EXPLORATION FOR GEOTHERMAL ENERGY

IN OAHU, HAWAII

By

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A Thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science in Geophysics.

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ABSTRACT

During August 1976 to January 1977 a combined geothermal reconnaissance survey was carried out on the island of Oahu, Hawaii. This survey consisted of an electrical resistivity survey, a microseismicity survey, and geochemical analysis of mercury in the soil.

The surveys provide a weak indication of potential for the occurrence of geothermal energy in the Koolau Range area. Two parallel fracture zones probably extending to the mantle are associated with the Honolulu volcanic series. These are the Koko Head fracture and the Diamond Head fracture, the latter consisting of the Diamond Head crater, the Kauu crater, and the Ulupau crater. The Diamond Head fracture passes over the center of the older Koolau caldera. Near the town of Waimanalo high values for the concentration of mercury in the soil are present along with low electrical resistivities. Microseismic stations in this area provide weak indication of low velocity events. High resistivities are also observed at Olomana Peak suggesting the presence of an intrusive of younger age than the Koolau caldera.
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ACKNOWLEDGEMENTS

I would like to express gratitude to Dr. G.V. Keller for his guidance as a thesis advisor and for making this project possible. My appreciation is extended to Dr. R.C. Holmer and Dr. T.L. Davis who served as committee members.

I am grateful to Dr. Augustine Furumoto of Hawaii Institute of Geophysics, Nelson Rodriguez, Paul L. Brown, and Tim Zeisloft for their assistance in collecting the field data. I am specially grateful to John Arestad for providing the modeling computer program.

I wish to acknowledge the Office of Naval Research for financial assistance of this survey. I thank the Universidad Simon Bolivar for providing the scholarship which has made continuing my education possible.
INTRODUCTION

Located 2000 km southwest of San Diego between the latitudes 18°54' and 28°15' N and longitudes 154°40' and 171°15' W lies the Hawaiian archipelago which constitutes the 49th State of the United States of America (see Figure 1).

These islands have developed along a zone of weakness in the bottom of the Pacific Ocean (Stearns, 1966). Each island is a shield volcano rising 3000 meters from the floor of the Pacific Ocean to the surface and additional elevations of 4205 m (13,796 ft.) above sea level in Maunakea, Hawaii. This constitutes the biggest mountain range on earth.

The archipelago developed along a narrow southeast-trending zone of progressively younger volcanoes extending over 2000 km and ending in the Island of Hawaii which is erupting and presently active.

Recent volcanic activity lava flows have made the Island of Hawaii the focus of geothermal interest. With the advent of the fuel crisis, marginal sources of power like geothermal energy started to receive attention. The question of demand came as an important factor, and the stress is placed in the highly populated areas with a fair degree of industrialization. This shifted the attention from the big island of Hawaii to Oahu, which is the residence
FIGURE 1. Hawaiian Island Map (National Geographic Society, 1976).
of 80% of the Hawaiian population (Furumoto, 1976).

The work presented here is aimed to contribute information on possible occurrences of geothermal fluids. Previous work by the Hawaii Institute of Geophysics defined two clear calderas which now constitute the Waianae and Koolau Ranges. A thorough geophysical investigation in the Koolau magma chamber using electrical, geochemical, and microseismic methods were combined in this survey. The results presented here indicate the possibility of a potential heat reservoir under Olomana Peak near the town of Waimanalo (see Figure 2).
GEOLOGY

The Islands of Hawaii came very late in the development of the earth. The oldest radiometric studies by the potassium argon method on the lava's age from the Hawaiian volcanics from the Necker Island date it only 11.3 million years old (Funkhouser, et al., 1968).

These volcanic edifices have been under weathering and erosion by the constant surf and rain. The history of these volcanic islands is fairly well understood. After the volcanic activity has ceased, the islands begin to subside with the simultaneous development of a fringing reef. In the late stages, the original volcanic rock is completely submerged, and the only remains are a barrier reef with an atoll enclosing a lagoon. Most of the Hawaiian Islands have reached this stage providing evidence of subsidence.

Structurally, the presence of the Hawaiian Islands in the middle of the Pacific is not fully understood; movement of the mantle with respect to the crust over a "hot spot" is a suggestive idea. Another approach suggests a zone of weakness in the east-west direction caused by stresses originated by the collision of the plates, or perhaps by the effect of one or more glaciation periods causing additional cooling near the poles.

Hawaiian volcanoes extruded primarily along faults oriented mainly east-west (MacDonald & Abbott, 1970).
Presently these faults are associated with the Molokai fracture system along which also lies the Koolau dike complex and the Musician Sea Mount. It is difficult to determine whether the NW-SE fracture system is a strike-slip fault or a simple tension crack, or tear, along the crest of a fold. The archipelago may have been built on an older ridge, perhaps contemporaneous with a chain of islands that existed in middle and early Tertiary time further NW. Stears (1966) suggests its existence since early Tertiary. There were at least two different periods of volcanism. During the Quaternary all the islands except Lanai experienced secondary eruptions.

The mass of the extruded lavas caused the islands to sink in order to re-establish isostatic equilibrium. The action of the wind, rain, and waves played an important role of the erosion of the islands at the same time that furnish a marker in the geologic time scale.

Fossils and shallow-water corals indicate development in Honolulu during late Miocene are now 518 m (1700 ft.) below sea level (MacDonald & Abbott, 1970). The older islands to the northwest are believed to have submerged 3000 m (Stearns, 1966). However, there is some evidence that complex submergences and emergences occurred, since there was limited reef formation.
REGIONAL GEOLOGY OF OAHU

Oahu is a volcanic doublet, formed by the Wainae Range on the west and the more recent Koolau Range on the east. Between the two ranges lies the Schofield Plateau which along with the Coastal Plain constitutes the four major geomorphologic provinces of Oahu (see Figure 3).

The Wainae is the older of the two ranges and is located in the western part of the island and extending for 35 km. During the Tertiary, the Wainae Volcanic Series erupted from the three rift planes (Stearns, 1966). They are divided into lower, middle, and upper members. The main mass of the volcano was formed by the lower member. It exposed part of the lava and is nearly 650 m thick consisting largely of thin beds of pahoehoe. These tholeiitic lava flows are associated with pyroclastic rocks. The middle basalts consist of tholeiitic rocks that accumulated in the caldera gradually filling it. Alkalic basalts begin to appear toward the top of the middle member. The upper lavas were massive andesite flows which issued from large cinder cones composed of largely Hawaiite, or andesitic lava in which the feldspar is mainly andesine and pyroxene, with lesser amounts of alkalic olivine basalt. Stream deposited alluvium from a 400 m (1300 ft.) deep well in Lualualei Valley show that the valley was once at that level, or that subsidence in
FIGURE 3. Geologic map of the island of Oahu (modified after Stearns, 1946).
that part of the island amounts to at least 400 m (1300 ft.). The Koolau Range is located to the east and was built along an elongated shield built principally during SE trending rift zone. The rocks of the Koolau Volcano are mainly tholeiitic and olivine basalts with small amounts of oceanite, orthorombic pyroxene, and hypersthene. The Kailua volcanic series are the eroded rocks of the ancient caldera. These rocks are altered by hydrothermal action due to steam rising in the vent area. The Kailua series followed with lavas and dikes lying outside the caldera and were altered only by hydrothermal fluids. After the Koolau Volcano ceased activity, a period of erosion and deposition started lasting 2 million years. Then the volcanic activity resumed on the southeastern end of the Koolau Range. About 30 vents have erupted, and they are called the Honolulu Volcanic Series. The vents are aligned chiefly along NE-SW fissures, and the lavas include nephelinites, basanites which contain both nepheline and plagioclase, and alkalic olivine basalts (Tascin, 1975). Calderas filling lavas extend all the way to the top of Olomana Peak. Recent geophysical work indicates that there is a mass of high density rock with high seismic velocities at about 2 km beneath the Koolau Caldera (Furumoto & Adams, 1965). This would be centered approximately beneath the Kawainui Swamp.

The Schofield Plateau was formed by the lavas from the Koolau Range banking against the already eroded slope
of the Waianae Volcano to form the gently sloping surface of
the Schofield Plateau. An erosional unconformity between
the interfringing lavas of the two volcanoes is visible
along Kaukonahua Gulch at the eastern foot of the Waianae
Range (MacDonald & Abbott, 1970).

The coastal plain lies mostly on the ponded lavas of
the Koolau Volcano north and south of the Schofield Plateau.
The plain is composed mainly of marine sediments deposited
on the lavas when the sea stood higher in mid-Pleistocene
time.
GEOLOGY OF THE STUDY AREA

The caldera of Koolau Volcano was about 13 km long and 7 km wide, extending from near Waimanalo at the southeast to Kaneohe at the northwest (MacDonald & Abbott, 1970). Its southwestern boundary lies near the base of the Pali, and its eastern boundary is somewhere between the hills at Lainakai and the Mokulua Islands offshore (MacDonald & Abbott, 1965). The presence of Olomana Peak can be explained as a landslide formed by eroding away the surrounding rocks in the caldera area (MacDonald & Abbott, 1970).

The dike complex formed by the Kailua series constitutes a rift zone trending NW. Traverses across the dike complex at various places have yielded more than 400 dikes per km, ranging from a few centimeters to 3 m thick. The lavas of the Honolulu volcanic series include nephelinites, melicites, basanites, and other basanitoids which are rich in magnesium, iron, and undersaturated with silica.

On a first glance at the map of the area, we notice the alignment of the three small craters formed during the eruption of Honolulu Series. Diamond Head is the largest and southern-most crater. Kauu Crater is at the edge of the Pali, and the Ulupau Crater is at the end of the Mokapu Peninsula. Along this line, we have the Kawainui Swamp and the Olomana Peak.

A similar alignment is observed along the SE coast.
The Koko Fissure formed a series of small spatter cones and lava flows. The Honolulu Volcanic Series seem to have concluded with the Koko eruption only 31,000 years ago (Furumoto, 1976).

The center of the magma chamber was approximately where the Kawainui Swamp lies today. Erosion seems to have removed the northeastern half of the volcanic edifice and left thick deposits of alluvium in the depressions. Geophysical studies of seismic refraction reveal sediments at depths of several hundred meters (see Figures 4 and 5).

FIGURE 5. Sedimentary profile along E-W line near the town of Waimanalo showing the location of water wells (Furumoto, 1976).
PREVIOUS GEOPHYSICAL INVESTIGATIONS

The internal structure of the volcanoes in Oahu and their relation to the surrounding oceanic crust were studied during the 1960's using gravity, magnetics, and refraction surveys (Furumoto, 1976). The data obtained on Oahu has contributed significantly to the then viable MOHCLE project and to the understanding of volcanoes.

In the Bouguer map of Oahu produced by Strange, Machesky, and Woollard (MacDonald, 1970), the island produces a Bouguer anomaly of 200 mgal (see Figure 6) with additional positive anomalies of 100 and 110 mgals associated with the Wainae and Koolau Calderas. The Koolau magma chamber and/or volcanic plug approximates a buried vertical cylinder of density $3.2 \, \text{gr/cc}$ whose dimensions calculated from gravity data have been estimated to be 16 km diameter and 10 km vertical height buried at 3 km from the surface.

