano (Cox, in press) have proven successful in delineating zones of deep thermal activity and of subsurface geologic structure. Results indicate that thermally driven convection systems can significantly increase the flux of radon from shallow depths in the ground. The radon emanometry technique has also delineated zones of high fracture intensity with which thermal fluid reservoirs may be associated.

The field survey technique utilizes an alpha particle-sensitive film (Fleischer et al, 1972) fixed inside an inverted cup that is buried in the ground about 30 cm deep. The cups are spaced at intervals ranging from a few hundred meters to approximately 1 km. Each film is exposed to the ground gases for three to four weeks; the film is processed and the alpha track density in a specified area of the film is counted. The type of surface material can have a significant effect on the observed radon concentrations; thus corrections are made to the radon count rate observed in the field to remove the effects of radon emanation from soil.

Results

Figure 14 presents a plot of radon measurements at 26 locations in and around Lualualei Valley. Results and corrections to the field data are listed in Table 4.

The observed alpha counts (corrected for soil background) range from -8.0 to 458.1 x 10^{-2} tracks per square centimeter of film per hour ($T \cdot 10^{-2}/cm^2/hr$). Contouring of the corrected measurements delineates three important patterns:

1. Two zones of negative values (field counts lower than soil background), one roughly in the center of Lualualei Valley (central to the inferred caldera) and a smaller one to the south of the inferred caldera boundary;

2. An indication of an approximately circular, high-value positive zone surrounding the central negative area;

3. A consistently increasing trend to extremely high values to the northeast (on Schofield Plateau).

Our present interpretation of these data is that "outgassing" of some form is occurring around the rim of the Waianae caldera. There is currently no indication that this outward flux of vapor is volcanic gas or steam; it is likely to be ground gas (i.e., air) circulating through rock fractures. The question most important to the present study is whether or not the observed outgassing is thermally driven. Although we cannot unequivocally conclude that it is, data obtained from soil mercury surveys (presented below) indicate that this is the case.

The increased "outgassing" however, is occurring in zones with a high degree of fracturing, and it appears that this fracturing is associated with the rim of the caldera and the northeast rift zone. Further field surveys would be necessary to determine whether similar outgassing is occurring along the other rift systems.

The lower flux of radon in the central region of the caldera may be in part related to the greater thickness of sediment of the valley floor. A second possibility that

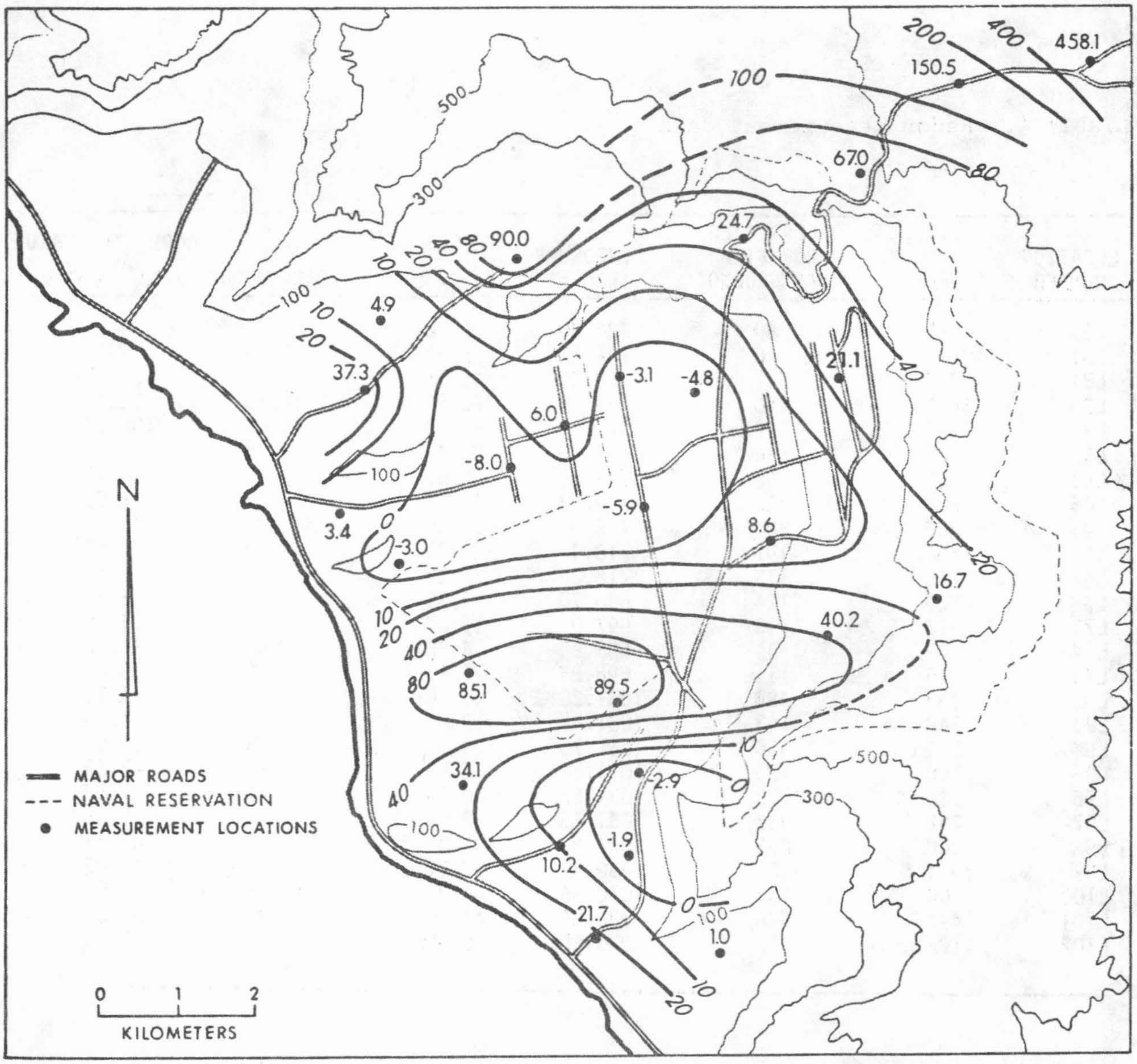


Fig. 14. Radon gas emanation contoured logarithmically. The units are $T \cdot 10^{-2}/cm^2/hr$. The broad pattern is of a negative zone central to the inferred caldera surrounded by positive zones of outgassing. The extremely high values on Schofield Plateau to the northeast are not fully understood.

Table 4. Radon measurement data

LOCATION NUMBER	TRACKS /cm^2	CORRECTED FOR FILM BACKGROUND	EXPOSURE (hours)	TRACKS·10^{-2} /cm^2/hr	SOIL BACKGROUND	CORRECTED VALUE (T·10^{-2}/cm^2/hr)
L30	55	50	722.00	6.92	12.83	-5.91
L31	75	70	721.90	9.70	12.83	-3.13
L34	316	311	722.20	43.06	18.39	24.67
L36	3445	3440	721.95	476.50	18.39	458.11
L38	1223	1218	721.30	168.90	18.39	150.51
L39	621	616	721.15	85.42	18.39	67.03
L42	63	58	719.25	8.06	12.83	-4.77
L45	228	223	719.03	31.01	9.92	21.09
L49	386	381	718.9	53.00	12.83	40.11
L51	196	191	718.4	26.59	9.92	16.67
L52	118	113	718.2	18.52	9.92	8.60
L68	129	124	698.70	17.75	12.83	4.92
L73	118	113	697.0	16.21	12.83	3.38
L74	39	34	696.95	4.88	12.83	-7.95
L76	116	111	696.85	15.93	9.92	6.01
L82	489	484	1031.20	46.94	12.83	34.11
L93	148	143	1031.85	13.86	12.83	1.03
L94	361	356	1031.75	34.50	12.83	21.67
L95	108	103	1031.72	9.98	12.83	-2.85
L96	118	113	1031.62	10.95	12.83	-1.88
L97	242	237	1031.15	22.98	12.83	10.15
L98	1060	1055	1031.00	102.30	12.83	89.47
L99	1014	1009	1030.57	97.91	12.83	85.08
L100	106	101	1030.95	9.80	12.83	-3.03
L101	491	486	1030.80	47.18	9.92	37.26
L102	1122	1117	1030.25	108.40	18.39	90.01

should also be considered for these "negative count" zones is that a relative down-draught of ground gas is occurring in these areas; downward circulation of ground gas has been observed as part of (thermally driven) convection cells in active volcanic areas on the island of Hawaii (Cox, in press).

Radon values increase dramatically onto the Schofield Plateau. The highest value, 458.1 $T \cdot 10^{-2}/cm^2/hr$ is approximately three times that recorded at Sulphur Bank on Kilauea volcano during September, 1978. As the type of overburden does not appear to be a factor in the exceptionally high radon values, and there is no known artificial source of radioactivity in this area, the results are highly anomalous. Although differences in elevation could be having some impact on the observed data, the presence of high soil mercury concentrations in this area suggests that anomalous thermal conditions are the primary cause of the high apparent radon concentrations. Although further field surveys in the Schofield area would aid our interpretation these were beyond the scope of the present work.

Soil Mercury

Introduction

Mercury, even though it is considered a metallic element, is highly volatile in its reduced (elemental) state. Mercury salts, even if present in trace concentrations, can also be stripped from most rocks by circulating thermal fluids and transported considerable distances. Because of its high volatility and mobility in thermal environments, mercury has frequently been detected in elevated concentrations in areas of active volcanism and geothermal activity (Koga and Noda, 1975; Matlick and Buseck, 1975).

In Hawaii, elevated mercury concentrations are associated with both volcanic activity on the island of Hawaii (Eshleman et al, 1971; Coderre and Steinthorsson, 1977) and with thermal activity on the lower east rift of Kilauea (M.E.C. unpub. data). Studies currently being carried out in both of these areas suggest a relationship between high soil mercury concentrations and areas of subsurface heat and zones of thermally driven movement of ground gas and steam. The ability of soil mercury to assist in defining areas of subsurface thermal activity in areas with no other obvious surface manifestations has led to the application of this technique in Lualualei Valley.

Results

Figure 15 presents a contour map of mercury concentrations in Lualualei Valley. Values of over 100 parts per billion (ppb) are considered significant in the present study, and values in excess of 150 ppb are considered high order anomalies. The background value is approximately 50 ppb and values lower than 50 ppb are classified as anomalously low.

Several broad trends are apparent in the contoured data, the most obvious being the elevated values that appear to follow the inferred boundary of the erosion caldera. The narrow zone of high mercury concentrations in the Makaha Valley suggests a possible continuation of this trend to the northwest. Also significant are the unusually high values obtained to the northeast of the Schofield side of the Waianae range. The low value area in the central Lualualei Valley floor is also considered to be significant.

The observed mercury anomalies, in general, tend to be localized and are interpreted as being related to zones of fracturing along the caldera boundary and possibly within the adjacent rift zones. The elevated mercury concentrations in Makaha are also possibly related to a structural feature. A continuation of anomalous values to the southeast is also suggested. Although cultural sources (contamination) of mercury must be considered, the results of secondary sampling appear to rule out contamination as a significant factor.

The very high values of mercury on the Schofield Plateau were initially questioned because of the proximity of artillery firing ranges. It has, however, been determined that mercury has not been used in munition primers for at least 10 to 15 years (A. Lum, pers. comm., 1978) and that this is unlikely to be the source. The extremely high radon values observed in this area tend to substantiate a natural source of these high mercury concentrations.

