DENSITY LOGS FROM UNDERGROUND GRAVITY SURVEYS IN HAWAII

by

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ABSTRACT

The gravity method has been applied in three wells in Hawaii to estimate density and porosity logs. The wells are the Schofield shaft on the island of Oahu, the Kihei #3 shaft on the island of Maui and the Pahala shaft on the island of Hawaii. The method determines the "averaged" density and porosity values for Hawaiian rocks.

On Oahu, the density at depth is 2.4 gm/cc and the corresponding porosity is 18 percent. For Maui, the density averages about 2.4 gm/cc and porosity at 17 percent. The Hawaii shaft shows a lower density of 2.0 gm/cc with a correspondingly higher porosity of 27 percent. All these values are based on a grain density of 2.9 gm/cc.

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THE NEED FOR DENSITY AND POROSITY LOGS IN HYDROGEOPHYSICAL WORK

In 1965 an exploratory geophysical well-logging effort was begun by the Water Resources Research Center (Lao, Peterson, and Cox, 1969) to ascertain the applicability of electrical, temperature and caliper well-logging techniques for Hawaiian conditions and to make recommendations for future work.

The logging techniques provided much useful information, but were not able to provide acceptable determinations of the rock porosity. The investigators attributed this difficulty to two factors: 1) an erroneous value for true formation resistivity, and 2) the quantitative interpretation techniques which have been developed for resistivity logs in oil wells and water wells in sedimentary rock are not directly applicable to well logs from Hawaiian basaltic aquifers. Despite these difficulties an attempt was made to calculate a range of possible porosities for Hawaiian aquifers from the electrical logging data. The porosity ranges were 41 to 26 percent for the maximum porosity and 26 to 17 percent for the minimum porosity. Neither of these ranges is believed to be representative of the Hawaiian basaltic aquifers.

Thane H. McCulloh (1965) successfully determined an underground density profile using gravity measurements. McCulloh states that "the only borehole geophysical method presently known that is theoretically capable of yielding accurate and unambiguous measurements of *in situ* density or porosity is the method of calculating the bulk rock-density for finite depth intervals from gravity variations measured with a borehole gravimeter."

The present study is based on three gravity surveys conducted in shafts on Oahu, Maui, and Hawaii. Estimates of density and porosity logs were obtained from the gravity data.

THEORY FOR ESTIMATING DENSITY AND POROSITY LOGS FROM UNDERGROUND GRAVITY MEASUREMENTS

The theory for the determination of a density log from gravity variations has been discussed at length by Hammer (1950), Smith (1950), Rogers (1952), and McCulloh (1965). McCulloh, in his introduction, presents a comprehensive review of the efforts by others to estimate a density log from underground gravity data. The method is based upon the difference in gravitational attraction due to the layer between any two observations. In making this calculation, the layer is assumed to be effectively horizontal and the density is assumed to not vary laterally. Therefore the method is effectively estimating the changes of density and porosity as a function of depth only. The expression for the difference in the gravitational attraction, derived in Appendix A, is

$$\Delta g = \left(F - 2B\sigma_b\right) \Delta h + \Delta T, \tag{1}$$

where F is the free air gradient, B is a constant defined in Appendix A, σ_b is the bulk density of the layer, Δh is the thickness of the layer, and ΔT is terrain connection. Equation (1) may be solved for the bulk density, σ_b.

$$\sigma_b = \frac{F}{2B} - \frac{1}{2B}\left(\frac{\Delta g - \Delta T}{\Delta h}\right) . \tag{2}$$

The constants may be evaluated, then this equation becomes:

$$\sigma_b = 3.865 - 39.20 \left(\frac{\Delta g - \Delta T}{\Delta h}\right) , \tag{3}$$

for Δg in milligals and Δh in feet.

The terrain term, ΔT, is dependent upon two factors: (1) the effect of surface topography and (ii) the effect of excavation in the shaft. If the surface is nearly flat, the effect of surface topography may be ignored.