The analysis of magnetic data correlates well with the results from the gravity study. A magnetic survey carried out by Strange and others (1965) shows definite centers of strong magnetic expressions over the two volcanoes. The Wainae volcano center is normally polarized while the Koolau center is reversely polarized. Cancellation of the magnetic fields of several layers is expected to be caused by the reversal of the earth fields or by the influence of previous layers in the orientation of new cooling lavas.
FIGURE 6. Map of the island of Oahu showing the relation of strong positive gravity anomalies to the calderas of the Koolau and Waianae volcanoes. The values for gravity are Bouguer anomalies, in milligals (after Strange, Machesky and Woollard, 1965).
The structure of the Koolau has been intensely studied by A. Furumoto and the H.I.G. (Hawaii Institute of Geophysics) (Furumoto, et al., 1965). Seismic refraction studies showed that the plug has velocity greater than 7 km/sec and adjoins material with a velocity of about 4.6 km/sec. Refractions from a horizon greater than 3 km deep may indicate an underlying magma chamber. Above the magma chamber of extruded Hawaiian rock layers with a P-wave velocity of 4.7 km/sec is associated with a bulk density of 2.65 to 2.7 g/cc and a porosity of 9 to 12%. With such porosity, this layer can act as an aquifer. Atop this porous layer is the relatively impervious sedimentary layer, as much as 700 m thick in places, acting as cap rock. With this we have the necessary ingredients for a conventional geothermal system—an aquifer heated from below and capped by an impervious rock.

Experimental research conducted at the Colorado School of Mines on the physical properties of geothermal reservoir rocks from six different states where there is evidence of high heat flow indicate that volcanic rock under saturated conditions exhibits porosities of about 25%, ranging between 5% and 50%. From the cross plots of calculated porosity versus bulk resistivity using a .5N saturating solution produced cementation factors from 2.23 to 1.57 (see Figure 7) (Keller, 1977).

Direct current resistivity was utilized by Zhody and
FIGURE 7. Linear regressions on a double logarithmic scale for the scatter plots of geothermal reservoir rocks. Archie's Law with $a = 1$ and $m = 2$ is shown as a dashed line. Data previously reported for Hawaiian basalts and rhyolites from the Oak Springs formation from southern Nevada are shown as the two dotted lines (Keller, 1977).
Jackson (1968) near the town of Waialua, Oahu. The purpose of this study was to locate fresh water aquifers, but the conclusions are interesting in the understanding the resistivity associated with the Koolau structure.

As it was expected, an increase was observed in the clay resistivity away from the shoreline. This increase reflects primarily the decrease in salinity of the groundwater that saturates the clay. The resistivity of the basalts when saturated with saline water is very low (30 ohm-m). The resistivity of fresh basalt, saturated with fresh water, ranges from about 300 ohm-m to 700 ohm-m. The depth to the fresh-salt water interface can be obtained from the Ghyben Herzberg relationship which predicts that this fresh salt water interface will be depressed about 40 m below sea level for every meter of fresh water above sea level.

During the summer of 1974, the Colorado School of Mines conducted geophysical studies in Lualualei and in the Waianae Caldera (Tascin, 1975). The studies consisted of dipole mapping resistivity, electric self potential, and small hole (one meter) temperature survey. Tascin outlines a potential geothermal target over an area of 2 by 1 Km where the three independent types of survey coincide in location of the "hot" spot. I intended to do further research in this area, but access to the area was regretfully rejected by the Navy.
Perhaps the most encouraging sign of latent heat in
the Koolau Range is the fact that two recent wells in the
vicinity of Olomana Peak have temperatures 10°C above am­
bient (Furumoto, 1976). The increase of a few degrees
centigrade can be more significant considering that it
represents a mixture of atmospheric water with hotter water
upwelling from a heat source.
MERCURY IN SOIL

In evaluating the potential of a geothermal prospect, a primary concern is the temperature at which groundwater exists at drillhole depths. Geochemical methods are used in preliminary prospecting as well as in subsurface exploration, development drilling, well testing, and production. The relative amounts of some elements present in hot water are diagnostic of subsurface temperatures. These elements can be used as geothermometers as temperature indicators.

An important fact to consider is that the presence of geothermal reservoir not only affects the solution of salts in groundwater but also contributes to the liberation of gases like helium or mercury vapor (Gutsalo, 1975, II UNSGD, p. 745). Mercury gas in soil is relatively inexpensive to measure due to the high atomic mass. These elements are not easily trapped in the rocks and tend to diffuse continuously to the surface of the earth. The presence of higher temperatures accelerates the rate of diffusion, and anomalously high concentrations of mercury and helium will occur in the soil. For example, the normal concentrations of mercury in soil are 10 to 100 ppb (parts per billion). It has been observed that in known geothermal areas, the concentration of mercury provides an anomaly that is 100 to 1000 times greater. At the Geyser Fields in California, at Roosevelt Hot Springs in Utah, and at the Hawaii Geothermal Test Well #1 in pumice the concentration of mercury
in the soil reaches levels of 1000 to 10,000 ppb (Matlick and Buseck, 1975). These three geothermal areas are characterized by relatively high reservoir temperatures in the range from 500°F to 600°F. At Heber Imperial Valley of California, the soil mercury content reaches 300 to 500 ppb where the reservoir temperature is 350°F to 400°F. These data are incomplete but are a direct indication of geothermal reservoir temperature.

Description of the Method

As part of this investigation, 34 soil samples were analyzed for mercury. Thirty-two of these soil samples were taken within the area of the Koolau Caldera as indicated by Figure 8. The other two soil samples were taken near the entrance of Lualualei Naval Magazine in the Waianae Caldera. Unfortunately, permission to sample on the magazine area where previous work had indicated a prospect for a geothermal reservoir to lie could not be obtained.

Each sample consisted of 30 to 50 gr of soil from a depth of 15 to 30 cm. The soil samples were sized using an 80 mesh stainless steel sieve to separate the fine sand sizes for analysis. The sieved fraction is immediately sealed in a clean air-tight glass vial. Soil analysis starts by placing the measured sample in a test tube and heated to volatilize any metallic mercury which might be present. The fumes derived from the sample were passed through a silver thimble to separate the mercury from organic compounds which
FIGURE 8. Mercury in soil survey in the Koolau Range shows anomalous highs in the vicinity of Olomana Peak near the town of Waimanalo.
could be volatized along with them. After heating for three minutes, the thimble was removed, and it, in turn, was placed in the oven. On heating, the thimble would release the amalgamated mercury which was then passed through a double atomic absorption cell. The accuracy of mercury determinations with this device is probably ± 20%. The range of concentrations to be expected is from 10 to 20 ppb in barren material to 10,000 ppb in material rich in metallic mercury (Matlick and Buseck, 1975).

Interpretation of Results

All of the values except for a few measured in the northern part of the Koolau area were anomalously high. Many values were in the range from 100 to 500 ppb, and two samples showed mercury concentrations of more than a 1,000 ppb. Station locations and mercury concentrations are shown on the map in Figure 8.

All the soil samples shown on Figure 8 were taken at locations within the Koolau Caldera. The normal values for soil mercury content determined on the Island of Hawaii are in the range from 40 to 100 ppb (Keller, 1977). Whether or not such normal values would be determined at locations outside the Koolau Caldera cannot be determined on the basis of the data presented here. The relatively high mercury contents on Oahu may possibly be attributed to a relatively high concentration of mercury in the basalt generated by the two volcanoes on Oahu. However, a more acceptable
explanation particularly in view of the fact that the highest mercury concentrations are aligned with the Diamond Head Fracture along which eruptive activity has occurred within the last 300,000 years is that the mercury is being mobilized by residual heat along this fracture line (Cox, 1966). The two mercury concentrations determined for the samples taken from the Lualualei area are 250 and 235 ppb, or roughly the same as the general level in the Koolau Caldera.

These relatively high mercury concentrations in the soil over Waianae Caldera and Koolau Caldera provide some hope that considerable residual heat exists in the subsurface (see Figure 9). High mercury in the soil concentrations are also encountered in the vicinity of geologic faults, since the fault planes offer least resistance to the mercury vapors.
### AGES OF LAVAS OF HONOLULU VOLCANIC SERIES, OAHU, HAWAII BY POTASSIUM-ARGON METHOD

<table>
<thead>
<tr>
<th>Vent Number</th>
<th>Location</th>
<th>Calculated Ages (Thousand years)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Salt Lake</td>
<td>416—430</td>
</tr>
<tr>
<td>2</td>
<td>Kaliki</td>
<td>457—464</td>
</tr>
<tr>
<td>3</td>
<td>Punchbowl</td>
<td>285—297</td>
</tr>
<tr>
<td>4</td>
<td>Nuuanu</td>
<td>416—422</td>
</tr>
<tr>
<td>5</td>
<td>Castle</td>
<td>846—850</td>
</tr>
<tr>
<td>6</td>
<td>Sugar Loaf</td>
<td>65—68</td>
</tr>
<tr>
<td>7</td>
<td>Kaaal</td>
<td>617—677</td>
</tr>
<tr>
<td>8</td>
<td>Kaumuki</td>
<td>285—256</td>
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<tr>
<td>9</td>
<td>Black Point</td>
<td>237—316</td>
</tr>
<tr>
<td>10</td>
<td>Koko</td>
<td>35—44</td>
</tr>
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<td>11</td>
<td>Kalama</td>
<td>36—33</td>
</tr>
<tr>
<td>12</td>
<td>Kaupo</td>
<td>31—33</td>
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</table>

![Map of Recent volcanic flows in Oahu](image_url)

**FIGURE 9.** Recent volcanic flows in Oahu (Cox, 1966).
SEISMICITY

The presence of a magma chamber in the upper crust will severely affect the adjacent rocks. The high heat flow establishes convection currents due to differences in temperature, and the rocks in the vicinity are affected, developing fractures. Convection currents occur not only in the ground waters, but also in the cooling molten rock. The circulation of the magma and the fractures in the surrounding rocks constitute weak sources of seismic waves that can be monitored in the near surface.

This method for detecting geothermal targets has been widely used (Kruger & Otte, 1973, Geothermal Energy, Stanford Press, Stanford, Calif., p. 106).

Many earthquakes with magnitudes varying from -2 to 0 can be observed around cooling intrusions. Such is the case at Kilauea Volcano on the Island of Hawaii. It is suspected that this volcanic activity is associated with the breakage of rock under thermal stresses as the rate of heating in a newly developed geothermal system is very high. In other geothermal systems, the level of micro-seismic activity may be quite low. However, travel times for earthquake waves through the crust and upper part of the mantle can be used to locate unusually high temperatures. Elevation of temperature along with fracturing of the crustal rock will reduce the velocity of transmission for both P and S waves. In an area where the rocks at considerable depths are unusually
hot, P waves arriving from distant earthquakes will be slow. This method has been used very effectively at Yellowstone National Park for mapping the magma chamber beneath the caldera area (Eaton, 1975).

Description of the Method

Microseismicity surveys are generally carried out by installing a net (10-12) of high frequency seismographs (1-30 Hz) near the area of interest. These seismographs are located in places where the cultural and human noise are expected to be minimum. The general type will consist of a vertical component geophone, the recording mechanism and a precision clock. The clock puts a tic mark every second, minute, and hour on the smoke paper drum (Figure 10). All seismographs are synchronized within 5 msecs, so a given arrival time can be established accurately in each of the stations. Later events are recognized by signature and time of arrival and analyzed in terms of P and S arrival times. The difference between P and S gives us a general idea of the epicentral distance. The directions and velocities are inferred in the different arrival times at the station locations. For events occurring at distances greater than 200 km, the propagation front can be assumed plane, but if the stations are near the epicenter, it is necessary to assume spherical wave propagation and correct arrival times.
FIGURE 10. Microearthquake record. A ten cents coin (dime) shown for scale. Time marks every second.
Interpretation of Results

A microseismicity survey of the Island of Oahu was carried out jointly by Microgeophysics Corporation of Golden, Colorado, and the Hawaii Institute of Geophysics as part of this study. During the interval from July 16 to August 5, 1976, micro-earthquake recording systems were operated at 14 locations as indicated on the map in Figure 11. Four of these locations had to be abandoned after a short period of recording because of high noise levels. For most of the survey, records were obtained continuously from seven or eight stations. The intervals during which each of the stations was operative are indicated on the operations log in Table 1.