The low mercury concentrations observed in the central Lualualei Valley probably originate from one of two possible sources. Although it is possible that these low values are a function of the local sediment cover, the presence of high mercury concentrations in other areas of alluvial fill indicate that this is not the case. In addition, the radon data suggest that the lower mercury values are related to the lower mobility of upward moving soil gas in this area. This lower mobility may be related to lower fracture permeability or to the local hydrological conditions. Figure 16 presents a plot of both mercury and radon data across two traverses (AA´, BB´) of Lualualei Valley (see Fig. 19). The correlation between the two data sets if apparent. We believe that the

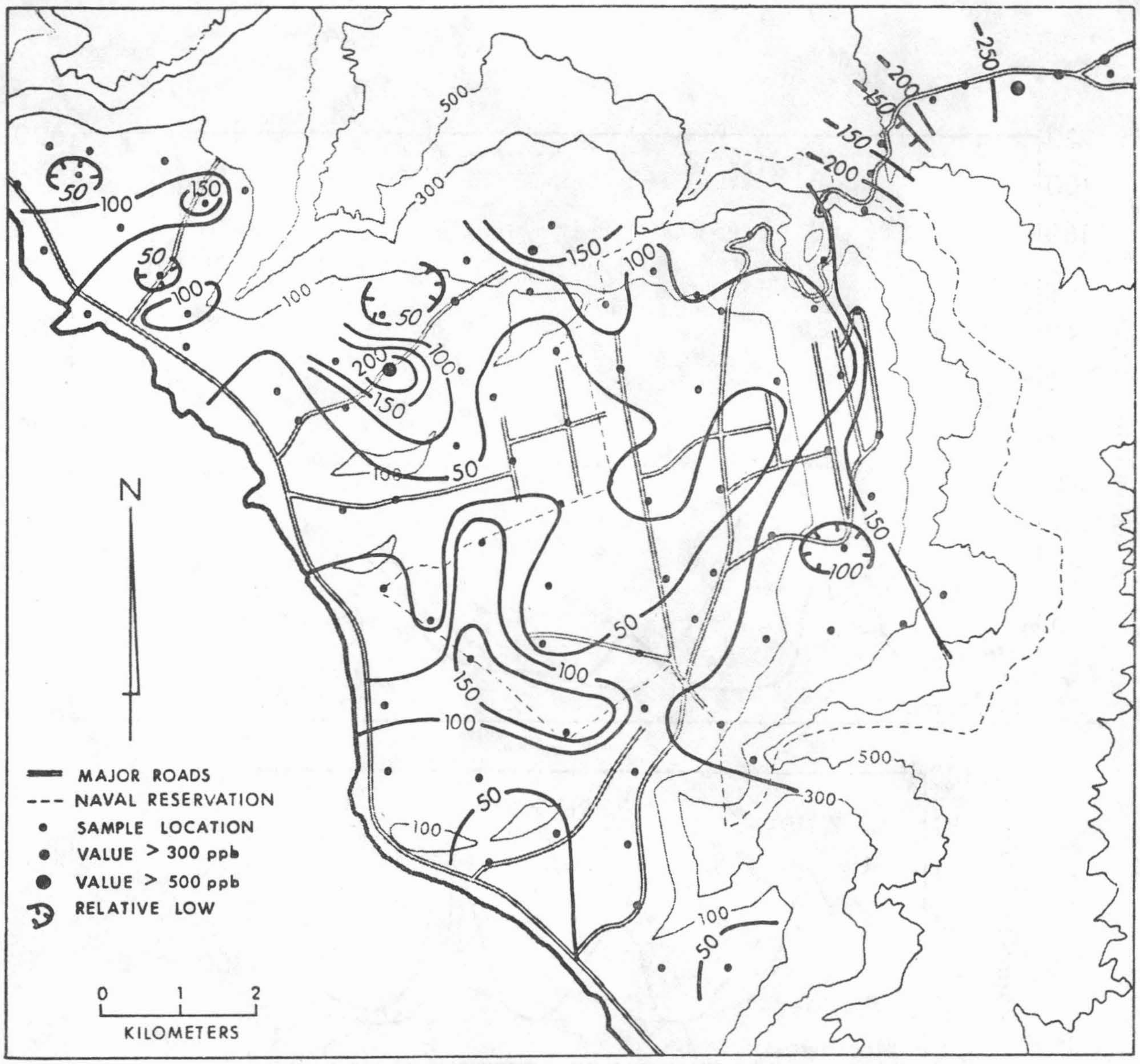


Fig. 15. Soil mercury map. Contour interval is 50 ppb. Values of greater than 100 ppb are considered to be significantly anomalous.

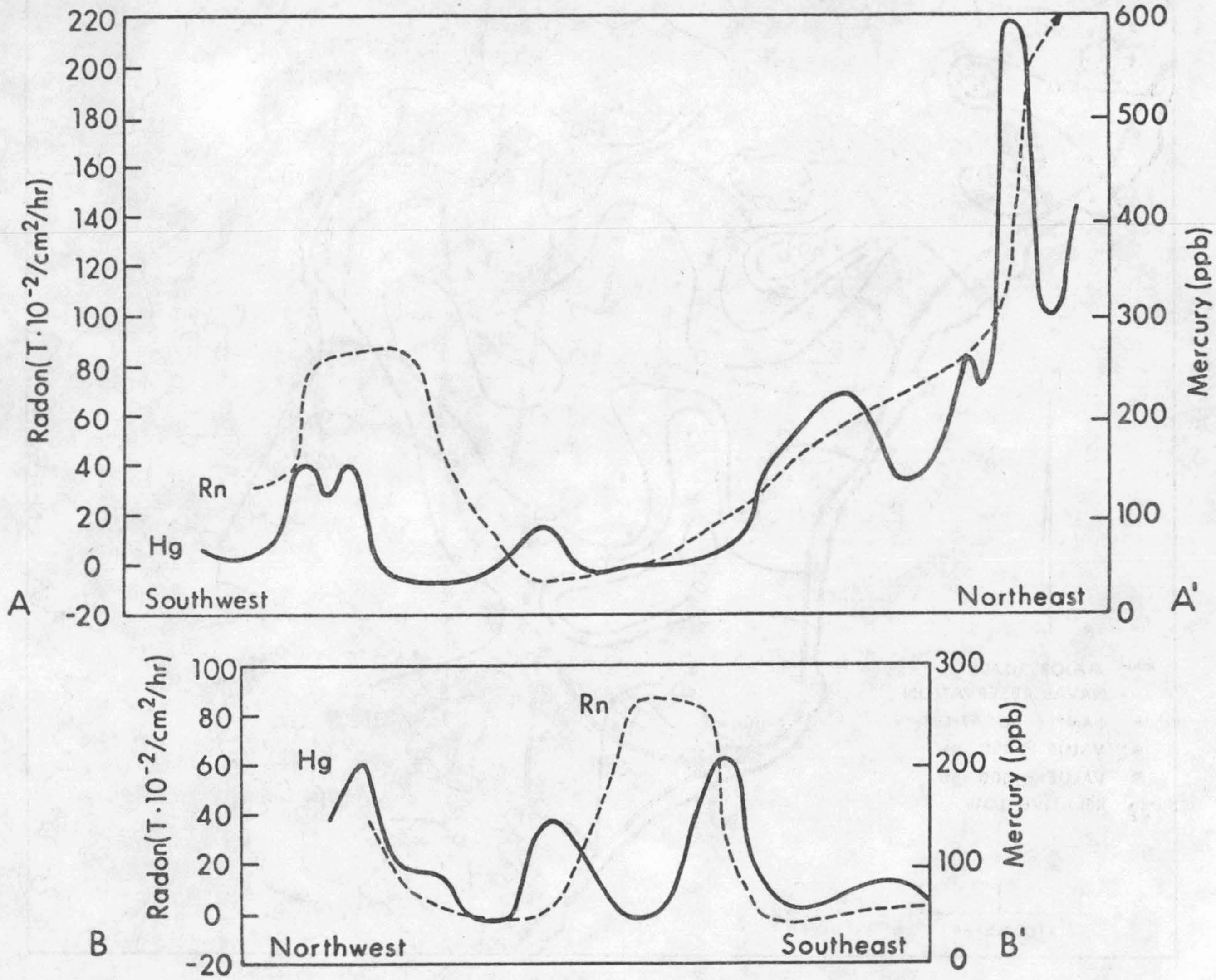


Fig. 16. Comparison of mercury and radon data along NW-SE and NE-SW profiles. Locations of profiles are shown in Fig. 19.

presence of mercury anomalies at the edges of the radon anomalies is significant; mercury tends to migrate away from areas of thermal activity and thus tends to concentrate in "halos" around transporting fractures rather than within the fractures themselves.

In general, the soil mercury data suggest that outgassing, which is probably thermally driven, is taking place through fracture systems of significant vertical extent around the caldera rim and within the associated rift zones.

Groundwater Mercury

Introduction

Significant concentrations of mercury have been recorded in several geothermal systems in a variety of different geologic terrains. Fluid sampled from geothermal well HGP-A on the Kilauea east rift has mercury concentrations ranging from values of 50 to several hundred µg/ℓ downhole (Kroopnick et al, 1978). High values of mercury of typically 0.125 to 1.145 µg/ℓ have been recorded in the open ocean near mid-ocean ridges and are considered derived from seafloor volcanic emanation (Carr et al, 1974).

Results

Mercury concentrations determined for several groundwater sources in Lualualei Valley are plotted in Figure 17. Although the data are limited, several wells appear to have mercury concentrations well above background values (0.015 µg/ℓ). The higher values appear to occur peripheral to the caldera boundary and to increase toward the northeast. The overall indication is that the higher concentration of groundwater mercury correlates with the observed elevated soil mercury. This finding further substnatiates the interpretation that the elevated soil mercury concentrations are in fact related to natural phenomena and not to anthropogenic sources.

Soil pH

Although soil pH is a complex function of soil type, vegetation coverage, and precipitation regime, the outgassing of acidic volatiles from buried magma intrusions and geothermal systems can lower surface soil pH. The gases primarily responsible for increased soil acidity in geothermal areas are CO_2, H_2S, SO_2, and H_2SO_4. Studies of soil pH on the Kilauea summit and east rift have shown that lower pH is often

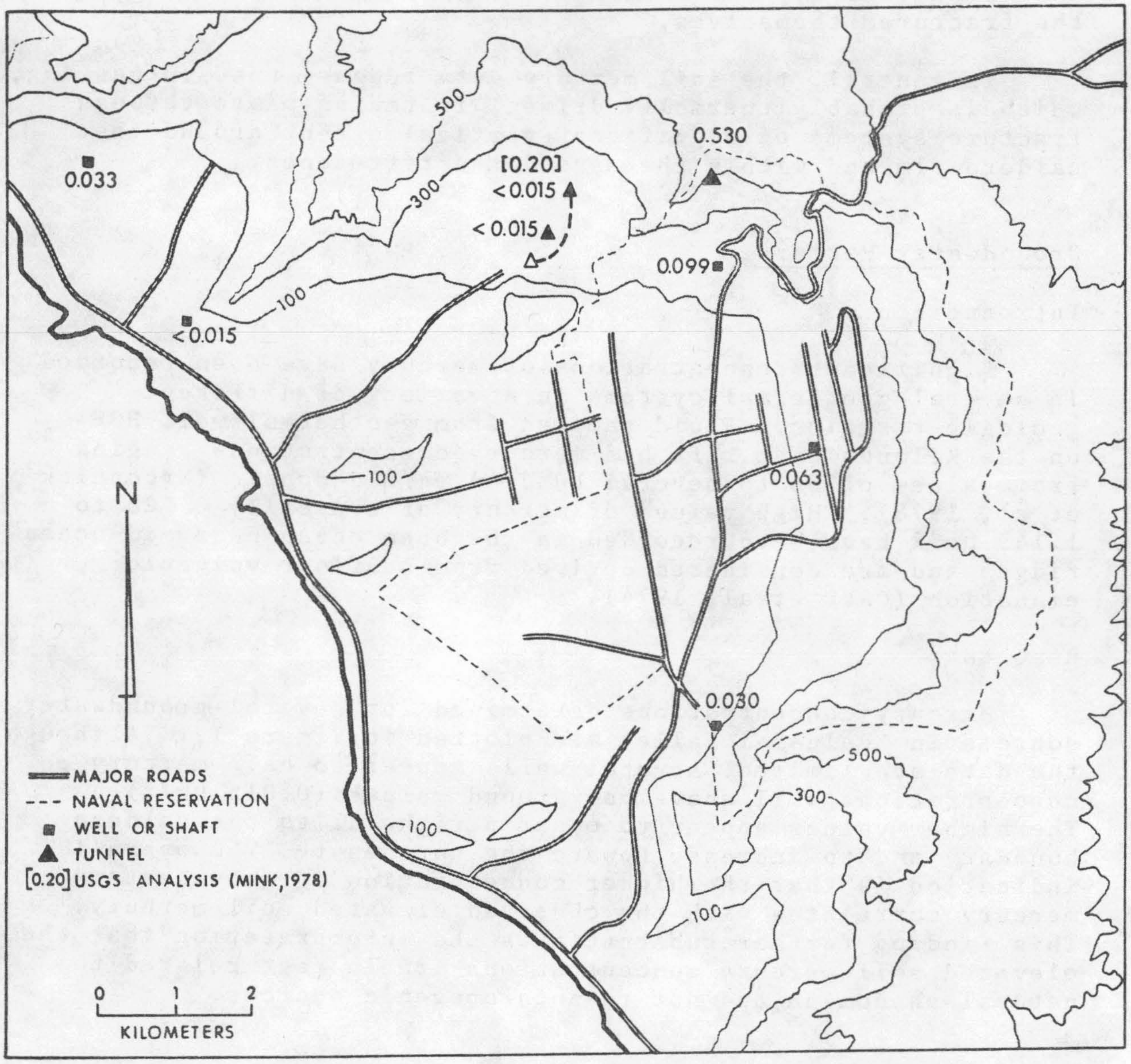


Fig. 17. Mercury concentration in groundwater samples from wells and tunnels. Values are in μ g/ℓ (approximately equivalent to ppb). The lower limit of detection is 0.015 μ g/ℓ.

associated with steaming ground and fumarolic activity (M.E.C. unpub. data).

