U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

A Preliminary Gravity Survey of the Kailua-Kona Area, Hawai'i, for Delineation of a Hydrologic Boundary

by

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Open File Report 98-110

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ABSTRACT

Gravity values were measured on ten profiles with the purpose of finding a hydrologic boundary responsible for impounding ground water tens of meters above sea level. Small gravity variations were found superimposed on the larger Hualalai anomaly and are interpreted, in one profile, to be due to a thin, west-dipping mass. Geologically, this may be one or more unusually dense lava flows that could be relatively impermeable.

INTRODUCTION

The Kailua-Kona area of west Hawai'i island is currently supplied with ground water from several wells drilled into a basal lens within a region extending no more than 8 km from the coastline and at elevations less than 400 m. This supply is expected to be augmented soon with ground water from several wells drilled recently at elevations above 400 m. Since 1990, these inland wells have demonstrated that water-table elevations increase abruptly above the 400-m elevation contour and that potentially large, new supplies of ground water are available for the Kailua-Kona region (Clark, 1994).

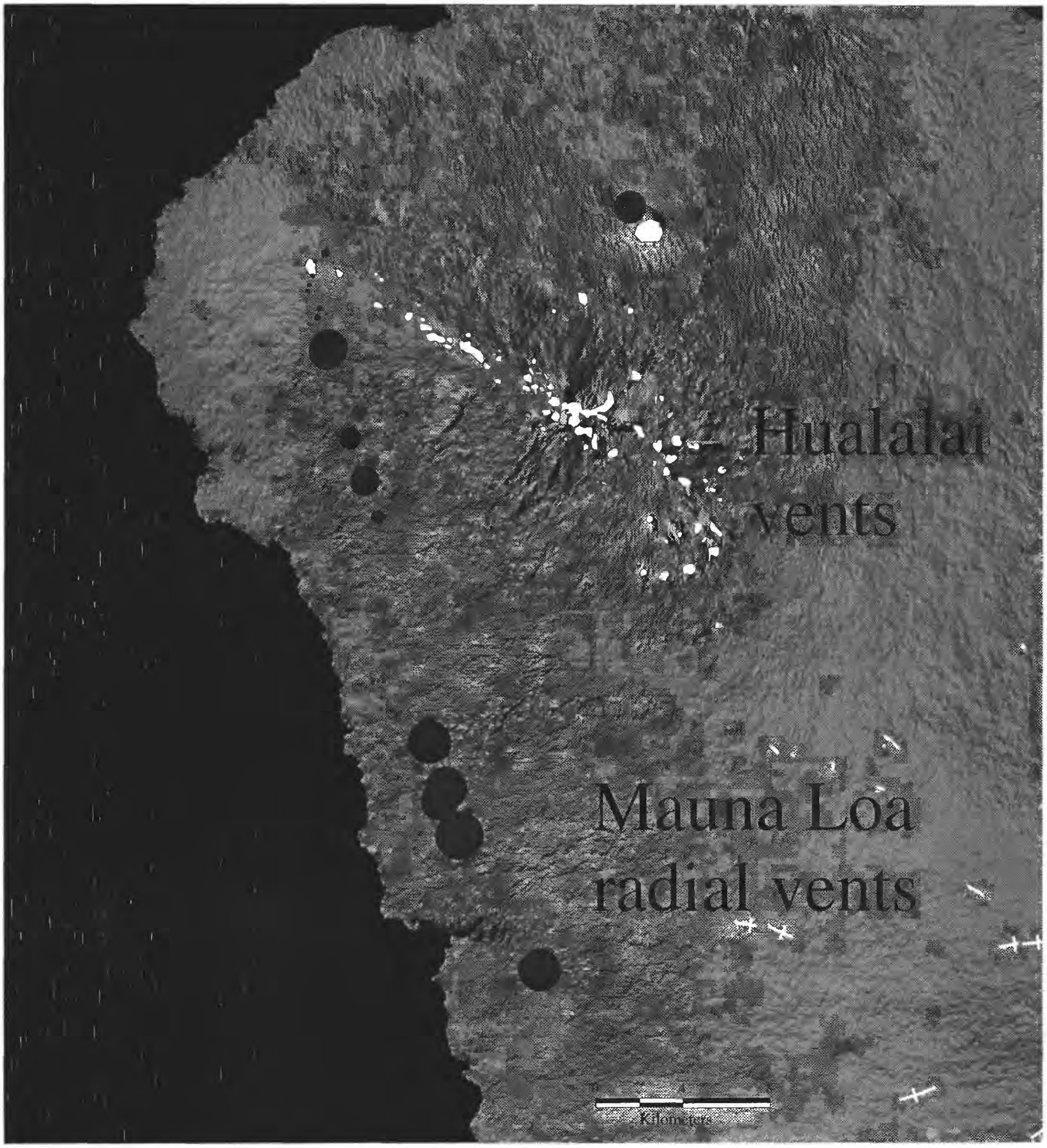

Figure 1: Shaded relief map of the Kailua-Kona area showing Hualalai vents (white polygons), Mauna Loa fissures (ticked lines), and water wells (filled circles with diameter proportional to the static water level within the well - highest level is about 150 m).