The assumption of a constant lateral density within a layer is not accurate for the Hawaiian basaltic aquifer. Generally the density will vary considerably throughout a layer so the calculated density is an average density for the layer. This average density should be more accurate than the average density estimated from averaging cores or hard samples in the laboratory.

Since the bulk density of the layer is calculated from the gravity survey, porosity may be calculated if grain density, σ_g, which can be determined from minerological and petrological investigations, is assumed. The equation for calculating the percent of porosity is

$$\text{percent porosity} = 100 \left(1 - \frac{\sigma_b}{\sigma_g}\right) . \quad (4)$$

For the purposes of this report, 2.90 gm/cc will be used as a grain density for Hawaiian basalts.

DESCRIPTION OF THE SURVEY SITES

Schofield Shaft No. 4, on the island of Oahu, was selected for the first survey. The shaft is located near Schofield Barracks east of Wheeler Field on the Schofield plateau (Fig. 1). The shaft is inclined at an angle of 30 degrees in an easterly direction and is 1,167 feet long. The 7.5-foot diameter shaft is lined with concrete from the portal inward for 346.4 feet of its length where it passes through soil and weathered rock. Two pump chambers are located at the bottom of the shaft. The water collected from vertical wells drilled at the bottom is pumped to the surface through a pipeline in the shaft. A cable car running on tracks provides transportation between the surface and the pump chamber. This site is the deepest shaft on Oahu and is located in a relatively flat area (minimizing the terrain effect).

The Schofield Plateau was formed by Koolau lavas ponding against the eroded slopes of Waianae Range. At the shaft, a zone of soil and weathered rock 173 feet thick is encountered before reaching flat-lying Koolau basalts, present through the remaining length of the excavation. Below the shaft, several vertical wells were drilled and cuttings indicate that the Koolau basalts extend at least to sea level.

When the shaft was dug, fresh water was encountered at approximately 276 feet above sea level. This was first thought to be perched water, but borings to near sea level did not reveal any aquiclude. After further testing and experimentation the anomalous condition was attributed to dike-impounded water. Swartz (1940) applied the resistivity technique to the area and partially outlined the high-head reservoir. Recent drilling operations in the Kipapa Gulch area to the south of the reservoir have located the southern barrier of this res-