Because of the high density of population on the Island of Oahu and because of the relatively small size of the island, extraneous noise from human activity and from wave action on the coast made detection of small events difficult. Four of the twenty days during which at least part of this network was operating, no events could be identified as occurring within either the Waianae or Koolau Calderas. While it is possible that the recording period was one of unusual quiet, it appears that microseismic activity in the two calderas is at a lower level than is normally encountered in volcanic areas with recent intrusives. P wave velocities across the Koolau Caldera were determined for five clearly recorded but more distant events as listed in Table 2. These events originated at distances ranging from 89 to 320 km,
FIGURE 11. Microseismicity survey. Station location indicating direction of arrival and velocity (Km/sec).
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**TABLE 1.** Table of microearthquakes events between the 16 of July and 5 of August, 1976.

- **☆** NOISY
- **●** EVENTS USED
- **△** INCOMPLETE
- **○** EVENTS NOT USED
- **✓** NO EVENTS
<table>
<thead>
<tr>
<th>EVENT</th>
<th>VELO</th>
<th>DIST</th>
<th>TIME</th>
<th>S-P</th>
<th>FROM</th>
</tr>
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<tr>
<td>23/6/15:39</td>
<td>8.5</td>
<td>320</td>
<td>37.65</td>
<td>37.27</td>
<td>SE</td>
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<tr>
<td>8/1/19 C2</td>
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<td>320</td>
<td>53.33</td>
<td>37.5</td>
<td>SW</td>
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<tr>
<td>27/7/21:20</td>
<td>6.1</td>
<td>26.6</td>
<td>43.5</td>
<td>3.0</td>
<td>WNW</td>
</tr>
<tr>
<td>19/7/9:32</td>
<td>5.22</td>
<td>249</td>
<td>47.70</td>
<td>32</td>
<td>ENE</td>
</tr>
<tr>
<td>20/7/4:46</td>
<td>7.0</td>
<td>89</td>
<td>12.71</td>
<td>11</td>
<td>NE</td>
</tr>
</tbody>
</table>

**VELOCITY** in kilometers/second  
**DISTANCE** in kilometers  
**TIME** in seconds  
**S-P** in seconds

**TABLE 2.** Table of velocities of the recorded events.
so that the first arrival should be a P wave refracted along the top of the mantle. The apparent travel time for the P wave across the array was determined simply by plotting arrival times as a function of distance from the epicenter. It should be noted that the epicentral distance need not be known precisely in order to determine the incremental velocity.

The travel time curves for the five events used are presented in Figures 12 through 16. In these figures the time of arrival is plotted in seconds representing the universal standard time versus distance from the first station to receive the micro-earthquake along the direction of the wave front.

The incremental velocities determined for the five events range from 5.2 km per second to 8.5 km per second. The higher interval velocities were not associated with the greater epicentral distances, as may be seen by the combined travel time plot in Figure 17. This assures us that the difference in velocity does not reflect a change in velocity with depth for the waves arriving from a greater distance. It seems more likely that the differences in interval velocity reflect changes in the velocity structure of the crust and upper mantle, some of which may be caused by temperature effects. A plot of the interval velocities for each of the stations used in their determinations with a vector showing the direction of arrival for the waves indicates that there
FIGURE 12. Travel time plot. In these figures the time of arrival is plotted in seconds representing the universal standard time versus distance from the first station to receive the micro-earthquake along the direction of the wave front.
FIGURE 13. Travel time plot. Plotted the same as Figure 12.
FIGURE 14. Travel time plot. Plotted the same as Figure 12.
FIGURE 15. Travel time plot. Plotted the same as Figure 12.
FIGURE 16. Travel time plot. Plotted the same as Figure 12.
is an area of relatively low interval velocity in the vicinity of Olomana Peak (see Figure 10) while the velocities from outside the caldera area are significantly higher.

While the amount of seismic evidence for an anomaly in wave speed within the caldera is weak, it is suggestive enough that further effort should be expanded in defining the velocity structure within the caldera.
DIRECT CURRENT RESISTIVITY SURVEY

A direct current resistivity survey was carried out in two areas on Oahu as part of this program. The dipole mapping method (bipole-dipole method) was used. Two sets of measurements were made about two source locations, one in the vicinity of Kailua Village on the Koolau side of Oahu, and the other along the east face of the Waianae Range near the town of Waipahu.

Description of the Method

In these surveys, a crossed dipole source was used. That is, at a source location, two bipole sources oriented roughly at right angles to each other were installed. These bipole sources were approximately one km in length each, consisting of AWG No. 8 wire grounded through sheets of metal buried in the soil. Each of the two sources was powered sequentially with an asymmetric square wave current wave form. The current wave form had a periodicity of 20 seconds, but current flow in one direction of the square wave lasted for about 50% longer than the current flow in the opposite direction. The asymmetry of the current wave form was used to identify the polarity of received signals.

Electric field measurements were made at many locations around each of these pairs of bipole sources. The electric field was detected using short grounded dipoles oriented approximately at right angles to one another,
with an interior spacing of 30 to 100 meters. The signals from the electrode pairs were recorded on an analog recorder, and later scaled to yield the voltage between receiver electrodes caused by current flow from the source bipole.

As a first step, the signals from each of the two bipole sources were treated independently to yield values of apparent resistivity using the formula based on the magnitude of the electric field at a receiver station (G.V. Keller, et. al., 1975) (See Figure 18):

\[
\rho_a = \frac{E_T}{I} \frac{2\pi R_1^2}{(1 + (R_1/R_2)^4 + 2(R_1/R_2)^2 \cos D)^{3/2}}
\]

where \( \rho_a \) is apparent resistivity in ohm-meters, \( R_1 \) and \( R_2 \) are distances in meters. \( E_T \) is the magnitude of the electric field in volts/meter and \( I \) is the current (see Figure 18). Apparent resistivity and apparent conductance can be computed assuming spherical spreading of current in a homogeneous earth. In general the model used for interpretation implies cylindrical spreading of currents for a conductive layer over a resistive basement, or the case of layered sediments, over crystalline basement.

Conductance is often more meaningful since it represents resistivity as well as depth. The formula to compute apparent conductance for dipole mapping data according to Furgerson and Keller (1974) is
where $S_a$ is apparent conductance in ohms, $R_1$ and $R_2$ are distances in meters, $E_T$ is the magnitude of the electric field in volt/meter and $I$ is the current in amperes.

**Interpretation of Results**

A preliminary calculation of apparent resistivities and conductances was performed at the end of each day or two at the field using a programable hand calculator. Electric field magnitudes and directions were picked from the chart paper records. Topographic maps with scale of 1 inch to 1 mile (1:62500) were used for station location. This was done to improve the receiver coverage in areas of potential interest.

Upon completion of the survey, the data was revised for correction of possible human error. The corrected field data was then recomputed on the CSM computer (Digital Equipment Corporation PDP-10). The bipole source computations were done with a program adapted from RCON.FOR of G.V. Keller.

The complexity of interpreting dipole mapping resistivity has been a subject of intensive study here at CSM. Simple structure modeling has been used by Morris (1975). Vertical faults and two horizontal layers were studied by Furgerson (1970). The dipping layer case was studied by Lee, (1974). The effect of anisotropy on apparent resistivities
and electric field directions has been demonstrated by Keller and Crewdson (1976) and Arestad (1977).

The rotating quadripole method is used to eliminate possible false anomalies due to the orientation of the sources. The effect of artificial rotation of the bipole sources provides information on the coefficient of anisotropy or the orientation of apparent resistivity ellipse. So for each station it is possible to obtain a minimum and maximum value for resistivities. It should be noted that the bipole sources orientation should be nearly perpendicular.

Contour maps of the single source apparent resistivity calculations are shown for the four apparent resistivities calculated in Figures 19 through 22. As may be seen, anomalously low resistivities were observed over a small area along the Diamond Head fracture zone adjacent to Olomana Peak. The resistivities in this area are as low as 1 ohm-m, and possibly less. Quite high resistivities are observed at Olomana Peak.

Resistivities measured along the east side of the Waianae Range show no anomalous behavior, and yield no indication of potential underground heat. The use of scatter plots of apparent resistivity versus distance from closest source can be helpful in understanding the general resistivity of an area. Keller and Furgerson (1974) showed that dipole mapping has more penetration for the stations.
FIGURE 19. Minimum resistivity map in ohm-meters.
FIGURE 20. Average resistivity map in ohm-meters.
FIGURE 22. Single source B resistivity map in ohm-meters.
away from the dipole.

From the model studies, the resistivity structure in this area suggests the presence of high resistivity basement. Effective penetration to crustal rock was probably not accomplished, but an understanding of the basement topography can be outlined from the direct current resistivity maps. The presence of the Olomana Peak is clearly outlined as a resistive body surrounded by more conductive terrain.

The two conductive zones north and south of the Olomana Peak constitute our two geoelectric anomalies. These can be explained by the extensive faulting associated with the different volcanic events, the caldera collapse and/or an intrusive body from the secondary volcanism during the Koko Series. In support of this approach we observe that in the direction of recent volcanism, south of the Olomana, a resistivity low of 5 ohm-meters (Figure 18) near the town of Waimanalo. This same area also produced a high mercury in the soil county and, according to Furumoto (1976), the water produced from the wells is a few degrees warmer than usual.

**Model Approximation**

A better understanding of the distributions of the electric fields of a dipole current source for simple model earth shows a striking resemblance with the way iron filings align around a bar magnet. Local disturbances of the field will indicate changes of resistivity.
The effect of the dipole is also observed on a model which includes a vertical slab. This implies two vertical planes separating three zones of different conductivities. We are able to observe the screening effect of a resistive slab due to the electric charge distributions on the contact surfaces.

A comparative set of results was calculated in order to observe the effect of a dipole field in various cases. The simplest case of a uniform earth is modelled first. Progressively the model is complicated by introducing one, the two vertical resistivity contacts. The single vertical contact represents the case of a fault; two vertical contacts will be our model of a slab. These cases are studied for conductive contacts in resistive terrain and vice versa, with and without the effect of resistive basement.

The results of these models were not the main objective of this thesis, but they are included in Appendix C for reference.

Of all of the obtained models, the conductive dike was the model that best approached the field data. This model consists of a conductive slab of approximately 1.5 km thick in the vicinity of the source and oriented 300 degrees and of resistivity 1 ohm-meter surrounded by 10 ohm-meters terrain. The results are calculated for each bipole source, one parallel to the slab (Figure 23), the other perpendicular (Figure 24).

The comparison is a reasonable match to the real data.
FIGURE 23. Conductive slab model source A (Ωm). Rho(1) = 10Ωm; rho(slab) = 1Ωm.
FIGURE 24. Conductive slab model source B (Ω m). Rho(1) = 10Ω m; rho(slab) = 1Ω m.
No agreement is expected for the resistive zone associated with the Olomana Peak since we are modelling the conductive zone to the NE of the source.

A different approach is presented in Figures 25 and 26 in which we treat the conductive zones as a single contact or fault model. The results fit better the field data since the 40 ohm-meter contour is more realistic.
FIGURE 25. Conductive contact model source A ($\Omega\text{m}$).

Rho(1) = 10$\Omega\text{m}$; rho(2) = 1$\Omega\text{m}$.
FIGURE 26. Conductive contact model source B (Ωm).
Rho(1) = 10 Ω m; rho(2) = 1 Ω m.
SUMMARY AND CONCLUSIONS

The geophysical and geochemical surveys carried out on the island of Oahu to evaluate the potential for the occurrence of geothermal energy have not been extensive enough to provide any conclusive results. However, each of the surveys provides weak indication that the potential for the occurrence of geothermal energy at the Olomana Peak area is possible.