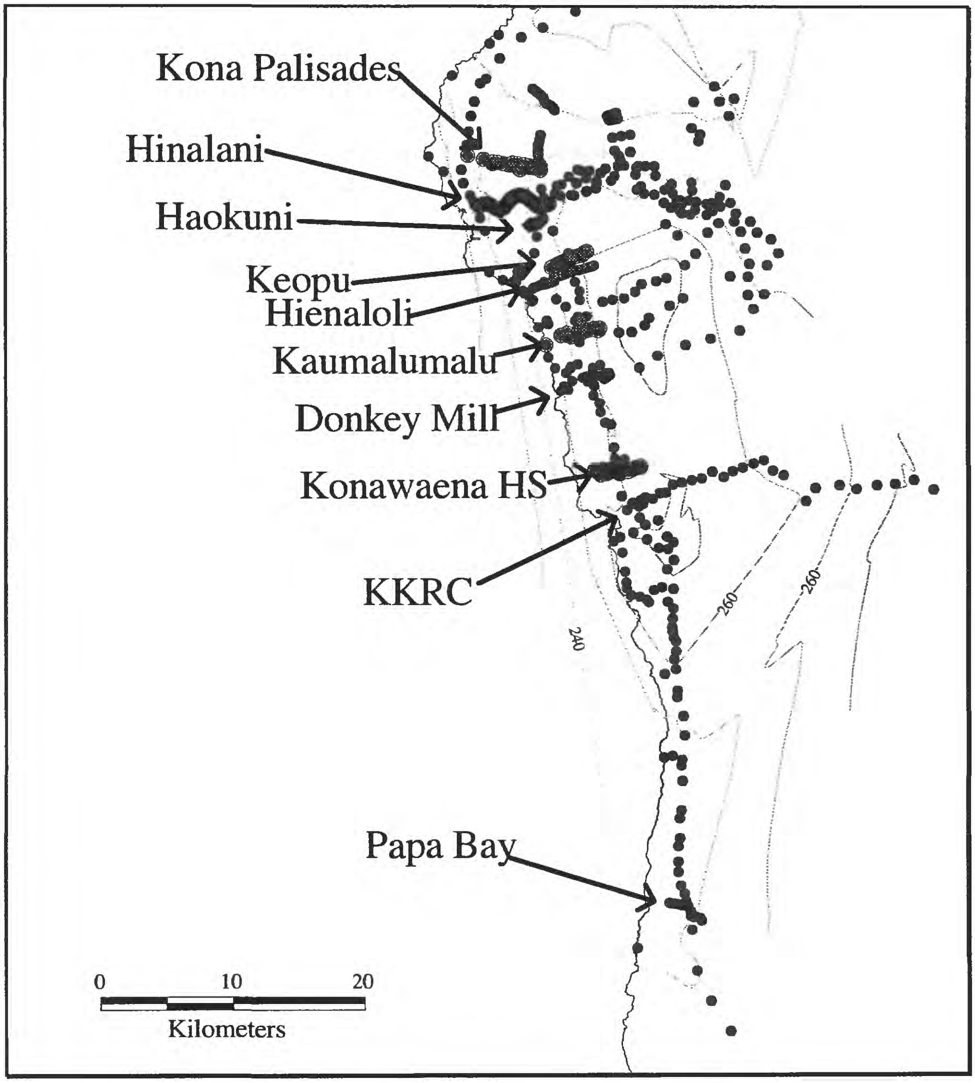

Figure 2: Map of the Kailua-Kona area showing the locations of gravity measurements and the ten gravity profiles (labeled). The corrected gravity values are contoured at a 10 mGal interval.

Although such a discontinuity in water table is expected when ground water, flowing from inland areas to the coast, is impounded by subsurface dikes (e.g., the dike-confined high-level water in Macdonald and others, 1983), no such structures were expected parallel to the Kailua-Kona coast beneath the 400 m elevation contour. Geologic maps of the area (Moore and Clague, 1991) show vent structures of Hualalai, the surface expression of subsurface dikes, farther north and east and nearly perpendicular to the coastline (fig. 1). Mauna Loa radial vents are also oriented approximately perpendicular to the coastline (Lockwood and others, 1988; Fig.

1).

Two geologic hypotheses have been suggested for the nature of the ground-water barrier responsible for the abrupt discontinuity in water-table elevations in Kailua-Kona. The first hypothesis requires a previously unknown complex of dikes whose associated vents are completely covered by later lavas. Hualalai activity then migrated northward toward its present summit. An alternative hypothesis is that the barrier is a normal fault scarp draped by later flows. Because permeability of a lava flow is a minimum from the top to the bottom flow surface (Takasaki and Valenciano, 1969), the drapery of flows over a near-vertical fault scarp would form a low-permeability zone for water flowing horizontally.

In order to obtain some new information about this ground-water configuration and the structures that confine it, we obtained 727 additional gravity measurements in the Kailua-Kona area. The use of gravity measurements for the investigation of subsurface ground-water configurations is unusual in Hawai‘i and was undertaken for several reasons. Electrical geophysical techniques, used in previous studies (Kauahikaua and Jackson, 1983; Kauahikaua and others, 1985) to map the fresh water-sea water contact by the change in electrical resistivity, can not penetrate deeply enough beneath a highly developed area such as Kailua-Kona because of the many forms of electromagnetic interference now present. On the other hand, development poses no special problems for gravity surveying. Gravity variations are produced by subsurface density variations; because the change in water table elevation is nearly 150 m in places and the average void space in Hawaiian lava flows is 20-30 per cent (Strange and others, 1965, based on gravity measurements), a discontinuity in water saturation of the subsurface rocks would likely produce a similarly abrupt change in surface gravity of as much as two mGals. In addition, dike complexes have been mapped with gravity measurements on other Hawaiian volcanoes because dikes are generally denser than lava flows (Kinoshita and others, 1963). An isolated dike complex should be detectable as a local gravity high. To distinguish the two hypothesized structures, subsurface dikes should produce a larger gravity anomaly than flows draping a fault scarp; however, the gravity anomaly produced by the impounded water alone should be significantly larger than the gravity effect of either barrier structure.