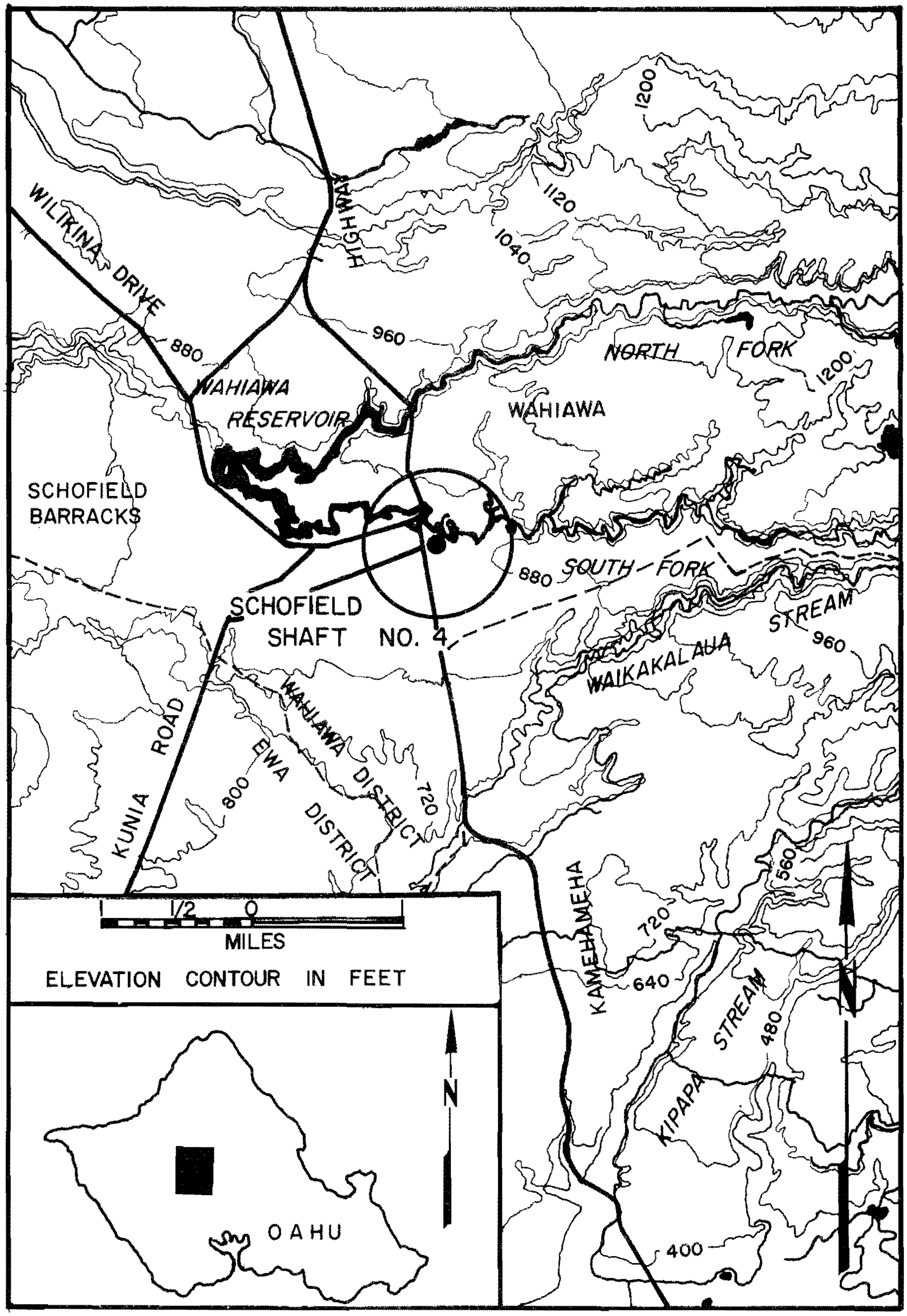

FIGURE 1. LOCATION MAP OF THE ISLAND OF OAHU SHOWING THE SCHOFIELD SHAFT NO. 4.

ervoir (Cox, personal communication).

A detailed description of the geology and water resources of Oahu has been published by Stearns and Vaksvik (1935) and Stearns (1940).

Maui

The second survey site is a vertical shaft on the island of Maui in the Kihei area near Camp K-3 (Fig. 2). Kihei No. 3 is located in East Maui and lies at the bottom of the western slope of Haleakala Volcano. The configuration of the water table around Kihei No. 3 is as described by the Ghyben-Herzberg principle. For a more detailed account of the general geology and water resources of Maui, consult Stearns and Macdonald (1942).

The shaft, 299 feet deep, is entirely cased with cement. Kihei No. 3 is a Maui-type well designed to skim water by collection tunnels from the top of the basal water-table. The pump chamber is located at the bottom of the shaft, approximately 4 feet above sea level, and the water from the collection tunnels is pumped to the surface through pipelines in the shaft. Transportation between the surface and the pump chamber is provided by an elevator.

This shaft was the site of previous geophysical work by Adams and Malahoff (1968).

Hawaii

The third site is the Pahala shaft -- located in the plantation town of Pahala on the southern slopes of Mauna Loa on the island of Hawaii (Fig. 3). The shaft physically resembles the Schofield shaft, being approximately the same length. The Pahala shaft strikes north and dips 30 degrees. Because the shaft cuts through "Recent" basalt, the entire shaft is unlined. The pump chamber in this shaft is located at the bottom. Water collects in a single horizontal collection tunnel and moves to the surface through a pipeline up the shaft. Transportation between the surface and the pump chamber is provided by a cable car running on tracks.