From a volcanogenic point of view, the potential for a latent heat source is significant since volcanoes were recently active during the Koko Head Series. It is interesting to observe the alignment of the Diamond Head crater, the Kauu crater, and the Ulupau crater. These three volcanoes are parallel to the Koko Head Fracture but displaced five kilometers inland. The Olomana Peak lies in this line. The resurgence of volcanism implies a fracture zone in the older Koolau volcano, possibly extending to the mantle allowing the magma to intrude and extrude along the more recent manifestations in the southern end of the island.

Perhaps the most encouraging information is provided by the mercury in the soil survey. In it we can clearly observe two anomalies of relative significance in the southern border of the Olomana. These anomalies are of the order of ten to fifteen times larger than background.

The agreement between the resistivity maps is best expressed in the minimum resistivity map (Figure 18) which
indicates a zone of 5 ohm-meters which coincides with the geochemical anomaly. The conductive zone is observed to extend and outline the Olomana as a more resistive body surrounded by a conductor.

Microseismicity provided weak information in support of a low velocity zone associated with a magma body in the crust. The occurrence of events recorded during the survey period was very low, but of the events recorded one had a velocity of 5.2 km sec from stations located near the Waimanalo area, not far from the Olomana.

The agreement of surface geochemical and geophysical methods, and warmer temperatures of the well waters in the same area, provide enough information to outline an area which lies in the direction of recent volcanism and where the potential for the occurrence of geothermal energy is more optimistic. Also, should be kept in mind, the extensive faulting associated with the different volcanic events, the caldera collapse and/or an intrusive body from secondary volcanism during the Koko series. Any or all of these can play an important roll in the justification (explanation) of the anomalies pointed out by surface exploration methods.

Considering the needs of the Island of Oahu for a more inexpensive source of power, the drilling of an exploratory deep well would be justified. The information from the well is multifold, since it would contribute to a better understanding of the geological history and structure of the island and in the best case, the desired power source.
BIBLIOGRAPHY


Gutsalo, L. K., 1975, Helium Isotopic Geochemistry in thermal waters of the Kuril Islands and Kamchatka, II UNSGD.


____, 1977, Usode la computadora en la solucion magneto-telurica: Primer Congreso AILAG, Caracas.


APPENDIX A
QOPL,F4 IS A PROGRAM TO COMPILn ROTATING DIOPTLE INFORMATION
FROM FIELD MEASUREMENTS MADE WITH THE CROSSED DIOPTLE ARRAY.
VERSION OCTOBER 15, 1975 REWISED J.M.SOUTO SEP/77

INPUT DATA CONSISTS OF:
1. A HEADER CARD IN ALPHANUMERIC FORMAT
2. A CARD IN 9F FORMAT WITH THE COORDINATES OF THE FOUR
POLES AND THE RECEIVER LENGTH, THE INTERSECTION POINT
OF THE TWO SOURCES IS THE ORIGIN, E= X- LINE IS THE X-
AXIS (EAST IS THE POSITIVE DIRECTION), N=S LINE IS THE
Y-AXIS (NORTH IS THE POSITIVE DIRECTION),
X1,Y1 NEGATIVE ELECTRODE, SOURCE 1
X2,Y2 POSITIVE ELECTRODE, SOURCE 1
X3,Y3 NEGATIVE ELECTRODE, SOURCE 2
X4,Y4 POSITIVE ELECTRODE, SOURCE 2
X1, XL2, RECEIVER LENGTHS FOR SOURCES 1 AND 2
3. A SERIES OF CARDS WITH DATA FOR INDIVIDUAL STATIONS
N, THE STATION NUMBER
R, THE DISTANCE FROM THE ORIGIN
BEAR, THE BEARING OF LINE TO RECEIVER
B1,EX1I THE BEARING, THE VOLTAGE, LINE ONE, SOURCE 1
B2,EX2I THE BEARING, THE VOLTAGE, LINE TWO, SOURCE 1
BR1,EX1I THE BEARING, THE VOLTAGE, LINE ONE, SOURCE 2
BR2,EX2I THE BEARING, THE VOLTAGE, LINE TWO, SOURCE 2
CUR1, THE CURRENT FOR SOURCE 1
CUR2, THE CURRENT FOR SOURCE 2
THE PROPER ORDER: N,R,BEAR,B1,B2,ER1,BR2,EX1,EX2,EY1,EY2,CUR1,CUR2
4. A FINAL CARD WHICH IS BLANK OR HAS A NEGATIVE NUMBER

DIMENSION A(10)
DIMENSION B(100), RES(100), CCN(100)
READ (1,10010) (A(I),I=1,10)
WRITE (2,10020) (A(I),I=1,10)
READ (1,10040) X1,X2,X3,X4,Y1,Y2,Y3,Y4
WRITE(3,10060) X1,X2,X3,X4,Y1,Y2,Y3,Y4
WRITE(1,10050)
10 CONTINUE
READ (1,10070) N,R,BEAR,B1,B2,EX1,EX2,EY1,EY2,CUR1,CUR2,
XL1=EX1-B1
XL2=EX2-B2
IF (N) 20,20,30
20 GO TO 330
30 CONTINUE

THE FOLLOWING SEGMENT MAKES ALL THE VOLTAGIE POSITIVE AND
CORRECTS THE BEARINGS.
C****************************************************************************
   IF (EX1) 40,50,50
   EX1=EX1
   B1=B1+180,
   IF (B1,GT,360;) B1=B1-360,
   IF (EY1) 60,70,70
   EY1=EY1
   B2=B2+180,
   IF (B2,GT,360;) B2=B2-360,
   IF (EX2) 80,90,90
   EX2=EX2
   BR1=BR1+180,
   IF (BR1,GT,360;) BR1=BR1-360,
   IF (EY2) 100,110,110
   EY2=EY2
   BR2=BR2+180,
   IF (BR2,GT,360;) BR2=BR2-360,
   C THIS SEGMENT REARRANGES VOLTAGES SO THAT B1<B2 AND BR1<BR2
   C THETA (FIRST SOURCE) AND THETA2 (SECOND SOURCE) ARE THE
   C ANGLES BETWEEN THE TWO RECEIVER LINES, POSITIVE AND LESS
   C THAN 180 DEGREES,
   C****************************************************************************
   IF (B1-B2) 120,130,130
   GO TO 140
130  TEX1=EX1
   EX1=EY1
   EY1=TEX1
   TB1=B1
   B1=B2
   B2=TB1
140  THETA=(B2-B1)/57.29573
   EX1=EX1/XL1
   EY1=EY1/XL1
   ET1=SQRT(EX1*EX1+EY1*EY1)
   YT=EX1*SIN(B1/57.29573)+EY1*SIN(B2/57.29573)
   XT=EX1*COS(B1/57.29573)+EY1*COS(B2/57.29573)
   IF (XT,GT,0,.AND.,YT,GT,0.) B3=ATAN(YT/XT)
   IF (XT,LT,0,.AND.,YT,GT,0.) B3=1,570796*ATAN(-XT/YT)
   IF (XT,LT,0,.AND.,YT,LT,0.) B3=3,141592*ATAN(XT/YT)
   IF (XT,EQ,0,.AND.,YT,GT,0.) B3=1,570796
   IF (XT,EQ,0,.AND.,YT,LT,0.) B3=3,141592
   IF (XT,EQ,0,.AND.,YT,EQ,0.) B3=0.
   IF (BR1-BR2) 150,160,160
150  GO TO 170
160  TEX2=EX2
   EX2=EY2
   EY2=TEX2
**CODE**

```fortran
TBR1 = BR1
BR1 = BR2
BR2 = TBR1

170 THETA2 = (BR2 - BR1) / 57.29573
EX2 = EX2 / XL2
EY2 = EY2 / XL2
EY2 = (EY2 - EX2 * COS(THETA2)) / SIN(THETA2)
ET2 = SQRT(EX2**2 + EY2**2)
YY = EX2 * SIN(BR1 / 57.29573) + EY2 * SIN(BR2 / 57.29573)
XX = EX2 * COS(BR1 / 57.29573) + EY2 * COS(BR2 / 57.29573)

IF (XX .GT. 0. AND. YY .GT. 0.) B4 = ATAN(YY / XX)
IF (XX .LT. 0. AND. YY .GT. 0.) B4 = 1.570796 * ATAN(-XX / YY)
IF (XX .LT. 0. AND. YY .LT. 0.) B4 = 3.141592 * ATAN(YY / XX)
IF (XX .GT. 0. AND. YY .LT. 0.) B4 = 4.712388 * ATAN(-XX / YY)
IF (XX .EQ. 0. AND. YY .GT. 0.) B4 = 1.970796
IF (XX .EQ. 0. AND. YY .LT. 0.) B4 = 4.712388
IF (XX .GT. 0. AND. YY .EQ. 0.) B4 = 3.141592

X84 = B4 * 57.29573
X83 = B3 * 57.29573

C *********************************************************
C ET1 AND ET2 ARE THE MAGNITUDES OF THE TWO TOTAL FIELDS,
C CONSIDERING THAN THE ANGLE BETWEEN RECEIVERS IS NOT
C NECESSARILY 90 DEGREES. B3 AND B4 ARE THE BEARINGS OF THE
C TOTAL FIELD VECTORS.
C *********************************************************
C THIS PROGRAM CALCULATES THE MAXIMA AND THE MINIMUM
C RESISTIVITIES, MAX. MIN. TOTAL E-FIELD DIRECTIONS
C AND THE RESISTIVITIES FROM INDIVIDUAL DIPOLE SOURCES.
C DATA FROM ONE DIPOLE SOURCE CAN ALSO BE TREATED, IN THIS CASE
C THE VALUE FOR R1 IS THE RESISTIVITY FOR THAT SOURCE.
C *********************************************************
C THIS SEGMENT VARIES THE CURRENTS IN BOTH SOURCES AND CALCULATES
C FACTORS AND THE RESISTIVITIES.
C *********************************************************

DO 220 J = 1, 41
FC = J / 21
CR1 = CUR1 * FC, 0.05
IF (J .GT. 21) GO TO 180
FD = J - 1
CR2 = CUR2 * FD, 0.05
GO TO 190

180 FD = 41 - J
CR2 = CUR2 * FD, 0.05
190 ET1COR = ET1 * FC, 0.05
ET2COR = ET2 * FD, 0.05
CX = ET1COR * SIN(B3) + ET2COR * SIN(B4)
CY = ET1COR * COS(B3) + ET2COR * COS(B4)
ET = SQRT(CX**2 + CY**2)
IF (CR1 .EQ. 0.0) BT = B4
```

**DESCRIPTION**

This code segment calculates the maximum and minimum resistivities, total E-field directions, and the resistivities from individual dipole sources. It varies the currents in both sources and calculates the amplitude and direction of the E-field, geometric factors, and resistivities.
IF (CR2.EQ.0.) BT=B3
IF (CX.GT.0., AND, CY.GT.0.) BT=ATAN(CX/CY)
IF (CX.GT.0., AND, CY.LT.0.) BT=1.570796*ATAN(-CY/CX)
IF (CX.LT.0., AND, CY.GT.0.) BT=3.141592*ATAN(CX/CY)
IF (CX.LT.0., AND, CY.LT.0.) BT=4.712388*ATAN(-CY/CX)