PREVIOUS WORK

A reconnaissance gravity map was completed in the early 1960s by Kinoshita and others (1963). It showed that Hualalai is the only one of the five subaerial volcanoes that make up the island of Hawai'i that does not have a gravity high associated with its summit. Instead, the Hualalai summit lies 12 km to the north of a low-amplitude gravity nose that runs parallel to the coast and about 8 km inland. The authors speculated that Hualalai may lie "on the north rift zone of an older volcano buried by Mauna Loa lavas" (Kinoshita and others, 1963). Later seismic refraction work (summarized in Hill and Zucca, 1987), interpreted with combined onshore and offshore gravity data, did not conflict with the earlier speculation: "The fairly narrow zone of elevated P-wave velocity beneath the coast is consistent with but not required by the seismic-refraction data. A comparable zone of elevated density is required, however, by the elongate gravity high that extends southward along the coast from Hualalai" (Hill and Zucca, 1987, p. 910). The most detailed geologic mapping to date found no vent structures over the Hualalai gravity anomaly (see Figure 1; Moore and Clague, 1991; Lockwood and others, 1988; updated and compiled in Wolfe and Morris, 1996). Hildenbrand and others (1993) note magnetic lows parallel to the surface rift zones of Hualalai, possibly due to thick accumulations of trachyte.

Kauahikaua and others (1985) reported the results of five deep Schlumberger soundings, obtained at 210 m elevation, along with several very shallow electromagnetic soundings. They concluded that the area between the Donkey Mill and Konawaena HS profiles (fig. 2) appears to have the thickest basal ground-water lens at an elevation of 200 m. These soundings were interpreted as if the earth under them were horizontally layered, but we now know that they are less than 2 km west of the high-level water body. Hence the interpretation of a thicker basal lens may have been due to the lateral detection of the high-level water body and not simply to the ground-water conditions beneath the sounding. So far, the distribution of wells intersecting high-level ground water and those intersecting basal ground water reveal the existence of this hydrologic barrier better than other data.

METHODS

Accurate measure of gravitational acceleration relative to a point of known absolute gravitational acceleration was obtained using LaCoste-Romberg gravity meters G-615 and G-721. Two gravity benchmarks were established in the Kailua-Kona area from very accurate gravity benchmarks on Kilauea Volcano that are measured frequently relative to the ISGN71 standard in Hilo, Hawai‘i.

All subsequent gravity measurements were made relative to either or both of these Kailua-Kona benchmarks and were corrected for tides and instrument drift. Final uncertainty is estimated to be less than 0.05 mGals for points measured once and 0.03 mGals for points measured two or more times.