A survey of the soil pH in the Waianae district was conducted to determine whether significant differences were observable that could reasonably be attributed to outgassing in the vicinity of the identified fracture systems. Laboratory measurements were made with a pH meter and a combination electrode. Soil samples were mixed into a slurry with distilled water at a water:soil ratio of 2:1. The pH of each soil sample was measured to within ±0.1 pH unit.

Figure 18 presents contours (at 0.5-unit intervals) of the data obtained. The soils in the survey area are largely neutral to slightly acidic. Although only generalized trends are discernible, the data do suggest a decrease in pH (more acid) toward the inferred caldera boundary. The most significant zones of lowered pH are an area to the east and northeast, and a second area toward the southwest. Because the total variation in pH is only 2.0 units throughout the area studied, and only 1 pH unit within the valley, we believe that the observed variations are probably the result of variations in soil type and vegetation cover rather than outgassing of acid volatiles.

Groundwater Surveys

Introduction

Surveys of the physical and chemical characteristics of shallow groundwaters have found wide application in the study of active geothermal systems. Such surveys are especially useful because deeply circulating thermally altered fluids can inject significant quantities of thermal energy and dissolved salts into near-surface groundwater aquifers. In addition, abnormally high heat flows associated with thermal reservoir leakages can often substantially alter normal groundwater flow patterns.

In an island environment, disturbances of this type usually occur as a disruption of the Ghyben-Herzberg lens by upwelling of heated saline water into the cooler overlying fresh water aquifers and are easily recognizable.

The specific techiques applied to the present study of Lualualei Valley have been controlled to a large degree by the complexity of the local hydrology, and many techniques with wide application in other geothermal surveys have been found to be either totally unworkable here or have allowed only qualitative interpretation.

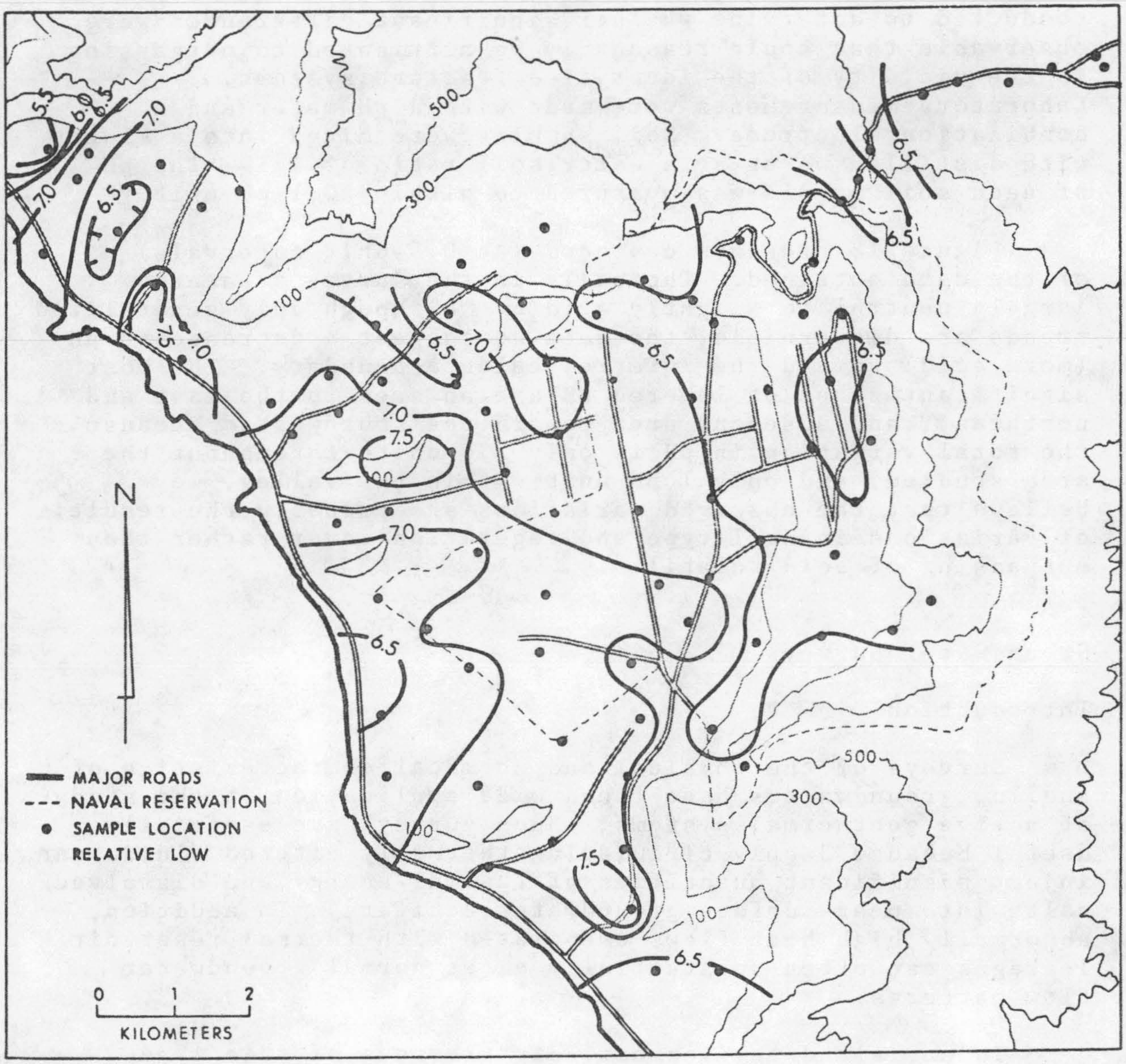


Fig. 18. Trends of soil pH. Contour interval is 0.5 pH units. The sample locations shown are the same as those for mercury.

Groundwater temperature surveys

Although the addition of thermal energy to near-surface waters is the most obvious effect of the entry of geothermal fluids to the near-surface environment, groundwater temperature contouring is effective only under favorable conditions. For definitive chemical assessment the thermal fluids must migrate upward through well-defined conduits that allow only a minimum of dilution from colder intermediate aquifers. Flow rates must be high to compensate for conductive heat loss to the colder country rock along the conduit walls. Under favorable conditions of rapid influx of thermal water and a large number of surface sampling points, it is possible to estimate absolute flow rates and temperatures of the leakages. More typically, however, the contribution of thermal energy to near-surface aquifers is small, and thus only qualitative identification of areas of discharge is possible. Note that in this area there are no natural surface discharges of thermal fluids such as hot springs.

Groundwater temperatures recorded for several wells and tunnels in this study area are listed in Table 5; the locations and temperatures of the sources listed are mapped in Figure 19. The well temperature data suggest that there are characteristic temperature ranges for each aquifer type. High level, dike-impounded groundwater temperatures range from 18°C to 21°C. These are the lowest groundwater temperatures in the valley and are indicative of higher elevation rainfall recharge. Water within the basal aquifer (below the alluvial valley fill) is slightly warmer with temperatures of approximately 20°C to 24°C corresponding to a mixture of high level recharge and lower altitude surface recharge. Groundwater temperatures within the sedimentary aquifer range from 22°C to 26°C, indicative of direct surface recharge. Median temperatures in the valley are approximately 24°C to 25°C, and thus groundwater temperatures above 26°C are considered anomalous.

Two areas in Lualualei Valley and one to the northwest were found to have anomalously high temperatures. Although the highest observed temperature is only 27°C, we believe it is significant that the observed anomalies are found along the perimeter of the caldera or within the rift zone complexes. These are the areas in which extensive fracturing is likely to provide highly permeable zones through which deeply circulating water can return to the surface environment. Without considerably more data, it is not possible to determine whether the low temperatures encountered in the anomalous wells are the result of thermal water that has been highly diluted in the near surface aquifers or the result of low temperature thermal waters that have not been significantly diluted by surface recharge.