BTT(J)=BT*57.29573
X=P*Sin(BEAR/57.29573)
Y=P*Cos(BEAR/57.29573)
XX1=X-X1
XX2=X-X2
XX3=X-X3
XX4=X-X4
YY1=Y-Y1
YY2=Y-Y2
YY3=Y-Y3
YY4=Y-Y4

R1=SQRT(XX1**2+YY1**2)
R2=SQRT(XX2**2+YY2**2)
R3=SQRT(XX3**2+YY3**2)
R4=SQRT(XX4**2+YY4**2)

IF (CR2) 200, 200, 210

200 GE0M=SQRT(R1**2+R2**2+R3**2+R4**2)

CON(J)=(CR1*GE0M)/(6.283185*ET1COR)
RES(J)=(6.283185*ET1COR)/(CR1*GE0M)
GO TO 220

210 CR12=CR1*CR2
T1=(CR12**2)/(R1**4+R2**4+R3**4+R4**4)
T2=((2., CR12**2)/((R1**2+R2**2+R3**2+R4**2)**2))*XX1*XX2*YY1*YY2
T3=((2., CR12/(R1**2+R3**2+R4**2))*XX1*XX3*YY1*YY3
T4=((2., CR12/(R1**2+R4**2))*XX1*XX4*YY1*YY4
T5=((2., CR12/(R2**2+R3**2))*XX2*XX3*YY2*YY3
T6=((2., CR12/(R2**2+R4**2))*XX2*XX4*YY2*YY4
T7=((2., CR12/(R3**2+R4**2))*XX3*XX4*YY3*YY4

C1=CR12**2/(R1**2+R2**2+R3**2+R4**2)
C2=((2., CR12**2)/(R1**2+R2**2+R3**2+R4**2))*XX1*XX2*YY1*YY2
C3=((2., CR12/(R1**2+R3**2+R4**2))*XX1*XX3*YY1*YY3
C4=((2., CR12/(R1**2+R4**2))*XX1*XX4*YY1*YY4
C5=((2., CR12/(R2**2+R3**2+R4**2))*XX2*XX3*YY2*YY3
C6=((2., CR12/(R2**2+R4**2))*XX2*XX4*YY2*YY4
C7=((2., CR12/(R3**2+R4**2))*XX3*XX4*YY3*YY4

GEOM1=T1*T2*T3*T4*T5*T6*T7
GEOM=SQRT(GEOM1)

GO M1=C1*C2*C3*C4*C5*C6*C7
GEOM=SQRT(GOM1)

RES(J)=(6.283185*ET)/(CR2*GEOM)
CON(J)=(CR2*GEOM)/(6.283185*ET)
GO TO 220

220 CONTINUE

TEST = ABS(BTT(41)-BTT(21))
RMN=RES(1)
RMAX=RES(1)
NMAX=1
NM1N=1
DO 260 J=2,41
   IF (RES(J)=RMAX) 240,230,230
230   RMAX=RES(J)
   NMAX=J
   240 IF (RMIN=RES(J)) 260,260,290
250   RMIN=RES(J)
260   NM1N=J
   DMIN=BTT(NMIN)
   DMAX=BTT(NMAX)
   RATIO=RMAX/RMIN
   RH1=RES(41)
   RH2=RES(21)
       RMEAN=(RMAX*RMIN)/2,
       CM1N=CON(1)
       CM1X=CON(1)
       KM1N=1
       KM1N=1
   DO 300 J=2,41
5   IF (CON(J)=CM1X) 280,270,270
270   CM1X=CON(J)
   KM1N=J
280   IF (CMIN=CON(J)) 300,300,290
290   CMIN=CON(J)
300   KM1N=J
   CON1=CON(41)
   CON2=CON(21)
   CON1=CON1*1000,
   CON2=CON2*1000,
   CMEAN1=(CM1X+CM1N)/2,
   CMEAN=CMEAN1*1000,
       IF (TEST,LE,145.,AND.,TEST,LE,215.,) GO TO 320
   IF (TEST,LE,35.,OR.,TEST,GE,329.,) GO TO 320
310   WRITE (2,10102) N,R,BEAR,RH1,CON1,RH2,CON2, RMEAN,CMEAN,RMAX,
1RMIN,TEST,BTT(41),BTT(21)
   WRITE (5,10102) N,R,BEAR,RH1,CON1,RH2,CON2, RMEAN,CMEAN,RMAX,RMIN,
1TEST,BTT(41),BTT(21)
   WRITE (11,10080) N,R,RMIN,RMAX,RHAVE
   GO TO 10
320   RHAVE = (RH1+RH2)/2,
   WRITE (2,10092) N,R,BEAR,RH1,CON1,RH2,CON2, RMEAN,CMEAN,RMAX,
1RMIN,TEST,BTT(41),BTT(21),RHAVE
   WRITE (5,10092) N,R,BEAR,RH1,CON1,RH2,CON2, RMEAN,CMEAN,RMAX,RMIN,
1TEST,BTT(41),BTT(21)
   WRITE (11,10080) N,R,RMIN,RMAX,RHAVE
   GO TO 10
330 CONTINUE
STOP
10010 FORMAT (10A4)
10020 FORMAT (11A4/)
10030 FORMAT (2X,'IN',5X,'R',6X,'BEAR',4X,'RH1',4X,'CON1',5X,
1 'RH2',4X,'CON2',4X,'RMEAN',3X,'CMEAN',
2 'RMAX',4X,'RHMIN',4X,'BTT1',1X,'BTT(1)',1X,'BTT(2)'
3 1X,'RHAVE'/)
10040 FORMAT (8F)
10050 FORMAT (1X,'STATION',3X,'DISTANCE',2X,'RHO MIN',3X,
1 'RHO MAX',3X,'RHO AVERAGE')
10060 FORMAT (7(F5,2,'.')F5,2)
10070 FORMAT (I,11F)
10080 FORMAT (1X,14,6X,4(F6,1,4X))
10090 FORMAT (14,1X,F6.3,1X,3X,F4.0,1X,6(F7.2,1X),
1 2(F7.2,1X),2X,3(F5.0,1X),1X,F7.2,2X,'(UNROTATED VALUES)'
10100 FORMAT (14,1X,F6.3,4X,F4.0,1X,6(F7.2,1X),2(F7.2,1X),
1 3X,F4.0,1X,2(F5.0,1X))
END
THE STORY OF THIS PROGRAM GCES LIKELY THIS:

JOHN ARESTAD GOT IT FROM P.B. PURGASON, ANY WAY SINCE ITS HARDLY DOCUMENTED I'LL TRY TO IMPROVED IT

NOV/15/77 JCSE M, SCUTO

THE PROGRAM READS FROM FILE FCR01.DAT WHICH CONSISTS OF:

S1 = CONDUCTIVITY OF THE FIRST LAYER
S2 = CONDUCTIVITY OF THE Dike
S3 = CONDUCTIVITY OF THE GROUND BEYOND DIKE
D = DISTANCE TO DIKE IN KM
T = THICKNESS IN KM
THETA = SOURCE ORIENATATION IN DEGREES
L = LENGTH OF THE SOURCE IN KM
NSERES = NUMBER OF TERMS IN SERIES CALCULATION

ALL THE ABOVE IN A SINGLE LINE, THEN IN ANOTHER LINE:

XMIN = DIST IN KM TO THE LEFT (WEST)
XMAX = DIST IN KM TO THE RIGHT (EAST)
YMIN = DIST IN KM TO THE SOUTH
YMAX = DIST IN KM TO THE NORTH
DXM = PLOTTER X DIRECTION SEPARATION
DYM = PLOTTER Y DIRECTION SEPARATION

---

C***PROGRAM= DIKE
C***LOGIC= COMPUTES RA AND SA MAPS FOR A MODEL WITH 2 VERTICAL CONTACT
C WITH AND WITHOUT BASEMENT
C***CORE= 21K
C***PUNCH= 026
REAL L,LSQ,
DIMENSION PROFIL(3,4,50), THET(2), R*(2,540), SNO(2,4,540)
DIMENSION JXLB(16), JYLB(4,16), LABEL(2,16), NYCHAR(4), ITHET(2)
COMMON YM(11), XM(50), IX, IY, CM(3,4,9,11)
COMMON/CQMR/ XK12, XK21, XK23, XK32, E1X, E1Y, E2X, E2Y, X, Y, YSQ, D, T, TER
& NSERES
EQUIVALENCE (PROFIL,SNO), (R*,CM)
DATA JXLB/"SEPAR","ATION",'/ SC',"LRC E ","LENGT","H ",
18"'
& (JYLB(1,N),N=1,16)/"APPAR","ENT R","ESIST","IVITY","12" ",/,
& (JYLB(2,N),N=1,16)/"APPAR","ENT C","CMDC","TANCE","12" ",/,
& (JYLB(3,N),N=1,16)/"RATIC"," OF C","ROSSE"," DIP","OLE A ",
& "PPARE","NT RE","SISTI","VITIE","S ","6 ",/,
& (JYLB(4,N),N=1,16)/"RATIC"," OF C","ROSSE "," DIP","OLE A ",
& "PPARE","NT CO","NDUCT","ANCES","7 ",/,
& NXCHAR/26/, NYCHAR/22,46,45/,
& (LABEL(1,N),N=1,16)/"DIKE ","WHI TH ","RESIS","TIVE ","BASEM ",
& "ENT ","10 ",/,
& (LABEL(2,N),N=1,16)/"DIKE ","15" ",/,
C***DEVICE ASSIGNMENTS
IN= 1
IOUT= 2
**READ IN MAP PARAMETERS**

```fortran
10 READ(IN,1001,END=9999) S1, S2, S3, C, T, THETA, L, NSERES
IF (L.EQ.0.0) L = 1.0
IF(NSERES.LT,20) NSERES = 20
THET(1) = THETA
15 READ(IN,1001) XMIN, XMAX, YMIN, YMAX, DXM, DYM
```

**REFLECTION COEFFICIENTS**

```fortran
XK12 = (S1-S2)/(S1+S2)
XK21 = -XK12
XK23 = (S2-S3)/(S2+S3)
XK32 = -XK23
```

**RESISTIVITIES OF MEDIA**

```fortran
RA1 = 1.0/S1
RA2 = 1.0/S2
RA3 = 1.0/S3
```

**CHOOSE MAP DIMENSIONS**

```fortran
IJKL = 1
IF (DXM.LE.0.0) DXM = 0.1
IF (DYM.LE.0.0) DYM = 0.3
IX = IFIX((XMAX-XMIN)/DXM) + 1
IX = MIN0(IX,49)
IY = IFIX((YMAX-YMIN)/DYM) + 1
IY = MIN0(IY,11)
WRITE(IOUT,1003) NSERES
```

**CHANGE THETA TO RADIANS**

```fortran
6 TH = THETA/57.4
DELEX = L*SIN(TH)/2.0
DELEY = L*COS(TH)/2.0
DD = D
```

**CHOOSE X AND Y**

```fortran
DO 500 K = 1,IX
XM(K) = XMIN + (K-1)*DXM
DO 500 J = 1,IY
YM(J) = YMIN + (J-1)*DYM
```

**SPECIAL CASE FOR FIELD AT A CURRENT ELECTRODE**

```fortran
IF(XM(K),EQ,DELEX,AND,YM(J),EQ,DELEY) GO TO 8
IF(XM(K),EQ,(-DELEX),AND,YM(J),EQ,(-DELEY)) GO TO 8
GO TO 20
```