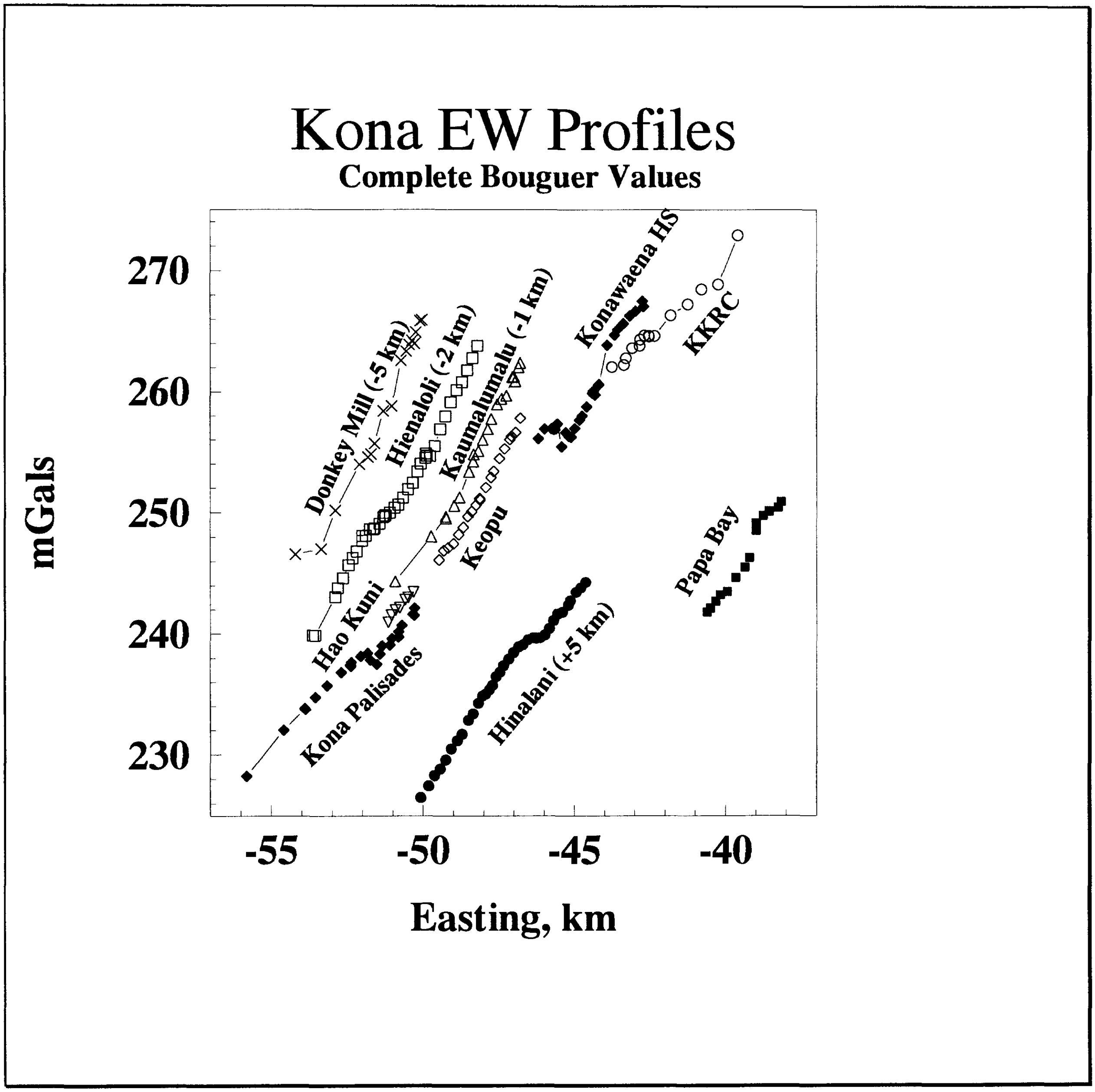

Figure 3: A composite plot of the reduced gravity data projected onto east-west profiles. The distance in parentheses after some of the profile names indicates a horizontal offset for the data from that profile for improved legibility.

The largest correction made to gravity measurements compensates for the known effects of elevation. Precise elevations were obtained in several ways for this study. The elevations of several sites along public roads were obtained from State and County Highways department surveys and were reported with errors less than 0.1", or 0.3 cm. The elevation of municipal water storage tanks and valves were obtained from the County Department of Water Supply with similar reported errors. All locatable USGS benchmarks were used. In addition, ten east-west profiles across the 400 m contour were surveyed with a Pentax PTS-V electronic total station surveying instrument. Elevations are repeatable to better than 5 cm.