Table 5. Groundwater analyses

Analyst*	Number	Locality	Type	Water Type†	Date	Temp. (°C)	pH (ppm)	Na (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Cl (ppm)	F (ppm)	HCO_3 (ppm)	SO_4 (ppm)	NO_3 (ppm)	SiO_2 (ppm)	Diam. (Cm)	Grd Elev. (m)	Total Depth (m)	Depth Rel. to S. L. (m)
HIG	2409-07	Maili	Well	A	9/78	25.5		680	18.2	96	61	1410			232		172	15.2	17.1	22.3	-5.2
HIG	2409-23	Maili	Well	A	9/78	25.0		690	20.1	101	60	1480			178		157	15.2	18.0	22.0	-4.0
HIG	2508-02	Lualualei	Shaft	A/B	8/78	27.0		102	10	40	80	260			48		68	213	51.8	53.3	-1.5
USGS	2508-02	Lualualei	Shaft	A/B	10/71	29.0	7.8	92	7.9	36	102	292	0.2	338	22	8.5	92	213	51.8	53.3	-1.5
USGS	2508-02	Lualualei	"(bottom)	"	10/71	29.0	7.7	126	9.6	41	108	382	0.2	313	25	8.7	89	213	51.8	53.3	-1.5
BH	2508-02	Lualualei	Shaft	A/B	2/54		9.5	(136)		286	127	520		258	51	1.2	84	213	51.8	53.3	-1.5
HIG	2508-07	Lualualei	Well	A	9/78	25.5		380	12.8	127	81	1330			59		186	15.2	23.5	26.0	-2.5
HIG	2607-01	Lualualei	Well	A/B	8/78	24.0		41	2.9	14	12	41			58		96	20.3	120.4	137.5	-17.1
USGS	2607-01	Lualualei	Well	A/B	2/72	24.3	7.5	38	2.8	13	12	46	0.3	113	8.5	4.3	65	20.3	120.4	137.5	-17.1
USGS	2607-01	Lualualei	Well	A/B	6/67		7.1	39	2.9	9.6	8.0	50	0.3	117	10	6.6	80	20.3	120.4	137.5	-17.1
USN	2607-01	Lualualei	Well	A/B	1966		6.7	28	3.0	7.2	8.5	48	0.3	105	8.0	3.5	78	20.3	120.4	137.5	-17.1
HIG	2609-X	Lualualei	Well	A	9/78	24.0		90		95	50	141			7.8		41		13.0	6.4	+6.6
HIG	2709-08	Lualualei	Well	A	9/78	26.0		92	2.6	11	9.6	147			22		165	15.2	30.5	57.9	-27.4
HIG	2712-01	Waianae	Well	A	8/78	24.5		75	3.6	24	39	143			58		94	30.5	9.1	54.9	-45.8
USGS	2712-01	Waianae	Well	A	2/76		6.9	48	4.3	17	30	82	0.2	176	14	9.3	80	30.5	9.1	54.9	-45.8
BWS	2712-01	Waianae	Well	A	2/76		7.1	55	4.1	19	34	97	0.2	183	16	8.4	75	30.5	9.1	54.9	-45.8
BWS	2712-01	Waianae	Well	A	1/76			50	3.7	17	30	83	0.2	171	14	7.5	74	30.5	9.1	54.9	-45.8
HIG	2808-01	Lualualei	Well	A/B	8/78	26.5		120	4	116	27	138	0.6		260		81	30.5	133.2	163.0	-29.8
USGS	2808-01	Lualualei	Well	A/B	2/72	26.7	7.8	120	3.2	66	28	160	0.3	97	222	0.3	63	30.5	133.2	163.0	-29.8
USN	2808-01	Lualualei	Well	A/B	9/57	26.6	7.5					165		180	700			30.5	133.2	163.0	-29.8
USN	2808-01	Lualualei	Well	A/B	12/56		7.5					164		200	390		34	30.5	133.2	163.0	-29.8
HIG	2808-02	Lualualei	Tunnel	B	8/78	19.0		19	3.0	11	6.5	23	0.12		33		58		457.2		
USGS	2808-02	Lualualei	Tunnel	B	2/72	18.5	7.7	19	3.1	11	7.4	26	0.1	75	3.6	2.5	49		457.2		
USGS	2808-02	Lualualei	Tunnel	B	2/72		7.2	19	2.8	11	7.3	26	0.1	74	4.6	2.3	49		457.2		
USGS	2808-02	Lualualei	Tunnel	B	6/67		7.6	19	2.9	6.4	6.0	32	0.1	76	7.0	4.2	56		457.2		
USN	2808-02	Lualualei	Tunnel	B	1966		7.5	19	3.8	8.8	8.2	30	0.1	71	5.8	2.9	62		457.2		
USGS	2809-05	Waianae	Well	A/B	1969	21.5	7.4	63	0.2	36	3.7	68	0.05		0.10	0.57	62		92.35		
HIG	2809-06	Waianae	Tunnel entrance	B	8/78	22.0		27	2.7	21	29	26			34		73		127.4		
BWS	2809-06	Waianae	Tun. entr.	B	9/77	22.7	7.4	29	3.7	31	16	33		166	26	0.2	57		127.4		
USGS	2809-06	Waianae	Tun. entr.	B	2/72		7.8	25	3.3	24	15	28	0.1	143	23	0.2	50		127.4		
HIG	2809-06	Waianae	Tunnel overflow	B	8/78	20.0		16	3.3	12	10	15			28		51		167.6		
BWS	2809-06	Waianae	Tun. ovfl	B	9/77	20.6	7.9	18	3.7	12	5.4	10		76	7.5	0.3	42		167.6		
BWS	2809-06	Waianae	Tun. ovfl	B	2/62	21.1	8.1	18	3.9	12	5.0	18	0.2	72	7.8	0.2	36		167.6		
BH	2809-06	Waianae	Tun. ovfl	B	8/58		7.6	(33.5)		16	8.7	22		75	14.5	0.8	40		167.6		

(continued)

Table 5 (continued)

Analyst*	Number	Locality	Type	Water Type †	Date	Temp. (°C)	pH (ppm)	Na (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Cl (ppm)	F (ppm)	HCO_3 (ppm)	SO_4 (ppm)	NO_3 (ppm)	SiO_2 (ppm)	Diam. (Cm)	Grd. Elev. (m)	Total Depth (m)	Depth Rel. to S.L. (m)
HIG	2811-02	Makaha	Well	A/B	9/78	25.0		34	3.5	21	24	48.6			<3		81	40.6	115.2	160.9	-45.7
USGS	2811-02	Makaha	Well	A/B	1967	25.2						92		215				40.6	115.2	160.9	-45.7
HIG	2812-01	Makaha	Shaft	A	8/78	26.0		46	3.7	20	34	92			48		86	182.9	42.7	51.2	-8.5
UH	2812-01	Makaha	Shaft	A	3/71		7.0			22		88		144			82	182.9	42.7	51.2	-8.5
UH	2812-01	Mahaka	Shaft	A	6/70		8.0			20		95		162			73	182.9	42.7	51.2	-8.5
USGS	2812-01	Makaha	Shaft	A	1969	26.5	7.2	16.9	0.4	34	4.9	93	0.3		3.5		66	182.9	42.7	51.2	-8.5
BWS	2812-01	Mahaka	Shaft	A	2/62		7.2	46	4.0	19	33	100	0.2	157	14	6.2	71	182.9	42.7	51.2	-8.5
BWS	2908-02	Waianae	Tunnel	B	9/73	18.3	8.1	12	1.2	7.2	5.4	14	0.1	49	3.6	4.5	31				
HIG	2911-01	Makaha	Tunnel	B	9/78	20.0		21	2.8	13	12	24			<3		73		242.6	48.8	+193.8
BWS	2911-01	Makaha	Tunnel	B	12/78		7.8					27				4.0			242.6	48.8	+193.8
BH	2911-01	Makaha	Tunnel	B	9/54	21.5	7.4	(16)		38	12	27	0.2	74	11	1.2	28		242.6	48.8	+193.8
HIG	2912-01	Makaha	Well	A/B	8/78			45	4.2	26	31	89	0.13		43				134		
USGS	2912-01	Makaha	Well	A/B	3/76	24.9	7.2	33	4.1	27	30	92	0.2	154	6.6	8.0	66		134		
BWS	2912-01	Makaha	Well	A/B	2/76		7.2	36	3.5	28	30	91	0.1	153	15	7.0	56		134		
USGS	Kaupuni	Waianae	Stream		1973		7.4	26	2.7	23	14	28	0.2	139	21	0.1	56				
USGS	Makaha	Makaha	Stream		1975	20.0	7.4	10	0.9	6.6	5.6	14	0.1	49	3.0	0.1	28				
BWS	Waianae	Waianae	Stream		1973		8.0	14	1.3	8.7	6.1	16	0.1	61	3.3	1.7	41				
USGS	Rain	Av. Hawaii Is.					5.25	4.46	0.42	0.85	1.10	7.90			1.84	0.5					

* Analyst = HIG: Hawaii Institute of Geophysics; USGS: U.S. Geological Survey; USN: U.S. Navy; BWS: Board of Water Supply; UH: University of Hawaii; BH: Board of Health.

† Water type from indicated source aquifer = A: sedimentary; A/B: mixture sedimentary/basal/dike-impounded; B: dike-impounded.

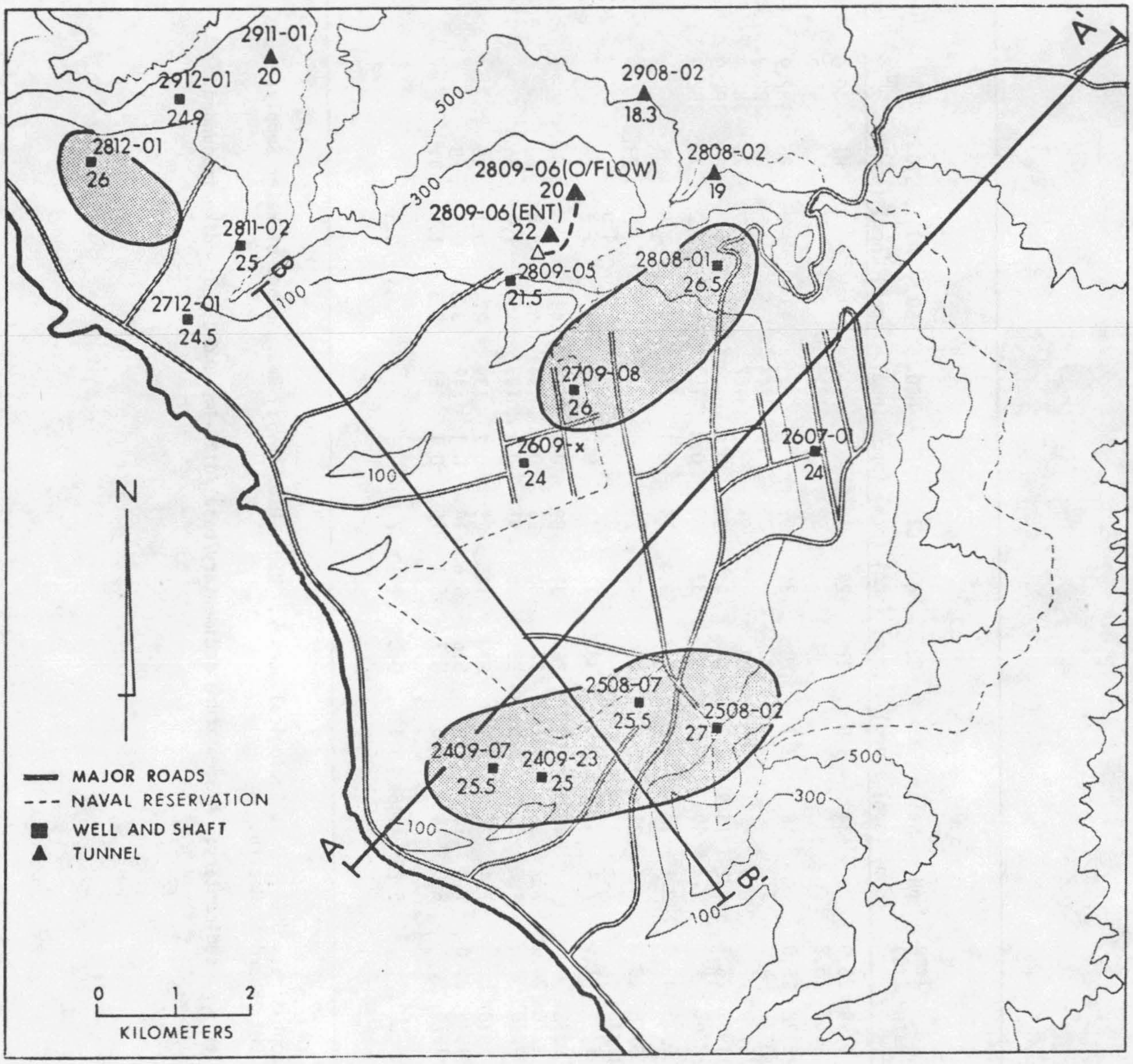


Fig. 19. Locations and numbers of groundwater wells, tunnels and shafts. The lower number is the mean of temperature measurements in T. 5. The water in 2809-06 (overflow) is tapped at a higher elevation than 2809-06 (entrance). Three generalized zones of anomalous water temperatures are shown by shaded areas. A-A' and B-B' are the Hg/Rn profiles in Fig. 16.

Silica (SiO_2)

The concentration of silica in groundwaters is a complex function of several factors: mean aquifer temperature, residence time, pH, soil type, and aquifer rock type. The effect of temperature on silica concentrations can be substantial; it is often possible to identify thermal discharges on the basis of this characteristic alone. In some cases if it is assumed that water-rock equilibrium has been reached in the reservoir and that no dilution or precipitation has occurred during ascent, minimum reservoir temperatures can be estimated from dissolved silica concentrations alone.

In (non-thermal) Hawaiian groundwaters, silica concentrations fall in the range of 20 parts per million (ppm) to slightly above 80 ppm (Mink, 1961; Davis, 1969). The lower concentrations are found in aquifers having high rates of recharge and short residence times. The higher concentrations commonly occur in areas where relatively high volumes of irrigation return water enter shallow aquifers.

Near surface thermal waters in the Puna district of Hawaii (lower east rift of Kilauea) have silica concentrations of approximately 80 ppm (McMurtry et al, 1977). Even though these concentrations fall within the range of normal Hawaiian groundwaters, they are considered anomalous against the background values of 20 ppm normally found in Puna groundwaters. Thus, it is necessary to evaluate silica concentrations relative to local background when assessing geothermal potential.