**TREAT NEGATIVE ELECTRODE FIRST**

```fortran
20 X = XM(K) - DELEX
Y = YM(J) - DELEY
D = DD - DELEX
NELEC = 1
```

**E1 IS WITH BASEMENT, E2 IS W/O BASEMENT**
50 E1X = 0.0
E1Y = 0.0
E2X = 0.0
E2Y = 0.0
YSQ = Y*Y
C**DETERMINE LOCATION OF CURRENT ELECTRODE
XA = XM(K) - X
IF(XA-DD,LE,0.0) GO TO 100
IF(XA-(DD+T),LE,0.0) GO TO 200
GO TO 300
C**DETERMINE LOCATION OF RECEIVER ELECTRODE
100 IF(XM(K)-DD,LT,0,0) GO TO 112
IF(XM(K)-(DD+T),LE,0.0) GO TO 120
GO TO 130
C**MEDIUM 1
C**R0 TERM
110 CALL R0
C**RD TERM
TERM = XK12
CALL RD
C**RDNT TERM
TERM = (1.0-XK12)*(1.0-XK21)
CALL RDNT
E1X = E1X/S1
E1Y = E1Y/S1
E2X = E2X/S1
E2Y = E2Y/S1
GO TO 400
C**MEDIUM 2
C**R0 TERM
120 CALL R0
C**RDNT TERM
TERM = 1.0
CALL RDNT
C**RTP TERM
CALL RTP
FACTOR = (1.0-XK12)/S2
121 E1X = FACTOR*E1X
E1Y = FACTOR*E1Y
E2X = FACTOR*E2X
E2Y = FACTOR*E2Y
GO TO 400
C**MEDIUM 3
C**R0 TERM
130 CALL R0
C**RTP TERM
CALL RTP
FACTOR = (1.0-XK12)*(1.0-XK23)/S3
GO TO 121
C**DETERMINE ELECTRODE IN MEDIUM 2

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**DETERMINE LOCATION OF RECEIVER ELECTRODE**

200 IF(XM(K)-DD,LT,0,0) GO TO 210
   IF(XM(K)-DD,T,LE,0,0) GO TO 220
   GO TO 230

**MEDIUM 1**

210 CALL R0

**RDNT TERM**

TERM = 1.0
CALL RDNT

**RTM TERM**

CALL RTM
FACTOR = (1.0-XK21)/S1
GO TO 121

**MEDIUM 2**

220 CALL R0

**RD TERM**

TERM = XK21
CALL RD

**RDNT TERM**

TERM = 1.0
CALL RDNT

**RTM TERM**

CALL RTM
E1X = E1X/S2
E1Y = E1Y/S2
E2X = E2X/S2
E2Y = E2Y/S2
GO TO 400

**MEDIUM 3**

230 CALL R0

**RD TERM**

TERM = XK21
CALL RD

**RDNT TERM**

TERM = 1.0
CALL RDNT

**RTP TERM**

CALL RTP
FACTOR = (1.0-XK23)/S3
GO TO 121

CURRENT ELECTRODE IN MEDIUM 3

**DETERMINE LOCATION OF RECEIVER ELECTRODE**

300 IF(XM(K)-DD,LT,0,0) GO TO 310
IF(XM(K)-(DD*T),LE.0.0) GO TO 320
GO TO 330
C***MEDIUM 1
C***R0 TERM
310 CALL R0
C***RTM TERM
CALL RTM
FACTOR= (1.0-XK21)*(1.0-XK32)/S1
GO TO 121
C***MEDIUM 2
C***R0 TERM
320 CALL R0
C***RD TERM
TERM= XK21
CALL RD
C***RDHNT TERM
TERM= 1.0
CALL RDHNT
C***RTM TERM
CALL RTM
FACTOR= (1.0-XK32)/S2
GO TO 121
C***MEDIUM 3
C***R0 TERM
330 CALL R0
C***RDT TERM
TERM= XK32
CALL RDT
C***RD TERM
TERM= (1.0-XK23)*(1.0-XK32)*XK21
CALL RD
C***RDHNT TERM
TERM= (1.0-XK23)*(1.0-XK32)
CALL RDHNT
E1X= E1X/S3
E1Y= E1Y/S3
E2X= E2X/S3
E2Y= E2Y/S3
GO TO 400
C***DO POSITIVE ELECTRODE
X= XM(K) + DELX
Y= YM(J) + DELY
D= DD + DELX
NELEC= 2
GO TO 50
C***CONVERT E FIELD TO APPARENT RESISTIVITY AND APPARENT CONDUCTANCE***

450 ELX = TE1X * ELX
E1X = TE1Y + E1Y
E2X = TE2X + E2X
E2Y = TE2Y + E2Y
E1 = SQRT(E1X * E1X + E1Y * E1Y)
E2 = SQRT(E2X * E2X + E2Y * E2Y)
X = XM(K) - DELX
Y = YM(J) - DELY
R1SQ = X*X + Y*Y
E1 = SQRT(E1X * E1X * E1Y * E1Y)
X = XM(K) + DELX
Y = YM(J) + DELY
R2SQ = X*X + Y*Y
RAMSQ = MIN1(R1SQ, R2SQ)
RBMSQ = MAX1(R1SQ, R2SQ)
RAM = SQRT(RAMSQ)
RB = SQRT(RBMSQ)
LSQ = L*L
CDELT A = (RAMSQ + RBMSQ - LSQ) / (2.0 * RAM * RB)
RATIO = RAMSQ / RBMSQ
RATOSQ = RATIO * RATIO
G3 = SQRT(1.0 + RATIO - 2.0 * (RAM / RBMSQ) * CDELT A)
G4 = SQRT(1.0 + RATOSQ - 2.0 * RATOSQ * CDELT A)
CM(IJKL,1,K,J) = RAMSQ * E1 / G4
CM(IJKL,2,K,J) = RAMSQ * E2 / G4
CM(IJKL,3,K,J) = ATAN2(E1X, E1Y) * 57.29578
CM(IJKL,4,K,J) = ATAN2(E2X, E2Y) * 57.29578
500 CONTINUE
D = DD
IF (IJKL.EQ.2) GO TO 510
C***SET UP PARAMETER FOR THET(2) DIPOLE
THETA = THETA + 90.0
THET(2) = THETA
IJKL = 2
GO TO 6
C***CALCULATE CROSSED DIPOLE RATIO***
510 DO 520 K = 1, IX
DO 520 J = 1, IY
DO 520 M = 1, 4
520 CM(3,M,K,J) = CM(2,M,K,J) / CM(1,M,K,J)
C***PRINT CONTOUR MAPS***
DO 525 M = 1, 4
DO 525 IJKL = 1, 3
IF (IJKL.EQ.3) GO TO 525
C***SINGLE DIPOLE
GO TO (5201, 5202, 5203, 5204), P
5201 WRITE(IOUT,1101)
GO TO 5210
5202 WRITE(IOUT,1102)
GO TO 5210
5203 WRITE(IOUT,1103)
GO TO 5210
5224 WRITE(IOUT,1104)
GO TO 5210
C**CROSSED DIPOLES
5205 GO TO (5206,5207,5208,5209), M
5206 WRITE(IOUT,1301)
GO TO 5210
5207 WRITE(IOUT,1302)
GO TO 5210
5208 WRITE(IOUT,1303)
GO TO 5210
5209 WRITE(IOUT,1304)
5210 IF (IJKL,EQ.3) GO TO 522
C**SINGLE DIPOLE
IF (M.GT.2) GO TO 521
WRITE(IOUT,1105) RA1, RA2, RA3, L, D, T, THET(IJKL)
GO TO 524
521 WRITE(IOUT,1106) S1, S2, S3, L, C, T, THET(IJKL)
GO TO 524
C**CROSSED DIPOLES
522 IF (M.GT.2) GO TO 523
WRITE(IOUT,1305) RA1, RA2, RA3, L, C, T, THET(1), THET(2)
GO TO 524
523 WRITE(IOUT,1306) S1, S2, S3, L, C, T, THET(1), THET(2)
C**PRINT MAP
524 CALL PRTPLT(IJKL,M,L,THET(IJKL))
525 CONTINUE
C**COMPILE PROFILES
C--------SKIP THIS SECTION IF PROFILES ARE NOT WANTED
GO TO 9999
WRITE(IOUT,1502)
DO 610 M= 1, 4
DO 610 IJKL= 1, 3
DO 610 K= 1, IX
610 PROFIL(IJKL,M,K)= CM(IJKL,M,K,1)
DO 620 K= 1, IX
620 WRITE(IOUT,1510) XM(K), ((PRCFIL(IJKL,M,K),IJKL=1,3,M=1,4)
C**OUTPUT PROFILES
NCY= 3
IFDATA= 0
MSTART= 5
MLAST= 5
DD= 2.45
XLENGT= 3.0*DD
FACT= 0.755
WRITE(IOUT3,1700) NCY,IFDATA,MSTART,MLAST,XLENGT,DD,FACT
NUMCUR= 12
WRITE(IOUT3,1625) NUMCUR
C**XM(I+1) AND PROFIL(IJKL,M,I+1) CONTAIN END OF DATA CODE
XM(I+1)= 0.0
PRFMIN= 0.0
ITHET(1) = INT(ITHET(1) + 0.1)
ITHET(2) = INT(ITHET(2) + 0.1)
DO 630 M = 1, 4
   IS2 = 1
   IF(M.EQ.2,OR,M.EQ.4) IS2 = 2
DO 630 IJKL = 1, 3
WRITE(IOUT3,1620) (LABEL(IS2,N),N = 1, 16)
   IF(IJKL.EQ.3) GO TO 622
C**SINGLE DIPOLE
   IF(M.GT.2) GO TO 621
   WRITE(IOUT3,1515) RA1,RA2,RA3,L,D,T,ITHET(IJKL)
   GO TO 624
621 WRITE(IOUT3,1520) S1,S2,S3,L,D,T,ITHET(IJKL)
   GO TO 624
C**CROSSED DIPOLES
   IF(M.GT.2) GO TO 623
   WRITE(IOUT3,1525) RA1,RA2,RA3,L,D,T,ITHET(1),ITHET(2)
   GO TO 624
623 WRITE(IOUT3,1530) S1,S2,S3,L,D,T,ITHET(1),ITHET(2)
624 WRITE(IOUT3,1620) JXLB
   WRITE(IOUT3,1625) NXCHAR
   IF(IJKL.NE.3,AND,M.LT.3) IL = 1
   IF(IJKL.NE.3,AND,M.GT.2) IL = 2
   IF(IJKL.EQ.3,AND,M.LT.3) IL = 3
   IF(IJKL.EQ.3,AND,M.GT.2) IL = 4
   WRITE(IOUT3,1620) (JYLB(IL,N),N = 1, 16)
   WRITE(IOUT3,1625) NXCHAR(IL)
   WRITE(IOUT3,1630) XM(1), PROFMIN
   PROFIL(IJKL,M,IX+1) = 0.0
630 WRITE(IOUT3,1635) ((XM(IL),PROFIL(IJKL,M,K)),K = 1, IX+1)
C**CONDENSE 2-D DATA FOR EACH MAP INTO 1-D DATA
   DO 722 M = 1, 4
DO 720 IJKL = 1, 2
   KJ = 0
DO 720 K = 1, IX
   KJ = KJ + 1
720 SEND(IJKL,M,KJ) = CM(IJKL,'1',K,
C**CALCULATE CORRESPONDING VALUES OF THE DISTANCE BETWEEN THE
C RECEIVER AND THE NEAREST SOURCE ELECTRODE
   DO 730 IJKL = 1, 2
   KJ = 0
   TH = THET(IJKL) / 57.4
   DELX = L*SIN(TH)/2.0
   DELY = L*COS(TH)/2.0
   DO 730 K = 1, IX
   X = XM(K) + DELX
   RX1SQ = X*X
   RX2SQ = RX1SQ
  730 CONTINUE
DO 730 J = 1, IY
Y = YM(J) + DELY
RY1SQ = Y*Y
Y = YM(J) - DELY
RY2SQ = Y*Y
RM1 = SQRT(RX1SQ + RY1SQ)
RM2 = SQRT(RX2SQ + RY2SQ)
KJ = KJ + 1
730 RM(IJKL, KJ) = AMIN1(RM1, RM2)
C WRITEM(IOUT, 1605)
C DO 735 J = 1, KJ
C 735 WRITE(IOUT, 1610) RM(1, J), (SND(1, M, J), M=1, 4),
C & RM(2, J), (SND(2, M, J), M=1, 4)
C***CALCULATE ZERO
X = AMIN1(DXM, DYM)
XL = ALOG10(1.01*X)
ZERO = 10.0**INT(XL)
IF (X.LT.1.0, AND, ABS(XL-4.INT(XL))).GT.0.01) ZERO = 0.1*ZERO
SNZ = 0.0
C***OUTPUT SOUNDINGS*****************************************************
NCX = 3
NCY = 3
IFDATA = 0
MSTART = 5
MLAST = 5
DD = 2.45
FACT = 0.755
NUMCUR = 8
WRITE(IOUT2, 1615) NCX, NCY, IFDATA, MSTART, MLAST, DD, FACT
WRITE(IOUT2, 1625) NUMCUR
DO 830 M = 1, 4
IS2 = 1
IF(M.EQ.2.0R,M.EQ.4) IS2 = 2
DO 830 IJKL = 1, 2
WRITE(IOUT2, 1620) (LABEL(IS2, N), N = 1, 16)
IF(M.GT.2) GO TO 821
WRITE(IOUT2, 1515) RA1, RA2, RA3, L, C, T, ITHET(IJKL)
GO TO 822
821 WRITE(IOUT2, 1520) S1, S2, S3, L, D, T, ITHET(IJKL)
822 WRITE(IOUT2, 1620) JXLB
WRITE(IOUT2, 1625) NXCHAR
IF(M.LT.3) IL = 1
IF(M.GT.2) IL = 2
WRITE(IOUT2, 1620) (JYLB(IL, N), N = 1, 16)
WRITE(IOUT2, 1625) NYCHAR(IL)
WRITE(IOUT2, 1630) ZERO, SND
C***RM(IJKL, KJ+1) AND SND(IJKL, M, KJ+1) CONTAIN END OF DATA CODE
RM(IJKL, KJ+1) = 0.0
SND(IJKL, M, KJ+1) = 0.0
830 WRITE(IOUT2, 1635) (RM(IJKL, J), SND(IJKL, M, J)), J=1, KJ+1
C***FORMAT STATEMENTS*****************************************************
RESISTIVITY MAP FOR A DIKE'/