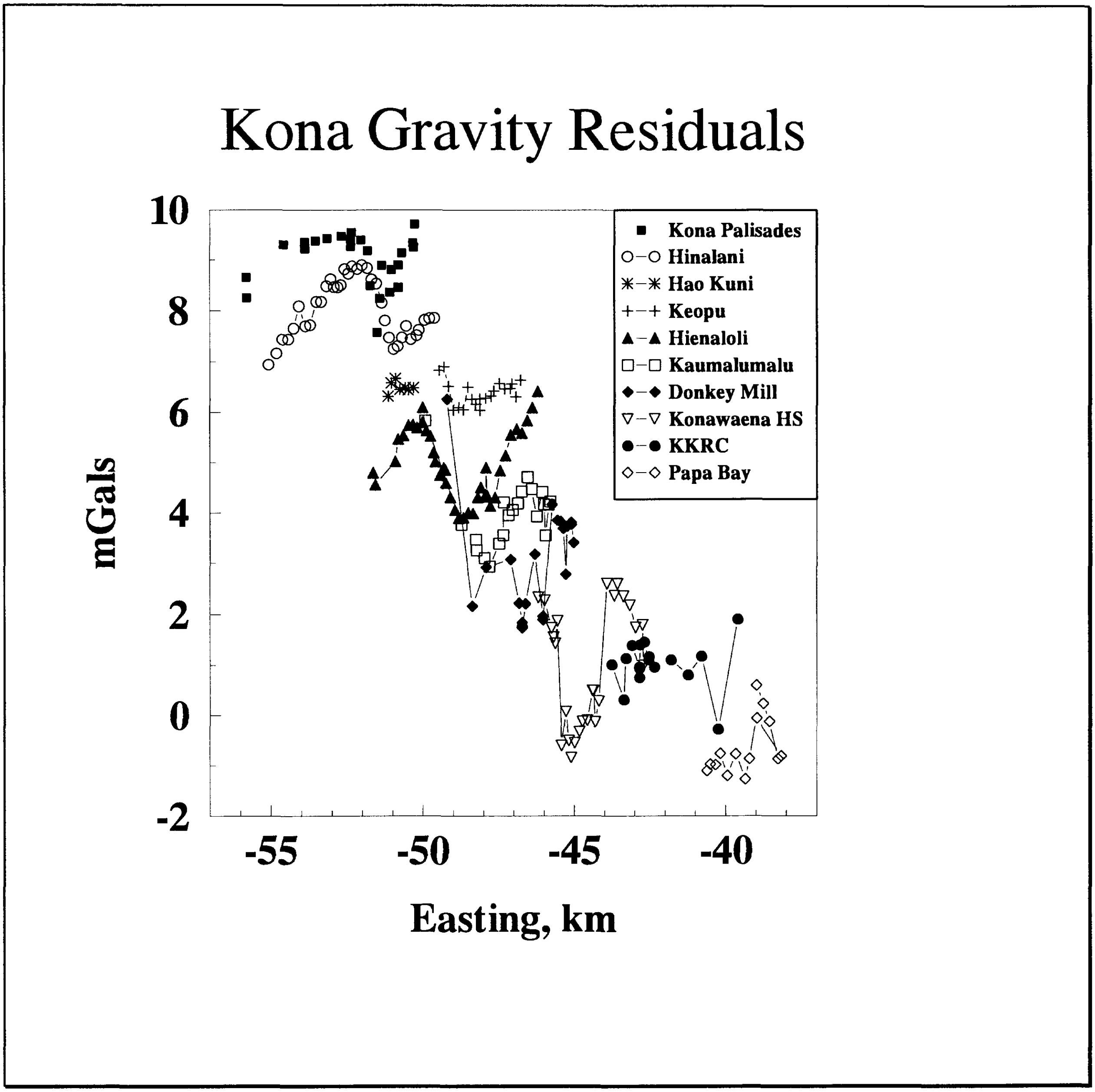

Figure 4: A composite plot of gravity residuals obtained by subtracting a best-fit line from each of the profiles plotted in figure 3. The residuals are offset from each other vertically for legibility.

Elevations for several of the most remote sites, where total-station surveying was not practical, were obtained using Global Positioning Satellite (GPS) equipment with an accuracy of better than 1 meter relative to the WGS84 ellipsoid. Gravity data reduction procedures require an elevation relative to the geoid (an orthometric elevation) and not an elevation relative to the

WGS84 ellipsoid. The GPS elevations were converted to orthometric elevations using the following procedure: The height of the geoid relative to the WGS84 ellipsoid was estimated at the few sites where both an orthometric and ellipsoid elevation had been measured. Orthometric elevations were then calculated at each of our gravity sites by interpolating the geoid height and subtracting that interpolated value from the ellipsoid elevation.

All gravity values discussed in this paper have also been corrected for the effect of topography and bathymetry (Chase and others, 1980) from 1 to 150 km away from each measurement site using standard terrain-correction procedures. The complete corrected map of gravity variations, shown in figure 2 along with the actual measurement locations, is similar in general shape to the map produced earlier by Kinoshita and others (1963).

GRAVITY PROFILES

Table 1:Parameters of best-fit lines for Complete bouguer anomaly profiles.

Profile	intercept	gradient
Kona Palisades	355.2	2.3
Hinalani	401.6	3.2
Hao Kuni	387.4	2.9
Keopu	461.2	4.4
Hienaloli	449.2	4
Kaumalumalu	404.5	3.2
Donkey Mill	505	5.3
Konawaena HS	416.5	3.5
KKRC	365.2	2.4
Papa Bay	366.2	3.1

Along each of the ten profiles located in figure 2, gravity increases from west to east as expected from examination of the reconnaissance map by Kinoshita and others (1963). Our increased density of data allows a better estimation of the spatial gradients, determined to be 2 to 5 mGals per km (fig. 3), and a better definition of this anomaly's shape (fig. 2). Some profiles in Figure

3 are smoother than others due to lower measurement error. Nonetheless, the final reduced data show similar variations in each profile. For example, the eastern parts of the Hinalani and Kona Palisades profiles have a similar "notch", and the western parts of the Keopu, Hienaloli, and Kaumalumalu profiles have a similar "hip". Only after removing these regional trends, can smaller, more local variations be seen. As an initial attempt, a least-squares best-fit line was drawn through each of the complete Bouguer profile data sets. Then this line was subtracted from the respective data set. The residuals obtained are plotted together in figure 4 and the parameters of the best-fit lines are given in table 1. All further discussion is directed toward these residuals.

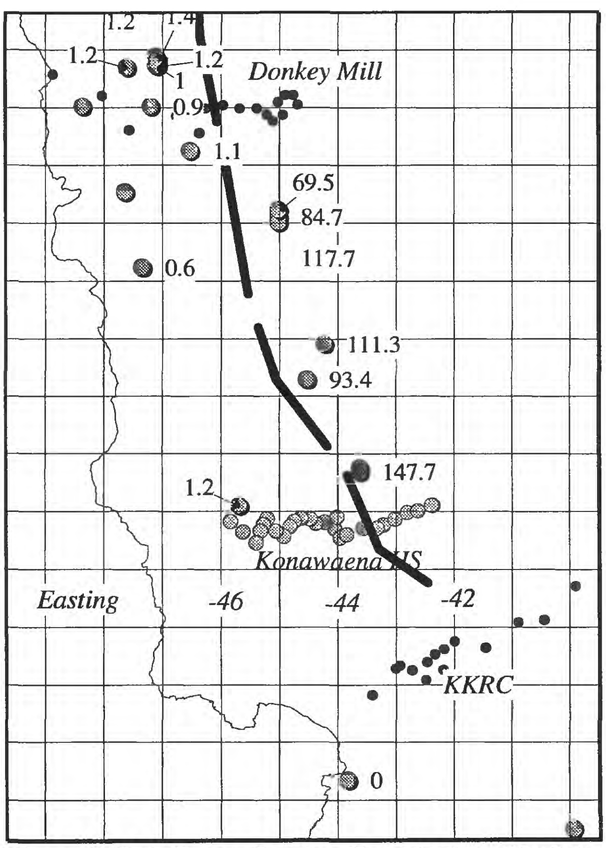

Figure 5: Detail map showing the actual profile data and well locations within a 1 km grid. Static water level is in meters above sea level. Heavy line indicates axis of residual gravity low.