Figure 20 presents a distribution map of the observed silica concentration in shallow groundwaters sampled. The values for high level groundwaters from tunnels ranges from 30 ppm to 60 ppm, whereas alluvial aquifers have concentrations as high as 80 ppm; concentrations greater than 80 ppm are considered anomalous.

Two zones within the valley have exceptionally high (>100 ppm) concentrations of silica. Three wells in the first zone near the southern boundary of the caldera have values above 150 ppm and are almost certainly indicative of deeply circulating groundwaters entering near-surface aquifers. The second zone, slightly below the northern boundary of the inferred caldera, includes one exceptionally high silica value (165 ppm) and two considerably lower silica concentrations (81 ppm and 96 ppm). The latter concentrations are not exceptionally high, but they are considered anomalous relative to others in the immediate area (e.g., 41 ppm and 58 ppm).

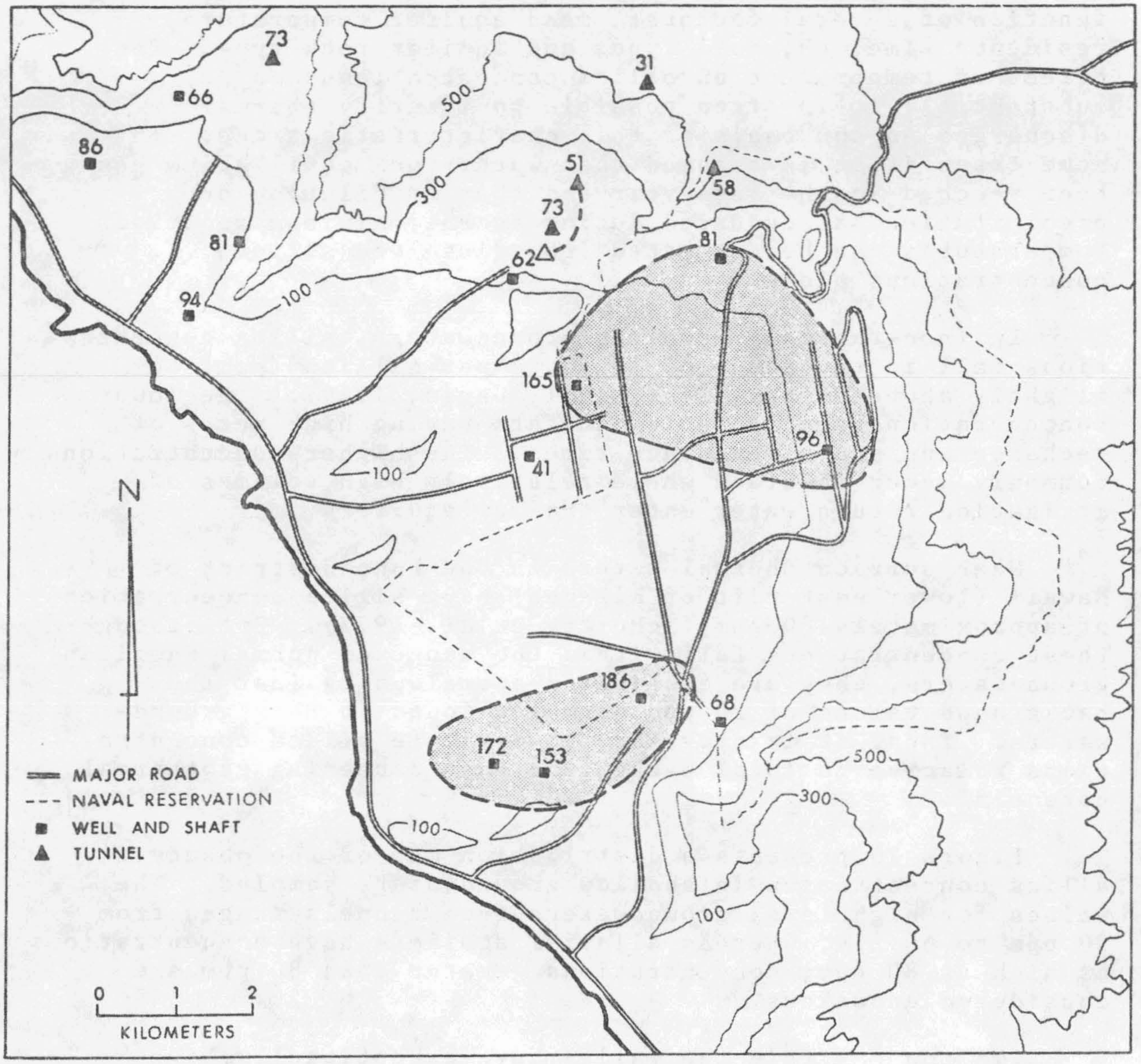


Fig. 20. Values of silica (SiO_2) in groundwater in ppm. Two generalized anomalous zones are shown by shading.

Even though variable mixing ratios of near-surface water (having imprecisely known silica concentrations) with upwelling thermal waters makes it impossible to estimate the character of the latter, the observed silica anomalies are considered significant in terms of locating areas in which thermal waters are likely to be found.

Chloride (Cl^-)

Chloride ions in seawater entering an island aquifer undergo minimal ion exchange. Consequently, groundwater chloride concentrations are usually good indicators of the magnitude of seawater encroachment into fresh water aquifers (Mink, 1961). Even though thermal fluids do contain significant concentrations of chloride ion stripped from the reservoir rock, the presence of anomalously high concentrations of chloride in some shallow groundwaters in Hawaii appears to be the result of thermally induced disruption of the Ghyben-Herzberg lens rather than of direct addition from thermal waters. Thermally induced mixing of fresh and saline waters has been oberved over widespread areas of the Puna district, and in a few wells, warm saline water has been found floating above cooler fresh water.

Figure 21 is a generalized contour map of the chloride ion concentrations observed in the water sources sampled in Lualualei Valley. The highest values measured indicate addition of approximately 7% seawater to the fresh water aquifers at the southern side of the valley. Although the degree of seawater mixing decreases up the valley, an elongate anomalous zone of high chloride concentration is indicated to extend toward the head of the valley. The relatively high chloride concentrations may be caused by saline water intruding the fresh water within fractured basal lavas. An alternative explanation is that convective circulation is transporting thermal saline water from below the fresh water lens into the near-surface aquifers. Well #2808-01, at the northern end of the anomalous zone, is at an altitude of 133.2 m and has a depth of 163.0 m. The concentration of chloride in this well is a factor of four higher than in its nearest neighbor (#2808-02), implying at least minor saline mixing. The indication of mixing and the fact that well #2808-01 has a water temperature above the local ambient suggest that thermal upwelling may be producing the saline intrusion.

Cation Concentrations (Na^+, K^+, Ca^{++}, Mg^{++})

It has been well established that water can strip considerable concentrations of mineral salts from geothermal reservoir rocks. Under conditions of high temperature

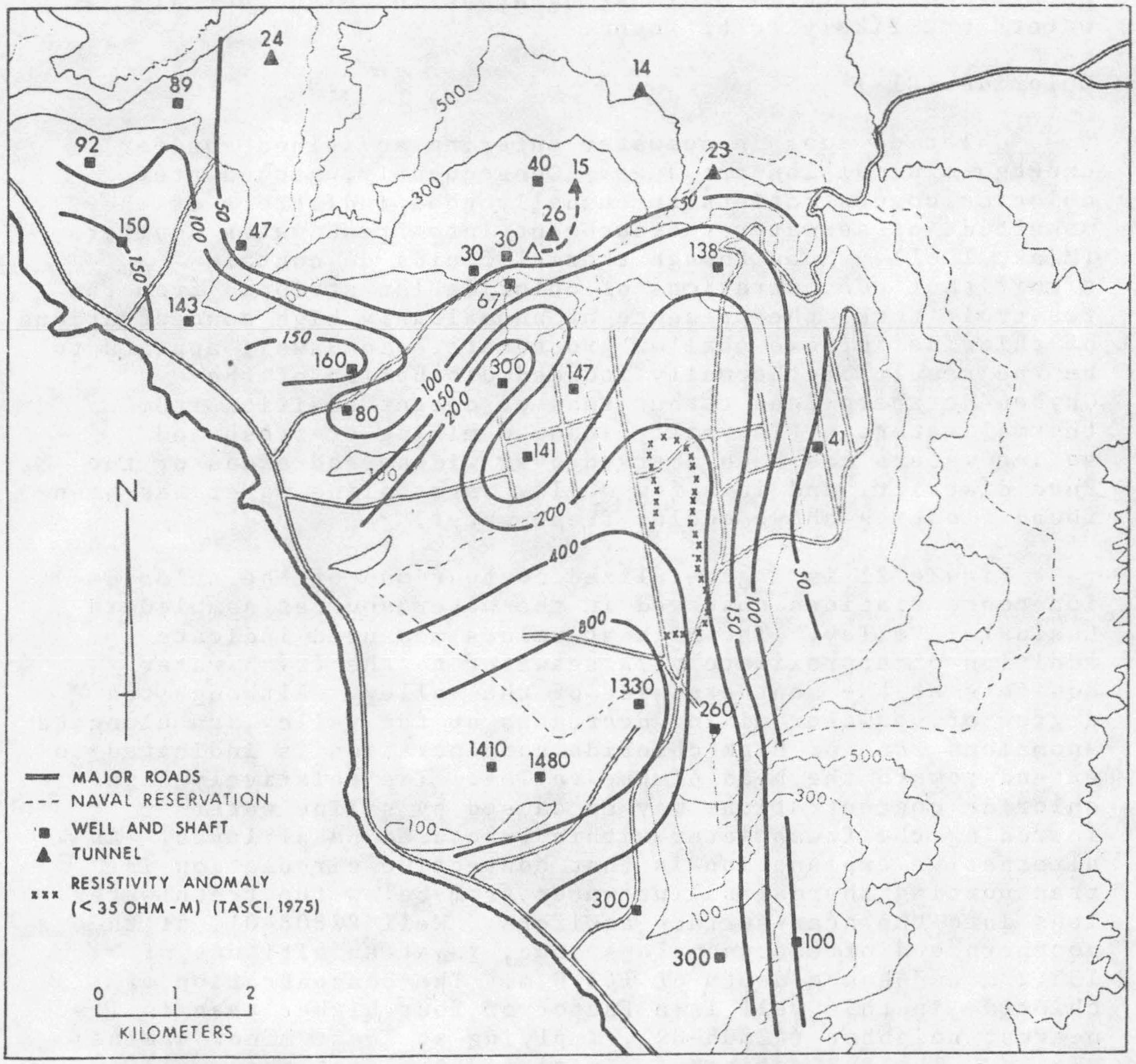


Fig. 21. Generalized trends of chloride content (ppm) in groundwater. The encroachment of saline water into the alluvial valley floor aquifers is shown.

equilibrium between water and rock minerals, the relative concentrations of several cations are present in specific ratios that correspond to the temperature at which equilibrium was achieved. It was on the basis of these equilibrium concentrations that cation geothermometers have been developed (e.g., Fournier and Truesdell, 1973). Specific conditions must be met before calculations of this type can provide reliable reservoir temperature estimates: equilibrium between hot waters and reservoir rock must have been attained, ascent of the reservoir fluids to the surface must be sufficiently rapid to prevent reequilibrium from taking place at intermediate temperatures, and contamination by surface or saline waters must be very minor. The presence of variable concentrations of seawater and the type of near-surface groundwater being studied render it virtually impossible to use these geothermometry calculations with any reliability. Nonetheless, marked anomalies have been observed in ion concentration ratios of several cations. Thus, even though quantitative estimates of reservoir temperatures are not usually possible, cation ratios can be used as reliable qualitative indicators of thermally altered groundwater.