FIELD DIRECTIONS FOR A DIKE'

1001 FORMAT(7F,12)
1003 FORMAT(1H1,9X,'NSERES= ',15)
1101 FORMAT(1H1,9X,'APPARENT RESISTIVITY MAP FOR A DIKE WITH A RESISTIVE BASEMENT')
1102 FORMAT(1H1,9X,'APPARENT RESISTIVITY MAP FOR A DIKE'/)
1103 FORMAT(1H1,9X,'ELECTRIC FIELD DIRECTIONS FOR A DIKE WITH A RESISTIVE BASEMENT')
1104 FORMAT(1H1,9X,'ELECTRIC FIELD DIRECTIONS FOR A DIKE'/)
1105 FORMAT(1H1,9X,'RATIO OF CROSSED DIPOLE APPARENT RESISTIVITIES FOR A DIKE WITH A RESISTIVE BASEMENT'/)
1106 FORMAT(1H1,9X,'RATIO OF CROSSED DIPOLE APPARENT RESISTIVITIES FOR A DIKE'/)
1107 FORMAT(1H1,9X,'RATIO OF CROSSED DIPOLE CONDUCTANCES FOR A DIKE WITH A RESISTIVE BASEMENT'/)
1108 FORMAT(1H1,9X,'RATIO OF CROSSED DIPOLE CONDUCTANCES FOR A DIKE'/)
1109 FORMAT(1H1,9X,'PROFILES THROUGH CENTER OF SOURCE NORMAL TO STRUCTURE')
1110 FORMAT(9X,5E10.3)
1111 FORMAT(5I5,5X,3F10.2)
1112 FORMAT(15)
1113 FORMAT(2E12.3)
1114 FORMAT(2E16.8)
1115 FORMAT(4I5,4F10.2)

9999 STOP
END
SUBROUTINE PRTPLT(IJKL,M,L,THETA)

C***LOGIC= PRINTS AN ARRAY IN A SQUARE GRID ON LINE PRINTER

C----------ALSO WRITES DATA TO A PLOTTING FILE (FCR10.DAT)

COMMON YM(11), XM(50), IX, IY, CM(3,4,49,11)

C***DEVICE ASSIGNMENTS

IN=1
IOUT=2
IPLLOT=10
IF(M,GE,3)IPLLOT=11
WRITE(IPLLOT,1004)IX,IY,L,THETA
WRITE(IPLLOT,1005)(XM(I),I=1,IX)
WRITE(IPLLOT,1005)(YM(I),I=1,IY)
WRITE(IPLLOT,1005)((CM(IJKL,M,K,J),J=1,IY),K=1,IX)

1004 FORMAT(IX,2(I4,1X),2(F6,1,1X))
1005 FORMAT(IX,F6,1)

DO 15 K=1,IX
WRITE(IOUT,1003)YM(J),J=1,IY)
1003 FORMAT(1H*,19X,'Y=',12(F5,2,5X))

DO 15 K=1,IX
WRITE(IOUT,1002)XM(K),CM(IJKL,M,K,J),J=1,IY)

1002 FORMAT(1H*,F5,2,11(1PE10,2))

RETURN
END
SUBROUTINE R0
COMMON/COMR/ XK12,XK21,XK23,XK32,E1X,E1Y,E2X,E2Y,X,Y,YSQ,D,T,TERM,
& NSERES
RSQ= X*X + YSQ
R= SQRT(RSQ)
CB= X/RSQ
SB= Y/RSQ
E1X= E1X + CB
E1Y= E1Y + SB
E2X= E2X + CB/R
E2Y= E2Y + SB/R
RETURN
END
SUBROUTINE RD

DX = X - 2.0*D
RSQ = DX*DX + YSQ
R = SQRT(RSQ)
CB = TERM*DX/RSQ
SB = TERM*Y/RSQ
E1X = E1X + CB
E1Y = E1Y + SB
E2X = E2X + CB/R
E2Y = E2Y + SB/R
RETURN
END
SUBROUTINE RDT
COMMON/COMR/ XK12, XK21, XK23, XK32, E1X, E1Y, E2X, E2Y, X, Y, YSQ, D, T, TERM,
& NSERES
DX = X - 2.0 * (D + T)
RSQ = DX * DX + YSQ
R = SQRT(RSQ)
CB = TERM * DX / RSQ
SB = TERM * Y / RSQ
E1X = E1X + CB
E1Y = E1Y + SB
E2X = E2X + CB / R
E2Y = E2Y + SB / R
RETURN
END
SUBROUTINE RDTN
   COMMON/COM/ XK12,XK21,XK23,XK32,E1X,E1Y,E2X,E2Y,X,Y,YSQ,D,T,TERM, & NSERES
   DO 100 N= 1, NSERES
   DX= X - 2.0*(D+FLOA(N)*T)
   RSQ= DX*DX + YSQ
   R= SQRT(RSQ)
   FACTOR= TERM*XK21**(N-1)*XK22**N/RSQ
   CB= FACTOR*DX
   SB= FACTOR*Y
   E1X= E1X + CB
   E1Y= E1Y + SB
   E2X= E2X + CB/R
   E2Y= E2Y + SB/R
   100 RETURN
END
SUBROUTINE RDMNT
COMMON/COMR/ XK12, XK21, XK23, XK32, E1X, E1Y, E2X, E2Y, X, Y, YSQ, D, T, TERM,
& NSERES
DO 100 N = 1, NSERES
DX = X - 2.0*(D=FLOAT(N)*T)
RSQ = DX*DX + YSQ
R = SQRT(RSQ)
FACTOR = TERM*XK12**N*XK23**N/RSG
CB = FACTOR*DX
SB = FACTOR*Y
E1X = E1X + CB
E1Y = E1Y + SB
E2X = E2X + CB/R
100 E2Y = E2Y + SB/R
RETURN
END
SUBROUTINE RTP
COMMON/COMR/ XK12, XK21, XK23, XK32, E1X, E1Y, E2X, E2Y, X, Y, YSQ, D, T, TERM, & NSERES
DO 100 N = 1, NSERES
DX = X + 2.0*FLOAT(N)*T
RSQ = DX*DX + YSQ
R = SQRT(RSQ)
FACTOR = XK21* N * XK23 * N / RSQ
CB = FACTOR*DX
SB = FACTOR*Y
E1X = E1X + CB
E1Y = E1Y + SB
E2X = E2X + CB/R
100 E2Y = E2Y + SB/R
RETURN
END
SUBROUTINE RTM
COMMON/COM/ XK12, XK21, XK23, XK32, E1X, E1Y, E2X, E2Y, X, Y, YSQ, D, T, TERM,
& NSERES
DO 100 N = 1, NSERES
DX = X - 2.0*FLOAT(N)*T
RSQ = DSQ*DX + YSQ
R = SQRT(RSQ)
FACTOR = XK21**N* XK23* N/RSQ
CB = FACTOR*DX
SB = FACTOR*Y
E1X = E1X + CB
E1Y = E1Y + SB
E2X = E2X + CB/R
100 E2Y = E2Y + SB/R
RETURN
END
PROGRAM TO PLOT DIPOLE DATA FOR MAPS (JMS, 1977)
USES POLAR COORDINATES
PLOT RESISTIVITY MODEL DATA FROM MODELING PROGRAM

DIMENSION X(50), Y(50), VALUE(600)
DIMENSION X1(600), Y1(600)

WRITE(4, 10)
10 FORMAT(1X, 'PLEASE ENTER 5 CHARACTER INPUT FILE ', $)
   READ(4, 20) FILIN
20 FORMAT(A5)
   OPEN(UNIT=1, ACCESS='SEQIN', FILE=FILIN)
   DO 1000 L=1, 4
      READ(1, 11) IX, IY, XL, THETA
11 FORMAT(1X, 2(I4, 1X), 2(F6.1, 1X))
21 FORMAT(1X, F6, 1)
      READ(1, 21)(X(I), I=1, IX)
      READ(1, 21)(Y(I), I=1, IY)
      IXY = IX*IY
      READ(1, 21)(VALUE(I), I=1, IXY)
      IF(L .EQ. 2 .OR. L .EQ. 4) GO TO 1002
      1=1
   DO 100 J=1, IX
      DO 100 K=1, IY
         X1(I) = X(J)
         Y1(I) = Y(K)
      IN = I
100   I = I + 1
      IF(IN .EQ. IXY) GO TO 200
   GO TO 2000
200 CALL MAP(X1, Y1, VALUE, XL, IN, THETA)
   WRITE(4, 23)
   23 FORMAT(1X, 'WAITING FOR PLOT VIEWING-HIT<CR> WHEN READY', $)
   READ(4, 24) A
24 FORMAT(I1)
   1000 CONTINUE
   CLOSE(UNIT=1)
   WRITE(4, 70)
60 FORMAT(1X, 'PLOT ANOTHER FILE? TYPE Y OR N- ', $)
   READ(4, 80) TEST
80 FORMAT(A1)
   IF (TEST .NE. 'Y') GO TO 2000
GO TO 1
20000 CONTINUE
STOP
END
C******************************************************************************
C PLOTTING SUBROUTINE MAP
C******************************************************************************