Of the ten residual profiles, five (Kona Palisades, Hinalani, Hienaloli, Kaumalumalu, and Konawaena HS) have a similar shape, with a sharp-sided gravity low in the center of the profile and with flanking highs on both sides (fig. 4). The others show broadly similar variations, but do not have the whole shape. The location of this subtle variation in an otherwise strong east-west gradient is consistently between those wells that clearly intercept high-level ground water and those that intercept basal ground water. Figure 5 shows that a high-level well (static water level of 147.7 meters above sea level) is located at an easting of approximately -43.5 km, east of the low in profile Konawaena HS residuals (fig. 4), and that a basal well (static water level of 1.2 meters above sea level) is located at an easting of approximately -45.5, near the west edge of the residual low. The Donkey Mill profile is 2 km north of a battery of three high-level wells at easting -45, within the highest residual values; the basal wells are west of easting -46.5. Figure 6 shows the same relationship between high-level and basal wells along the Kona Palisades and Hinalani profiles; the high-level wells are east of the residual low while the basal wells are west. The Keopu and Hienaloli profiles also are near high-level wells that project east of the lowest residuals plotted in Figure 5.

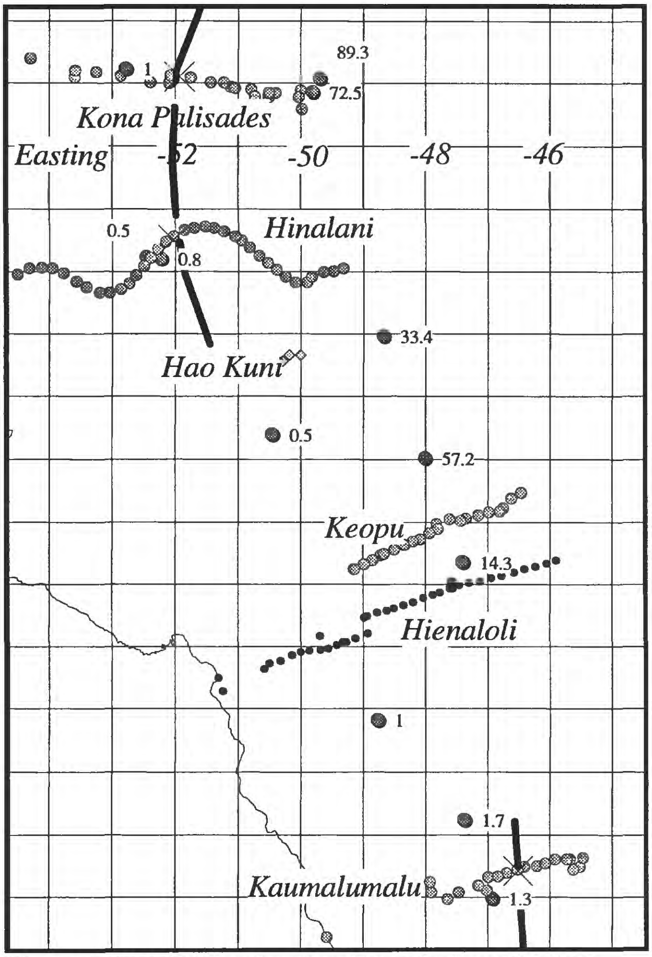

Figure 6: Detail map showing the actual profile data and well locations within a 1 km grid. Static water level is in meters above sea level. Heavy lines indicate axis of residual gravity low.

DISCUSSION AND CONCLUSION

The exact shape of the residual is less important for this analysis than the fact that several of the profiles have a similar shape that can be emphasized by subtracting a best-fit line. Removing the best-fitting linear trend from the data and comparing the residuals from different profiles for similar features is a simplistic way of removing the effect of the larger gravity anomaly running along the coast (see figure 2) and comparing any remaining local anomalies. These local anomalies could be due to buried structures that may be responsible for the large difference in static water level observed in this part of the island.