The cation concentrations observed in eighteen of the wells in Lualualei Valley area are presented in Table 5; Figures 22 and 23 present plots of the Na/K ratio and Ca/Mg ratio versus chloride ion concentration. The data indicate a tendency toward higher concentrations of Ca and Mg relative to Na and K with increasing distance inland. We believe that this is the result of progressive ion exchange between intruding seawater (which loses Na and K) and the calcareous valley fill (which takes up Na and K and loses Ca and Mg). Mink (1961) provides a detailed discussion of the ion exchange reactions that take place between marine sediments and seawater. In the plot of Na/K ratio versus chloride ion concentrations, several other water sources known to contain thermally altered water are also included for purposes of comparison. Decreasing chloride concentration with increasing distance inland and with increasing altitude is apparent in the groundwater chemistry. There appears to be no obvious trend in the Na/K ratios that can unequivocally be attributed to thermal alteration (i.e., toward ratios similar to those observed in HGP-A). Although well #2508-02 (which has the highest water temperature observed in Lualualei Valley, 27°C) falls within the "altered groundwater" triangle, its nearest neighbors (2409-07, 2409-23, and 2508-07) do not. It is suggested that a combination of at least two different reactions is being observed: low-temperature clay mineral-salt water ion exchange is increasing the relative Na/K ratio, whereas thermal alteration of deeper circulating groundwaters is decreasing the Na/K ratio.

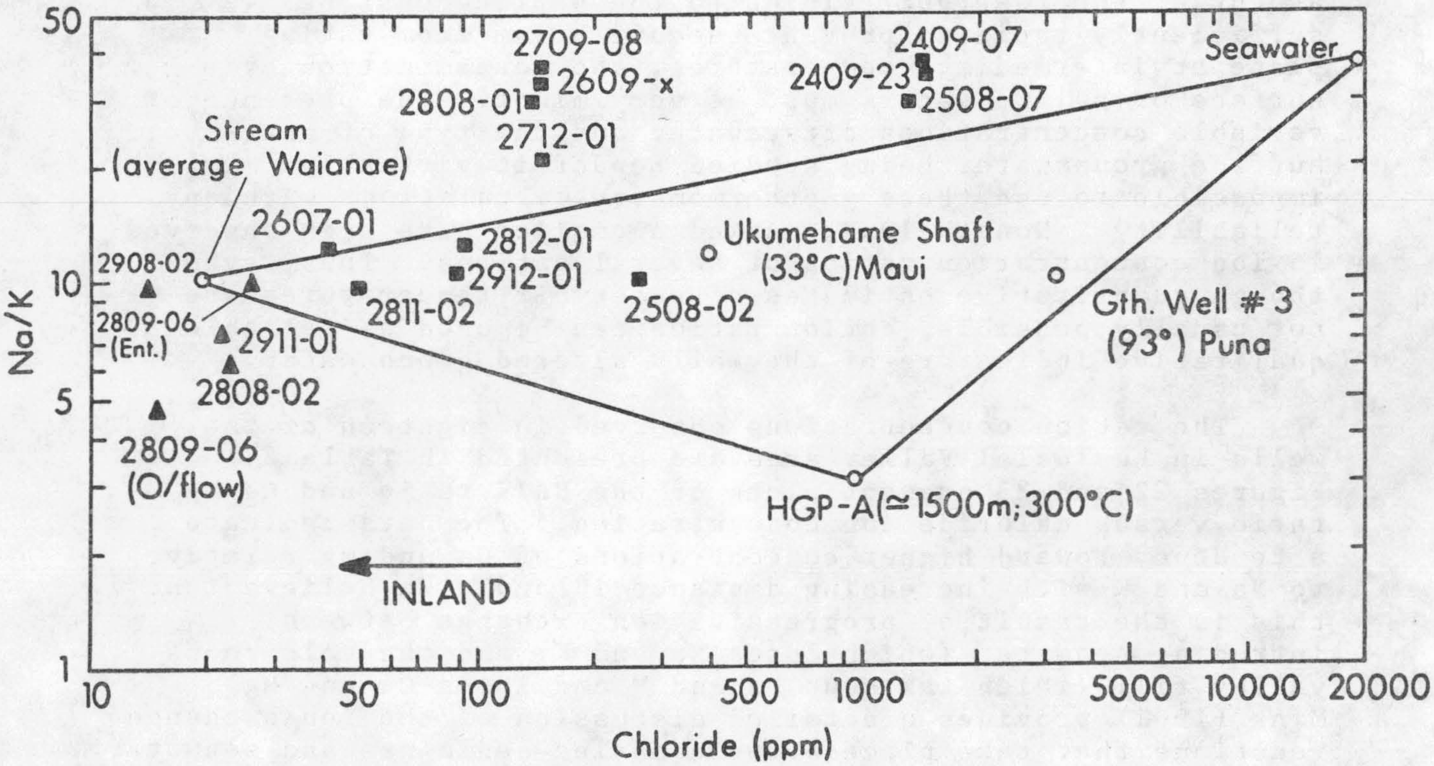


Fig. 22. Logarithmic plot of Na/K against chloride (ppm). A general decrease occurs in the Na/K ratio with distance from the coast.

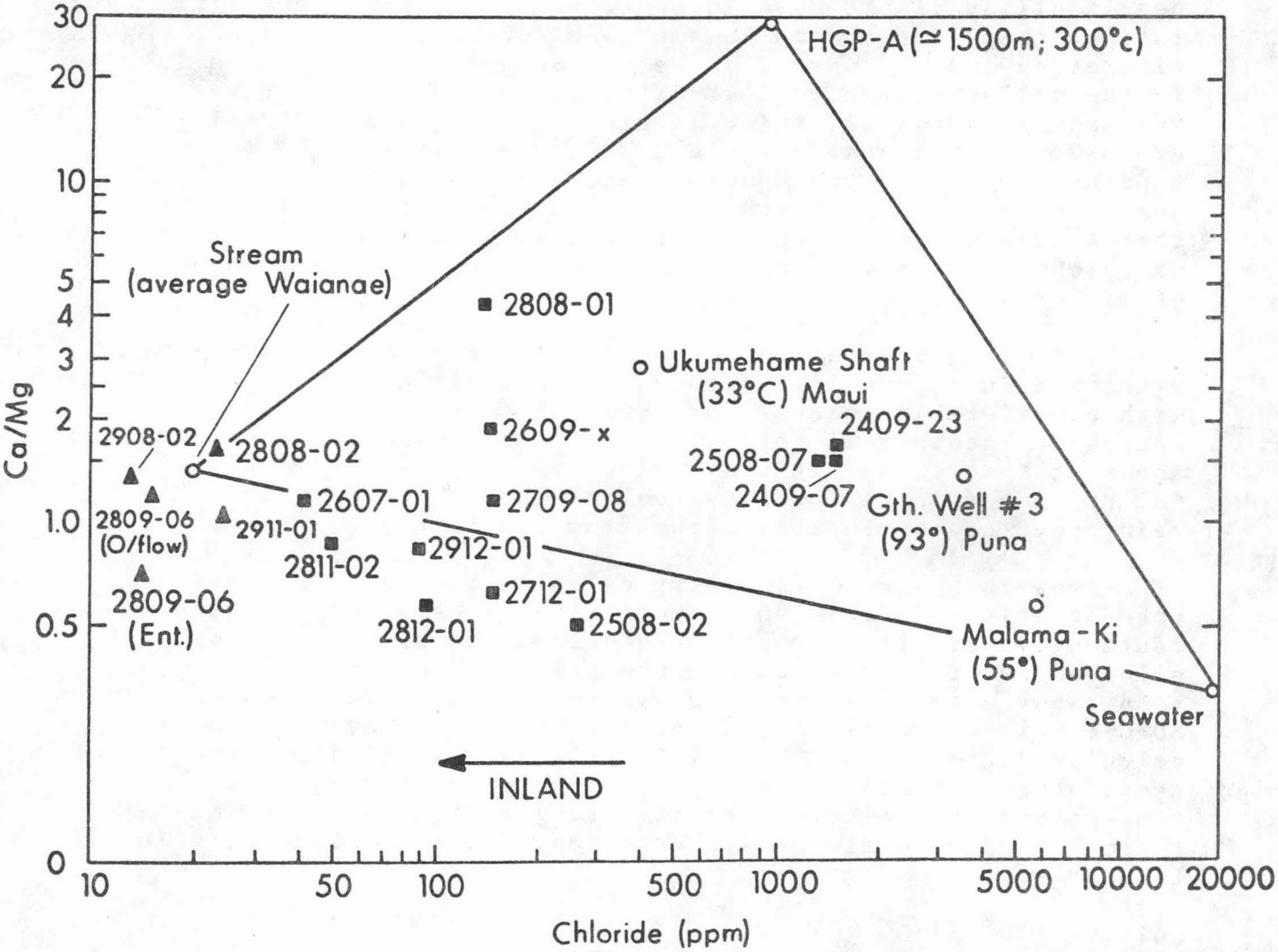


Fig. 23. Logarithmic plot of Ca/Mg against chloride (ppm). The groundwaters in the Waianae area are compared to other known thermal waters in Hawaii. The Ca/Mg ratio is shown to increase with distance from the coast. The more anomalous groundwaters plot higher in the diagram.

Figure 23 presents a plot of Ca/Mg ratio versus chloride ion concentration; other thermally altered groundwaters are also plotted. It is apparent that several of the water samples indicate substantial thermal alteration of the Ca/Mg ion ratios. The correlation between increasing Ca/Mg ion ratios with thermal alteration is thought to originate from higher temperature rock-water interactions that strip Ca from the reservoir rock whereas clay mineral formation can remove nearly all available Mg. In contrast to the Na/K versus Cl ratios, there appears to be a strong correlation between Ca/Mg alteration and the observed thermal anomalies; all the wells in the valley that have thermal anomalies are within the "altered groundwater" triangle with the exception of well #2508-02. (The data in Table 5 indicate that 2508-02 is tapping water from two aquifers and that the water in the shaft is stratified; the water at the top is less saline than that at the bottom. Thus, it is unlikely that samples of water obtained from this well will give a valid representation of either water source.)

The Cl/Mg ion ratios for several of the water sources are presented in Figure 24. Although this ratio has been used with considerable success for regional assessment of groundwaters for geothermal potential (Cox and Thomas, 1979), it is apparent that these ratios provide results similar to those for Ca/Mg versus Cl in this area and thus serve only to reinforce the conclusions drawn from the latter.

Even though geothermometry calculations based on cation concentrations in this environment should be attempted with caution, if at all, several such calculations were made on selected water sources within the valley. The resultant temperatures for most sources were relatively low (40°C to 80°C); however, well 2808-01 at the head of the valley had a calculated temperature of 141°C. Although this calculated temperature may not correspond precisely to the reservoir temperature, we believe that it strongly suggests that thermally altered fluids are entering shallow groundwaters in this area.