SUBROUTINE MAP(X, Y, VALUE, XL, IN, THETA)
DIMENSION X(IN), Y(IN), VALUE(IN)

WRITE(4,110)
110 FORMAT(1X, 'SCALING FACTOR ', $)
READ(4,120) FACTR

WRITE(4,124)
124 FORMAT(1X, 'ENTER 35 CHARACTER TITLE FOR PLOT-', $)
125 FORMAT(7A5)
NAME(1) = 'SCALE'
NAME(2) = ' (Km)'
THETA = 180. - THETA
SX = .5 * XL * SIND(THETA) * .25
SY = .5 * XL * COSD(THETA) * .25
S2X = -SX
S2Y = -SY

121 K = I PLOT(1)
IF(K.NE.0) STOP 'PLOT STOPPED'

CALL FACTOR(FACTR)
CALL NEWPEN(2)
CALL ISETAB(9)
CALL PLOT(1,1,1,-3)

CALL AXES(.5,.5,NAME,10,2.5,2,2,4,25,2,-1,2)

CALL PLOT(1,1,2,3)
CALL PLOT(1,3,2)
CALL PLOT(.8,.2,75,2)
CALL PLOT(1,.3,3)
CALL PLOT(1,2,2.75,2)

CALL SYMBOL(.9,.3,25,.2,46,.2)
CALL SYMBOL(1.5,0,.2,TITLE,.35)
CALL PLOT(4,4,-3)
CALL ISETAB(1)

CALL SYMBOL(0,0,.1,.2,.0,-1)
CALL SYMBOL(SY,SX,.2,11,.0,-1)
CALL SYMBOL(S2Y,S2X,.2,11,.0,-2)

DO 1 J = 1, IN
   X0 = Y(J) * .25
   XN = X0 + .05
   Y0 = X(J) * .25
   YN = Y0 + .02
   VAL = VALUE(J)
   1 continue
CALL SYMBOL(XO,YO,.25,2,2,-1)
CALL NUMBER(XN,YN,.05,VAL,2,.0)
CONTINUE
CALL PLOT(0,0,.999)
RETURN
END
C-----------------------------
C PROGRAM TO PLOT DIPOLE DATA FROM MODELING PROGRAM
C PLOTS ELECTRIC FIELD MODEL DATA JP SOUTC /77
C-----------------------------

DIMENSION X(50), Y(50), X1(602), Y1(602), E(602)

1  WRITE(4,10)
10  FORMAT(1X,'PLEASE ENTER 5 CHARACTER INPUT FILE ',$)
   READ(4,20)FILIN
20  FORMAT(A5)
   OPEN(UNIT=1, ACCESS='SEQIN', FILE=FILIN)
   DO 1000 L=1,4
   READ(1,11) IX, IY, XL, THETA
11  FORMAT(1X,2(14,1X),2(F6.1,1X))
   DO 100 J=1,IX
   READ(1,21)(X(I),I=1,IX)
   READ(1,21)(Y(I),I=1,IY)
   IX=IX+1
   IF(L.EQ.2.0R,L.EQ.4) GO TO 1200
   I=1
   DO 100 K=1,IY
      XI(I)=X(J)
      Y1(I)=Y(K)
100  I=I+1
   IF(IN.EQ.IXY) GO TO 200
   GO TO 20000

200  CALL MAP(X1,Y1,E,IN, XL, THETA)
   WRITE(4,23)
23  FORMAT(1X,'WAITING FOR PLOT VIEWING-WHIT <CR> WHEN READY',$)
   READ(4,24)
24  FORMAT(I1)

1000 CONTINUE

999  CLOSE(UNIT=1)
   WRITE(4,70)
70  FORMAT(1X,'PLOT ANOTHER FILE? TYPE Y OR N- ',$)
   READ(4,80)TEST
80  FORMAT(A1)
   IF(TEST.NE.'Y') GO TO 20000
   GO TO 1
20000 CONTINUE
STOP
END
C**********************************************************************
C   PLOTTING SUBROUTINE MAP
C**********************************************************************

SUBROUTINE MAP(X,Y,E,IN,IXL,THETA)
DIMENSION X(IN),Y(IN),E(IN),TITLE(7),NAME(2)
WRITE(4,110)
110 FORMAT(1X, 'SCALING FACTOR ',F9.5)
READ(4,120) FACTR
120 FORMAT(F)
WRITE(4,115)
115 FORMAT(1X, 'ENTER 35 CHARACTER TITLE FOR PLOT-',I4)
READ(4,116) (TITLE(I),I=1,7)
116 FORMAT(7A5)
NAME(1)='SCALE'
NAME(2)='(KM)'
THETA=180.-THETA
SX=-.5*IXL*SIND(THETA)*.25
SY=.5*IXL*COSD(THETA)*.25
S2X=-SX
S2Y=-SY
101 K=1
IF(K.NE.0)STOP 'PLOT STOPPED'
CALL FACTOR(FACTR)
CALL NEWPEN(2)
CALL ISETAB(9)
CALL PLOT(1.,1.,-3)
CALL AXES(.5,.5,NNAME,12,2.5,.0,.4,.25,.0,-1,2)
C CALL PLOT(1.,2.,3)
C CALL PLOT(1.,3.,2)
C CALL PLOT(.8,2.75,2)
C CALL PLOT(1.,3.,3)
C CALL PLOT(1.,2.75,2)
C CALL SYMBOL(.9,3.25,.2,46,.0,.2)
C CALL SYMBOL(.5,1.,2,TITLE,.0,.35)
C CALL PLOT(4.,4.,-3)
C CALL ISETAB(1)
C CALL SYMBOL(.0,.0,.1,2,.0,.1)
CALL SYMBOL(SY,SX,.2,11,.0,.1)
C CALL SYMBOL(S2Y,S2X,.2,11,.0,.2)
DO 1 J=1,IN
   X0=Y(J)/4,
   XN=X0+.1
   Y0=X(J)/4,
   YN=Y0-.1
   EV=E(J)
   EV1=90.*EV

C**********************************************************************
CALL SYMBOL(X0,Y0,.15,.13,EV1,-1)
CALL NUMBER(XN,YN,.07,EV,.0,.0)
CONTINUE
CALL PLOT(Z,0,999)
RETURN
END
Code Explanation:

1. First three letters indicate the model resistivities for the two vertical contacts. The first letter indicates the resistivity of the zone adjacent to the source. The second letter indicates the resistivity of the dike, and the third letter indicates the resistivity in the other side of the dike.

   \[ U = \text{UNO} = \text{one} \ (1 \ \Omega \text{m}) \]
   \[ D = \text{DIEZ} = \text{ten} \ (10 \ \Omega \text{m}) \]
   \[ C = \text{CIEN} = \text{one hundred} \ (100 \ \Omega \text{m}) \]
   \[ M = \text{MIL} = \text{one thousand} \ (1,000 \ \Omega \text{m}) \]

2. The first number indicates the distance from the center of the source to the dike in km.

3. The second number indicates the thickness in kilometers of the dike.

4. The next number indicates the angle in degrees between the source and dike.

   \[ 00 = \text{EAST} \]
   \[ 45 = \text{NE} \]
   \[ 90 = \text{NORTH} \]

5. Indicates whether the model was considered with basement present or without it.

   \[ A = \text{Resistive basement present.} \]
   \[ B = \text{No basement.} \]

EXAMPLE:

   \[
   \text{DMD} \ 33 \ 90 \ A \\
   \text{DMD} = \text{Dike resistivity of} \ 1,000 \ \Omega \text{m in} \ 10 \ \Omega \text{m terrain} \\
   3 = \text{distance of dike from center of source in km}
   \]
3 = dike thickness in km
90 = source perpendicular to dike
A = resistive basement present in this model
**MODEL : UNIFORM EARTH BASEMENT**

```
SCALE (KM)
0  2  4  6  8  10

CCC 3 3 00 A
```
MODEL : UNIFORM EARTH
NO BASEMENT

SCALE (KM)

CCC 3 3 000 B
MODEL : UNIFORM EARTH
BASEMENT

SCALE (KM)

CCC 3 3 00 A
MODEL : UNIFORM EARTH
NO BASEMENT
MODEL: CONDUCTIVE DIKE WITH BASEMENT

SCALE (KM)

0 2 4 6 8 10

CDC 3 3 90 A
MODEL : CONDUCTIVE DIKE
NO BASEMENT

SCALE (KM)

CDC 3 3 90 B
MODEL : CONDUCTIVE DIKE
WITH BASEMENT

SCALE (KM)

CDC 3 3 90 A
MODEL : CONDUCTIVE DIKE
NO BASEMENT

SCALE (KM)

CDC 3 3 90 B
MODEL : CONDUCTIVE DIKE
WITH BASEMENT

SCALE (KM)
0  2  4  6  8  10

CDC 3 3 00 A
MODEL : CONDUCTIVE DIKE
NO BASEMENT

SCALE (KM)
0  2  4  6  8  10

CDC 3 3 00 B
MODEL : CONDUCTIVE DIKE
WITH BASEMENT

SCALE (KM)

0  2  4  6  8  10

CDC 3 3 000 A
MODEL : CONDUCTIVE DIKE
NO BASEMENT

SCALE (KM)

0 2 4 6 8 10

CDC 3 3 000 B
MODEL: CONDUCTIVE DIKE
WITH BASEMENT

SCALE (KM)
0  2  4  6  8  10

CDC 3 3 45 A
MODEL : CONDUCTIVE DIKE
NO BASEMENT

SCALE (KM)

CDC 3 3 45 B
MODEL : CONDUCTIVE DIKE WITH BASEMENT

SCALE (KM)

CDC 3345A
MODEL : CONDUCTIVE DIKE
NO BASEMENT

SCALE (KM)

CDC 3 3 45 B
MODEL : RESISTIVE FAULT
WITH BASEMENT

SCALE (KM)
0 2 4 6 8 10

DCC 3 3 45 A
MODEL: RESISTIVE FAULT
NO BASEMENT

SCALE (KM)

DCC 3 3 45 B
MODEL : RESISTIVE DIKE
WITH BASEMENT

SCALE (KM)

0 2 4 6 8 10

DMD 3 3 90 A
MODEL : RESISTIVE DIKE
NO BASEMENT

SCALE (KM)

DMD 3390 B
MODEL : RESISTIVE DIKE
WITH BASEMENT

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SCALE (KM)

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DMD 3 3 45 A
MODEL : RESISTIVE DIKE
NO BASEMENT

SCALE (KM)

DMD 3 3 45 B
MODEL: RESISTIVE DIKE
WITH BASEMENT

SCALE (KM)

DMD 3 3 45 A
MODEL : RESISTIVE DIKE
NO BASEMENT

SCALE (KM)

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WITH BASEMENT

SCALE (KM)
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MODEL : RESISTIVE DIKE
NO BASEMENT

SCALE (KM)

DMD 3 3 00 B
MODEL : RESISTIVE DIKE
WITH BASEMENT

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SCALE (KM)

DMD 3 3 000 2 20 A
MODEL : RESISTIVE DIKE
NO BASEMENT

SCALE (KM)

0 2 4 6 8 10

DMD 3 3 000 2 20 B
MODEL : RESISTIVE DIKE
BASEMENT

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SCALE (KM)

0  2  4  6  8  10

CDC  3 3 000 A
MODEL : RESISTIVE DIKE
NO BASEMENT

SCALE (KM)

CDC 33000 B
MODEL : RESISTIVE DIKE
BASEMENT

SCALE (KM)

CDC 3 3 000 A
MODEL : RESISTIVE DIKE
NO BASEMENT

SCALE (KM)

CDC  33 000 B