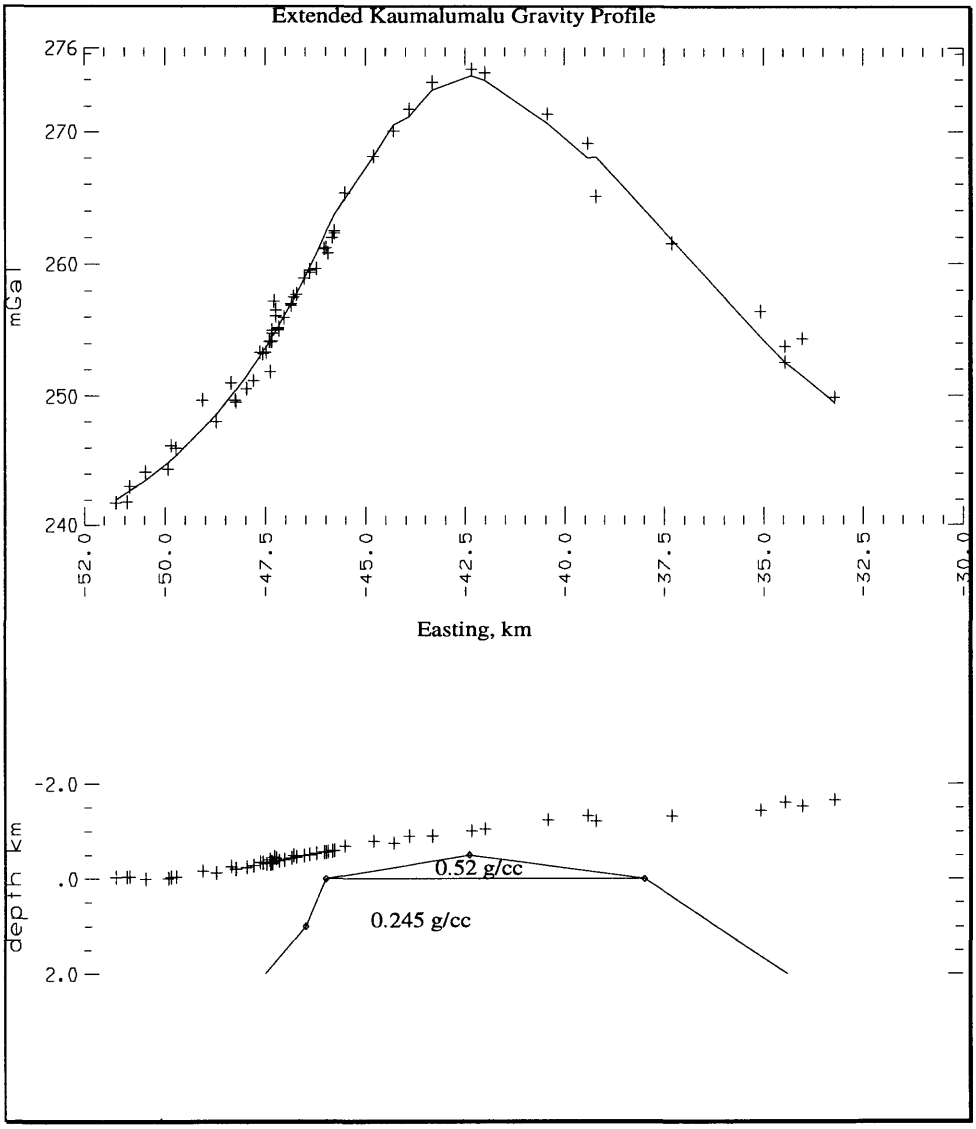

Figure 7: Comparison plot of model response and data. Model shape and data locations are shown in the lower portion. Density contrasts are shown for the model.

A better way to remove the regional anomaly from the profile data is to model it using a larger data set. The new gravity values were obtained across the Hualalai anomaly in only three places - near the Kaumalumalu, Donkey Mill, and Konawaena HS/KKRC profiles. The latter profile is significantly affected by the mass of Mauna Loa so we will proceed with the regional analysis using an extended data profile that includes Kaumalumalu profile.

Figure 7, the result of this effort, shows that the fit between model response (line) and data (pluses) in the upper part is rather good. Modeling was done using the computer program SAKI

(Webring, 1985). Much of the data scatter results from including data within 3 km off the profile. The model itself is shown in cross-section in the lower portion of Figure 7 along with the data locations (pluses). The model mass is 21.5 km wide at a depth of 5 km below sea level, 8 km wide at sea level, and has a top 500 m above sea level. SAKI can compute the responses of terminated bodies, so the masses in this model were terminated 5 km north of the profile and several tens of kilometers south of the profile. The density of the mass is just above 2.8 g/cc; below sea level, the reduction density of 2.6 g/cc plus the model density contrast of 0.245 represents a real density of 2.845 g/cc. Above sea level, the reduction density of 2.3 g/cc plus the model density contrast of 0.518 represents a real density of 2.818 g/cc. The model mass is similar in shape to the core of the summit and rift zones of Kilauea volcano (Kauahikaua and others, 1996).

Figure 8 shows the result of taking the regional Hualalai model and comparing its response to the Kaumalumalu profile data alone. It does a much better job matching most of the variation in the profile and is more geologically reasonable. A flattening can still be seen in the data between eastings of -46 and -47 km. A better fit is achieved by adding a relatively thin mass dipping westward from a point within 100 m below the ground surface (fig. 9). Shallower gradients to the west than to the east require the westward dip. The fit between model and data is improved from a RMS error of 0.543 for figure 8 to 0.387 for figure 9. The density of this rather small, shallow body is also about 2.8 g/cc.