Sulfate (SO_4^{--})

Sulfate concentrations in most of the Lualualei Valley groundwaters are within the range normally expected in high level and basal aquifers. Three wells, however, do have sulfate concentrations distinctly higher than average: 2409-07 and 2409-23 in the southern side of the valley and 2808-01 at the head of the valley. On the basis of the median SO_4/Cl ion ratios found in other parts of the valley, the sulfate concentrations in both 2409-07 and 2409-23 appear to be normal,

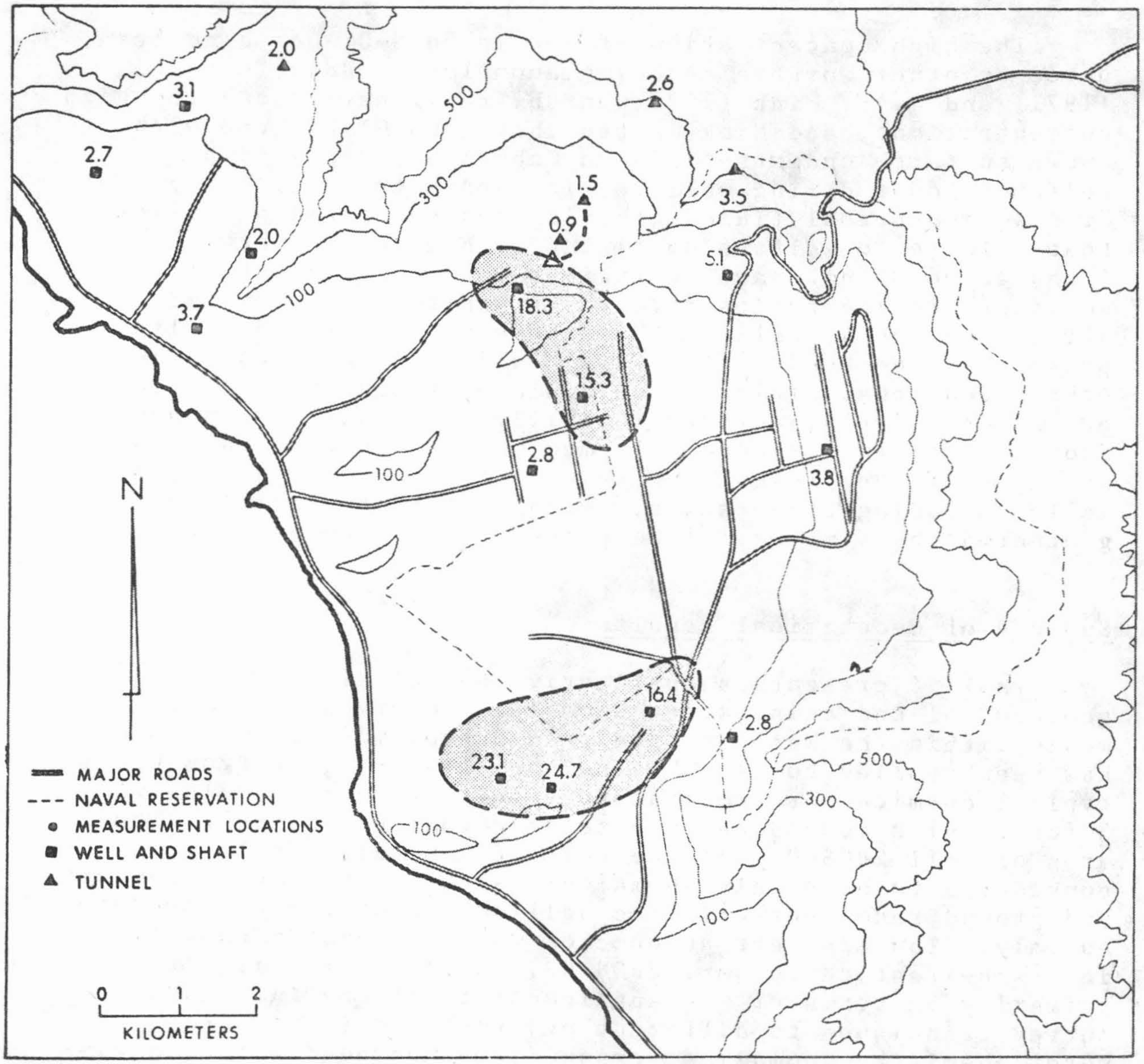


Fig. 24. Cl/Mg ratio of different groundwaters sampled. Ratios of 15 (that in sea water) or greater are considered anomalous. Two generalized anomalous zones are shown in shading.

whereas 2808-01 has a ratio that is a factor of five higher than most of the other sources. Further, wells 2808-02 and 2809-06, which are located to the north of 2808-01, also have slightly elevated SO_4/Cl ratios.

The high concentration of SO_4 in 2808-01 has also been noted by other workers as being anomalous. Both Takasaki (1971) and J. F. Mink (1978; unpub. rep.) have noted the high concentrations, and Mink stated that 2808-01 had the highest known sulfate concentrations on Oahu. He described a sulfurous odor during well testing and attributed it to "rising goethermal fluids carrying reduced forms of sulfur that oxidize to sulfate on mixing with meteoric water." Although we do not have sufficient data to attribute the high sulfate/chloride ratios directly to thermal groundwater alteration, we do believe that there is a source of sulfate present at the head of the valley which is not present in other locations. This source could be rising thermal fluids or, alternatively, sulfate remobilized by shallow groundwaters from hydrothermal minerals formed within the caldera boundary. In light of the presence of several other anomalies in this well, including temperature, we suggest that significant geothermal heat may still be present in the general area.

Summary of Geochemical Results

Table 6 presents a qualitative appraisal of the geochemical and temperature anomalies observed at sampled wells within the Waianae area. An approximate point system has been applied to each of the anomalies ranging from 0 for typical chemical or temperature results through a value of 3 for results considerably outside normal variations. The area of well 2808-01, at the head of Lualualei Valley, is considered to be highly anomalous, with strong water chemistry and ground radon anomalies as well as a moderate temperature anomaly. The apparent absence of water chemistry anomalies in its nearest neightbor, 2808-02, is considered significant primarily in terms of the applicability of the individual survey techniques to different environments (e.g., basal water chemistry anomalies versus dike-impounded water chemistry) rather than as a contradiction of the anomalies observed in 2808-01.

A second group of wells (2409-07, 2409-23, 2508-02, 2508-07) are also sufficiently different from the typical characteristics of groundwater in the valley to indicate alteration of the water and soil chemistry. Although not as strong as those at the head of the valley, the anomalous results in nearly all the survey techiques applied are considered significant.

Table 6. Summary of geochemical anomalies

WELL NUMBER	GROUND RADON	SOIL MERCURY	TEMPERATURE	SILICA	$\frac{Ca/Mg}{Cl}$	$\frac{Cl}{Mg}$	SO_4	TOTAL
2409-07	2	1	1	3	2	2	1	12
2409-23	1	2	1	3	2	2	1	12
2508-02	2	2	3	1	0	0	0	8
2508-07	3	1	1	3	2	2	0	12
2607-01	1	2	0	3	0	0	0	6
2609-X	0	1	0	0	2	1	0	4
2709-08	1	1	2	3	1	2	0	10
2712-01	0	2	0	3	0	0	0	5
2808-01	2	2	2	2	3	1	3	15
2808-02	3	2	0	1	0	0	0	6
2809-05	1	2	0	1	0	0	0	4
2809-06	3	2		1	0	0	0	6
2811-02	0	0	1	1	0	0	0	2
2812-01	0	1	1	1	0	0	0	3
2908-02	3	0	0	0	0	0	0	3
2911-01	0	0	0	1	0	0	0	1
2912-01	0	0	0	0	0	0	0	0

0 = not significantly anomalous   1 = slightly anomalous near the upper limit of natural, nonthermal variation
2 = above the upper limits of natural, nonthermal variations   3 = highly anomalous, probably of thermal origin

The areal distribution of the geochemical, chemical and temperature anomalies is summarized in Figure 25. Geochemical anomalies of varying magnitude have been identified in many parts of Lualualei Valley; however, at least two broad areas have an obvious coincidence of anomalies determined by different techniques: one at the southern edge of the inferred caldera and the other at the head of the valley, to the northeast. Although none of the observed surface anomalies can be uniquely attributed to the presence of geothermal fluids, we consider the coincidence of several anomalies in a few areas around the valley to be indicative of a strong perturbing influence on both groundwater chemistry and ground gas chemistry which we believe can be most reasonably attributed to thermal fluids entering the near-surface environment. For this condition to occur, the existence of anomalously high rock temperatures below these areas must be assumed.

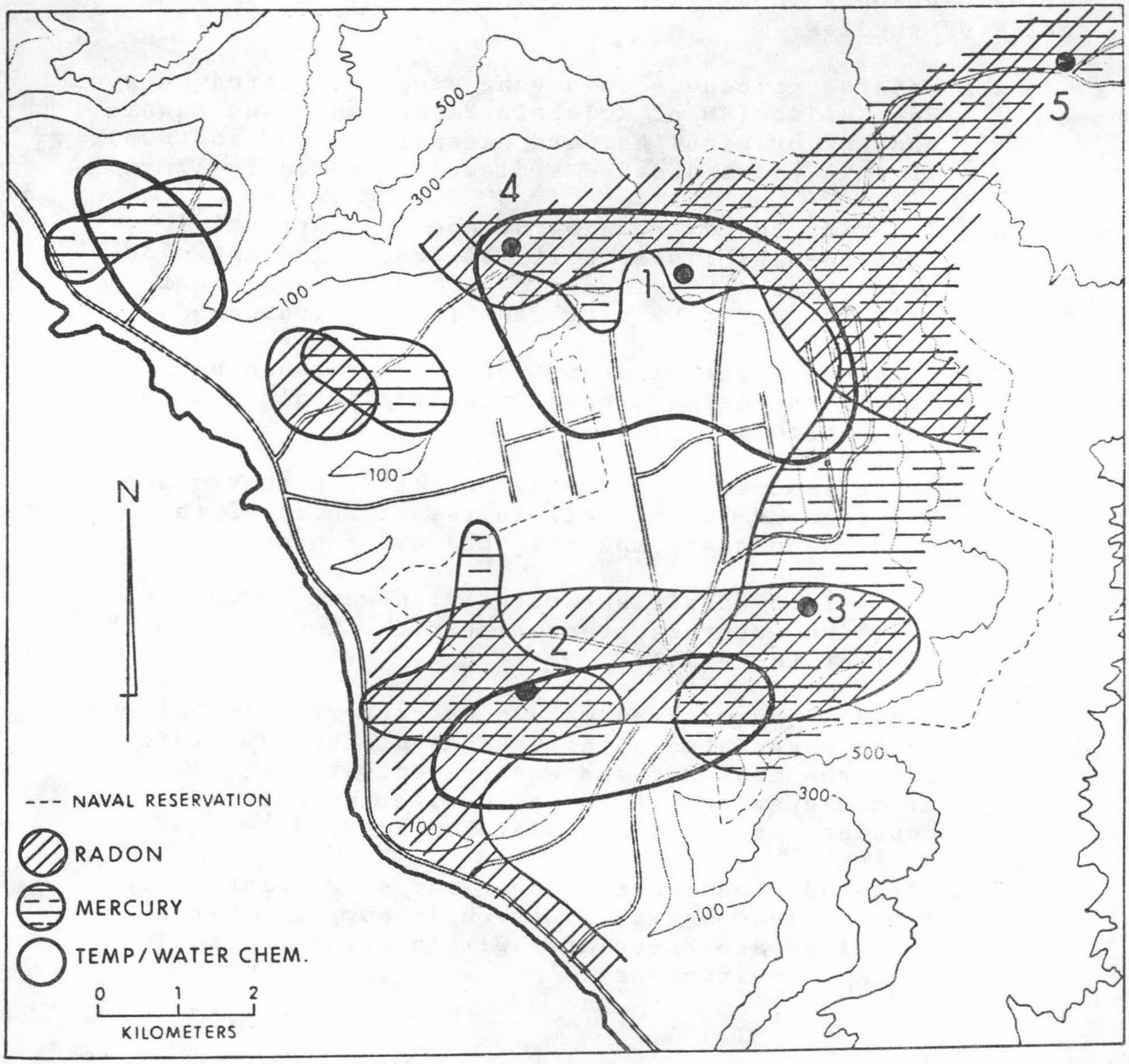


Fig. 25. Summary of areas with anomalous characteristics from these surveys. Five possible sites for exploration drilling are located and numbered 1 to 5 in order of priority.

CONCLUSIONS

Several important features of the geology in Lualualei Valley have been identified or reinforced by the present series of studies:

1. Waianae volcano's main vent area is located between Puu Kailio (SW of Kolekole Pass) and Mauna Kuwale, and the original caldera extended to the southwest of this point and had a diameter of nearly 17 km.

2. Two rift zones trending NW and SE, currently expressed by linear belts of fracturing and old eruptive features, extend out from the ancient caldera, and a NE rift zone is also indicated.

3. Erosion, fracturing and subsidence around and within the caldera have dramatically altered the volcano to its present form.

4. Minor amounts of hydrothermal alteration products are present in the soil in the vicinity of the caldera boundary and near the rift zones.

5. A layer of basalt saturated with warm, fresh to brackish water is present near the head and in the east of the valley.

6. Broad areas with anomalous characteristics believed to be associated with leakages of thermal fluids into the near-surface environments through deep fracture systems associated with the calera boundary and rift zones are delineated.

7. Elevated groundwater temperatures associated with the chemical anomalies strongly suggest that these anomalies are associated with a presently active thermal environments.

RECOMMENDATIONS

Although more surface studies would provide a more detailed delineation of the observed anomalies, we believe that evidence is sufficient to substantiate the presence of geothermal heat in the Lualualei Valley area. We now consider it necessary to obtain subsurface data to gain an understanding of whether the required geological conditions exist for the formation of a geothermal fluid reservoir. If such a reservoir exists, data must be obtained to provide more direct indications of the magnitude of temperatures and its capacity.

Consequently, we recommend that the next phase of investigations be comprised of a preliminary (exploratory) drilling program.

1. On the basis of the current studies five drill sites have been selected, and numbered 1 to 5 in order of priority (Fig. 25).

2. We suggest that exploratory holes be considered at least for sites 1 to 3 (within the Lualualei Naval Reserve).

3. We recommend that drillholes should be about 10 cm (4") diameter (at bottom of hole), and between 500 to 1000 m (1600 to 3200 ft) deep.

4. We recommend downhole studies of:

   a. hydrological conditions/controls

   b. stratigraphy/petrology

   c. alteration mineralogy

   d. temperature/thermal gradients

   e. deep aquifer water chemistry

   f. downhole geophysics.

5. We also recommend that geological field mapping continue in the Waianae region to provide a better understanding of the volcanic structure.

ACKNOWLEDGMENTS

We thank the following HIG staff who assisted in this study: Dale Erlandson, Leslie Kajiwara, Paul Eyre, Barry Fankhauser, Tom Thomas and Curtis Won. We especially thank Chuck Fraley for the water analyses, and Sandy Siegel for the water mercury analyses. The cooperation of the staff at the U.S.G.S. Honolulu Office, and Mr. Alex Lum and Captain Messick of the Lualualei Naval Reserve is appreciated.

The work was carried out under Department of Energy grant number DOE/ID/01713-5.

REFERENCES

Anderson, W.L., 1979. Program MARQDCLAG: Marquardt Inversion of DC-Schlumberger Soundings by Lagged-convolution. U.S. Geol. Survey Open-File Rept. 79-1432, 58 p.

Carr, R.A., M.M. Jones and E.R. Russ, 1974. Anomalous Mercury in Near Bottom Water of a Mid-Atlantic Rift Valley. Nature, v. 251, p. 489-490.

Coderre, J.A. and S. Steinthorsson, 1977. Natural Concentrations of Mercury in Iceland. Geochim. Cosmochim. Acta, v. 41, p. 419-424.

Compagnie Generale de Geophysique, 1955. Alaques de Sondage Electrique. Geophys. Prospect., v. 3, suppl. no. 3.

Cox, M.E., in press. Ground Radon Survey of a Geothermal Area in Hawaii. Geophys. Res. Lett.

Cox, M.E. and D.M. Thomas, 1979. Cl/Mg Ratio of Hawaiian Groundwaters as a Regional Geothermal Indicator. In Expanding the Geothermal Frontier, Transactions, Vol. 3. Geothermal Research Council, Davis, CA, p. 145-148.

Davis, S.N., 1969. Silica in Streams and Groundwater of Hawaii. Tech. Rep., Water Res. Research Cntr., v. 29, Univ. Hawaii, Honolulu, 31 p.

Doell, R.R. and G.B. Dalrymple, 1973. Potassium-argon Ages and Paleomagnetism of the Waianae and Koolau Volcanic Series, Oahu, Hawaii. Bull. Geol. Soc. Am., v. 84, p. 1217-1241.

Eshleman, A., S.M. Siegel and B.Z. Siegel, 1971. Is Mercury from Hawaii Volcanoes a Natural Source of Pollution? Nature, v. 233, p. 471-472.

Fan, Pow-foong, 1978a. Clays and Clay Minerals of Hydrothermal Origin in Hawaii. In M.M. Mortland and V.C. Farmer (eds.), International Clay Conference 1978, Developments in Sedimentology 27, Elsevier, Amsterdam, p. 369-374.

Fan, Pow-foong, 1978b. Mineral Assemblages of Hydrothermal Alterations of Basalts from Hawaii. In Geothermal Energy: A Novelty Becomes Resource, Geothermal Resources Council, Transact. v. 2, p. 185-187.

Fleischer, R.L., H.W. Alter, S.C. Furman, P.B. Price and R.M. Walker, 1972. Particle Tracking Etching. Science, v. 178, p. 255-263.

Fournier, R.O. and A.H. Truesdell, 1973. An Empirical Na-K-Ca Geothermometer for Natural Waters. Geochim. Cosmochim. Acta, v. 37, p. 1255-1275.

Funkhouser, J.G., I.L. Barnes and J.J. Naughton, 1968. The Determination of a Series of Ages of Hawaiian Volcanoes by the Potassium-argon Method. Pac. Sci., v. 22, p. 369-372.

Furumoto, A.S., N.N. Nielson and W.R. Phillips, 1973. A Study of Past Earthquakes, Isoseismic Zones of Intensity, and Recommended Zones for Structural Design in Hawaii. Hawaii Inst. Geophys. Rept., HIG-73-4, 50 p.

Gasparini, P. and M.S.M. Mantovani, 1978. Radon Anomalies and Volcanic Eruptions. J. Volcanol. Geotherm. Res., v. 3, p. 325-341.

Keller, G.V. and F.C. Frischknecht, 1966. Electrical Methods in Geophysical Prospecting. N.Y., Pergammon Press, p. 95.

Koga, A. and T. Noda, 1975. Geochemical Prospecting in Vapor-dominated Fields for Geothermal Exploration. Geochem. J., p. 761-766.

Kroopnick, P.M., R.W. Buddemeier, D. Thomas, L.S. Lau and D. Bills, 1978. Hydrology and Geochemistry of a Hawaiian Geothermal System: HGP-A. Hawaii Inst. Geophys. Rept., HIG-78-6, 64 p.

Kruger, P., A. Stocker and A. Umana, 1977. Radon in Geothermal Engineering. Geothermics, v. 5, p. 13-19.

Macdonald, G.A., 1940. Petrography of the Waianae Range, Oahu. Bull. Hawaii Div. Hydrogr., v. 5, p. 63-91.

Macdonald, G.A., 1968. Composition and Origin of Hawaiian Lavas. Geol. Soc. Am. Mem., v. 116, p. 477-522.

Macdonald, G.A. and A.T. Abbott, 1970. Volcanoes in the Sea. Univ. Hawaii Press, Honolulu, 441 p.

Macdonald, G.A. and T. Katsura, 1964. Chemical Composition of Hawaiian Lavas. J. Petrol., v. 5, no. 1, p. 82-133.

Malahoff, A. and G.P. Woollard, 1965. Magnetic Surveys Over the Hawaiian Ridge. Hawaii Inst. Geophys. Rept., HIG-65-11, 63 p.

Malahoff, A. and G.P. Woollard, 1966. Magnetic Measurements Over the Hawaiian Ridge and Their Volcanological Implications. Bull. Volcanol., v. 29, p. 735-760.

Matlick, J.S. and P.R. Buseck, 1975. Exploration for Geothermal Areas Using Mercury: A New Geochemical Technique. U.N. Geotherm. Conf., San Francisco., v. 1, p. 785-792.

McDougall, I., 1964. Potassium-argon Ages From Lavas of the Hawaiian Islands. Geol. Soc. Am. Bull., v. 75, p. 107-128.

McMurtry, G.M., P.F. Fan and T.B. Coplen, 1977. Chemical and Isotopic Investigations of Groundwater in Potential Geothermal Areas in Hawaii. Am. J. Sci., v. 277, p. 438-458.

Mink. J.F., 1961. Some Geochemical Aspect of Sea Water Intrusion in an Island Aquifer. Int. Assoc. Sci. Hydrol. Comm. Subterr. Waters, Pub. 52, p. 424-439.

Stearns, H.T., 1939. Geologic Map and Guide of Oahu, Hawaii. Hawaii Div. Hydrog. Bull. 2, 75 p.

Stearns, H.T., 1967. Geology of the Hawaiian Islands. Hawaii Div. Hydrol. Bull. 8, p. 4-82.

Stearns, H.T. and G.A. Macdonald, 1942. Geology and Groundwater Resources of the Island of Maui, Hawaii. Hawaii Div. Hydrog. Bull. 7, 344 p.

Stearns, H.T. and K.N. Vaksvik, 1935. Geology and Groundwater of the Island of Oahu, Hawaii. Hawaii Div. Hydrol. Bull. 1., p. 29-33.

Stearns, H.T., J.H. Swartz and G.A. Macdonald, 1940. Supplement to the Geology and Groundwater Resources of the Island of Oahu, Hawaii. Hawaii Div. Hydrol. Bull. 5, p. 72-85.

Strange, W.E., L.F. Machesky and G.P. Woollard, 1965. A Gravity Survey on the Island of Oahu. Pac. Sci., v. 19, p. 350-353.

Malahoff, A. and G.P. Woollard, 1965. Magnetic Surveys Over the Hawaiian Ridge. Hawaii Inst. Geophys. Rept., HIG-65-11, 63 p.

Malahoff, A. and G.P. Woollard, 1966. Magnetic Measurements Over the Hawaiian Ridge and Their Volcanological Implications. Bull. Volcanol., v. 29, p. 735-760.

Matlick, J.S. and P.R. Buseck, 1975. Exploration for Geothermal Areas Using Mercury: A New Geochemical Technique. U.N. Geotherm. Conf., San Francisco., v. 1, p. 785-792.

McDougall, I., 1964. Potassium-argon Ages From Lavas of the Hawaiian Islands. Geol. Soc. Am. Bull., v. 75, p. 107-128.

McMurtry, G.M., P.F. Fan and T.B. Coplen, 1977. Chemical and Isotopic Investigations of Groundwater in Potential Geothermal Areas in Hawaii. Am. J. Sci., v. 277, p. 438-458.

Mink. J.F., 1961. Some Geochemical Aspect of Sea Water Intrusion in an Island Aquifer. Int. Assoc. Sci. Hydrol. Comm. Subterr. Waters, Pub. 52, p. 424-439.

Stearns, H.T., 1939. Geologic Map and Guide of Oahu, Hawaii. Hawaii Div. Hydrog. Bull. 2, 75 p.

Stearns, H.T., 1967. Geology of the Hawaiian Islands. Hawaii Div. Hydrol. Bull. 8, p. 4-82.

Stearns, H.T. and G.A. Macdonald, 1942. Geology and Groundwater Resources of the Island of Maui, Hawaii. Hawaii Div. Hydrog. Bull. 7, 344 p.

Stearns, H.T. and K.N. Vaksvik, 1935. Geology and Groundwater of the Island of Oahu, Hawaii. Hawaii Div. Hydrol. Bull. 1., p. 29-33.

Stearns, H.T., J.H. Swartz and G.A. Macdonald, 1940. Supplement to the Geology and Groundwater Resources of the Island of Oahu, Hawaii. Hawaii Div. Hydrol. Bull. 5, p. 72-85.

Strange, W.E., L.F. Machesky and G.P. Woollard, 1965. A Gravity Survey on the Island of Oahu. Pac. Sci., v. 19, p. 350-353.

Takasaki, K.J., 1971. Groundwater in the Waianae District, Oahu, Hawaii. Hydrol. Investigation Atlas, J.S.G.S., HA-358.

Tasci, M.T., 1975. Exploration For a Geothermal System in Lualualei Valley, Oahu, Hawaii. In L.T. Grose and G.V. Keller, (eds.), Geothermal Energy in the Pacific Region, 75 p.

U.S. Geological Survey, 1979. Well Logs and Data on File. Honolulu Office, Hawaii.

Woollard, G.P., 1951. A Gravity Reconnaissance of the Island of Oahu. Trans. Am. Geophys. Union, v. 32, no. 3, p. 358-368.

Zohdy, A.A.R. and D.B. Jackson, 1969. Application of Deep Electrical Soundings for Groundwater Exploration in Hawaii. Geophysics, v. 34, no. 4, p. 584-599.