While still not definitive, this analysis suggests that a geologic model for the gravity data includes a broad, dense core, which may be a volcanic dike zone, and a thin body dipping west, which may represent unusually dense flows. These flows may be so dense that they can impede ground-water that would normally flow to the coast, resulting in a high-level water body like that found here. Similar features appear in some of the other profiles: in the Kona Palisades and the Hinalani profiles at an easting of -52 km, the Kaumalumalu profile at an easting of -46.5 km, and the Donkey Mill profile at an easting of -46 km. Two of the profile data sets have two “flattenings” - Konawaena HS at an easting of -45 and -42.5 kms and KKRC at an easting of -42 and -40 kms. The Hao Kuni, Keopu, and Hienaloli profiles do not have this feature, although

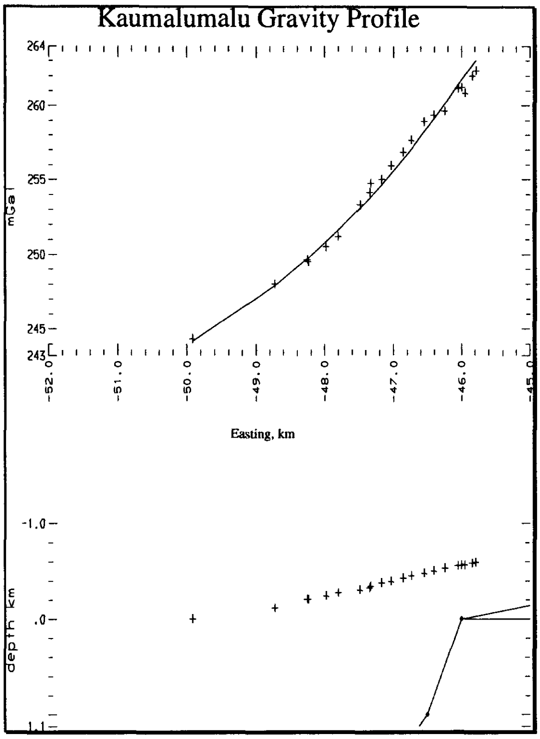

Figure 8: SAKI plot of extended profile model with Kaumalumalu profile data. RMS error=0.543.

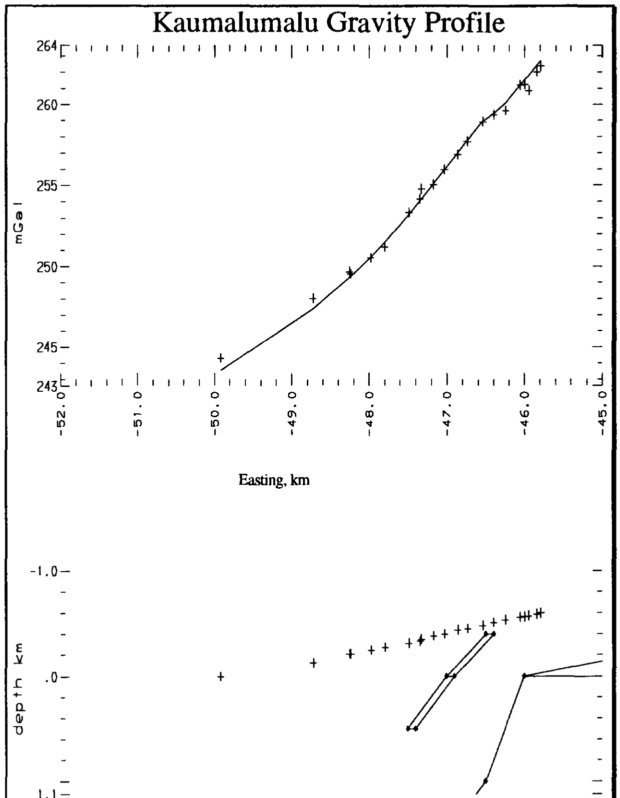

Figure 9:SAKI plot identical to Figure 8 with the addition of a thin mass dipping to the west. RMS error = 0.387

they display broad variations in the lower parts of the profiles. We conclude that the profiles are either too short (Hao Kuni) or that the local structure does not occur beneath the profiles (Keopu and Hienaloli).

Our original goal was to locate the structures that are responsible for impounding the high-level water. The secondary goal was to identify the nature of the structures. Based on the data in this study, we can say that the western boundary of the high-level water body is characterized by a gravity variation that appears as a 1-2 mGal flattening of the limb of the main Hualalai gravity anomaly. This characteristic is small relative to the much larger Hualalai anomaly but is observable in many of the data profiles obtained for this study. The shape of the anomaly is asymmetric favoring interpretation as a dense lava flow, or a sequence of flows dipping westward rather than nearly-vertical dikes. These flows may be thick trachytes found in some water wells drilled into the northwest rift zone of Hualalai (Clague, 1987; Steve Bowles, oral communication, 1997). The western edge of the mass interpreted to be responsible for the larger Hualalai anomaly is closely coincident with the hydrologic boundary. This mass must represent one or more intrusion complexes; however, the gravity model does not rule out single or sparse dikes that may extend beyond the edges of the complex. The apparent absence of a step gravity increase over the area of high-level water table suggests that the saturated rocks are fairly dense.

Acknowledgements

The authors would like to thank Kamehameha Schools/Bishop Estate, Lanihau Properties, and Kealakekua Ranch Development Corporation for granting us access to their property, and the county and state Departments of Transportation, in particular Rick Warshauer, and the County Department of Water Supply for their help in obtaining the old highway survey records. Asta

Miklius, Kathryn Riesenberg, and Annabelle Pleininger helped with the elevation control. In addition, Jennifer Pallon, Louise Timmermans, and Marije van Koolwijk operated the total field survey station for the detailed gravity profiles. Louise Timmermans, Jennifer Pallon, and Gary Puniwai made many of the gravity measurements We thank the U.S. Geological Survey Water Resources Division, Hawaii District, Bill Meyer, chief and Glenn Bauer and Rae Loui of the State of Hawaii Department of Land and Natural Resources for providing funding with which to initiate this study.

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