The high-level ground water aquifer encountered by this shaft was

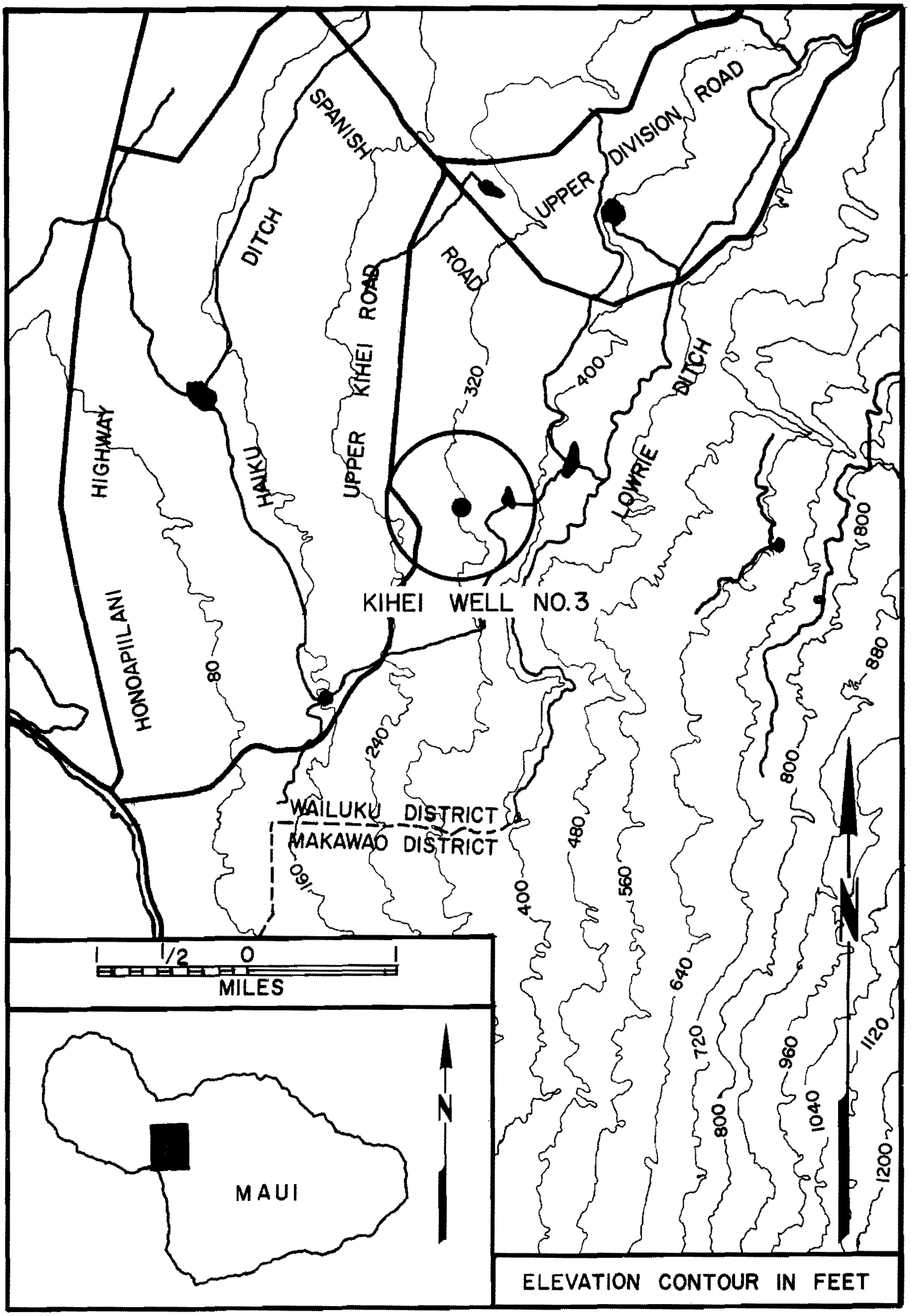

FIGURE 2. LOCATION MAP OF THE ISLAND OF MAUI SHOWING WELL KIHEI NO. 3 (FROM ADAMS AND MALAHOFF, 1968).

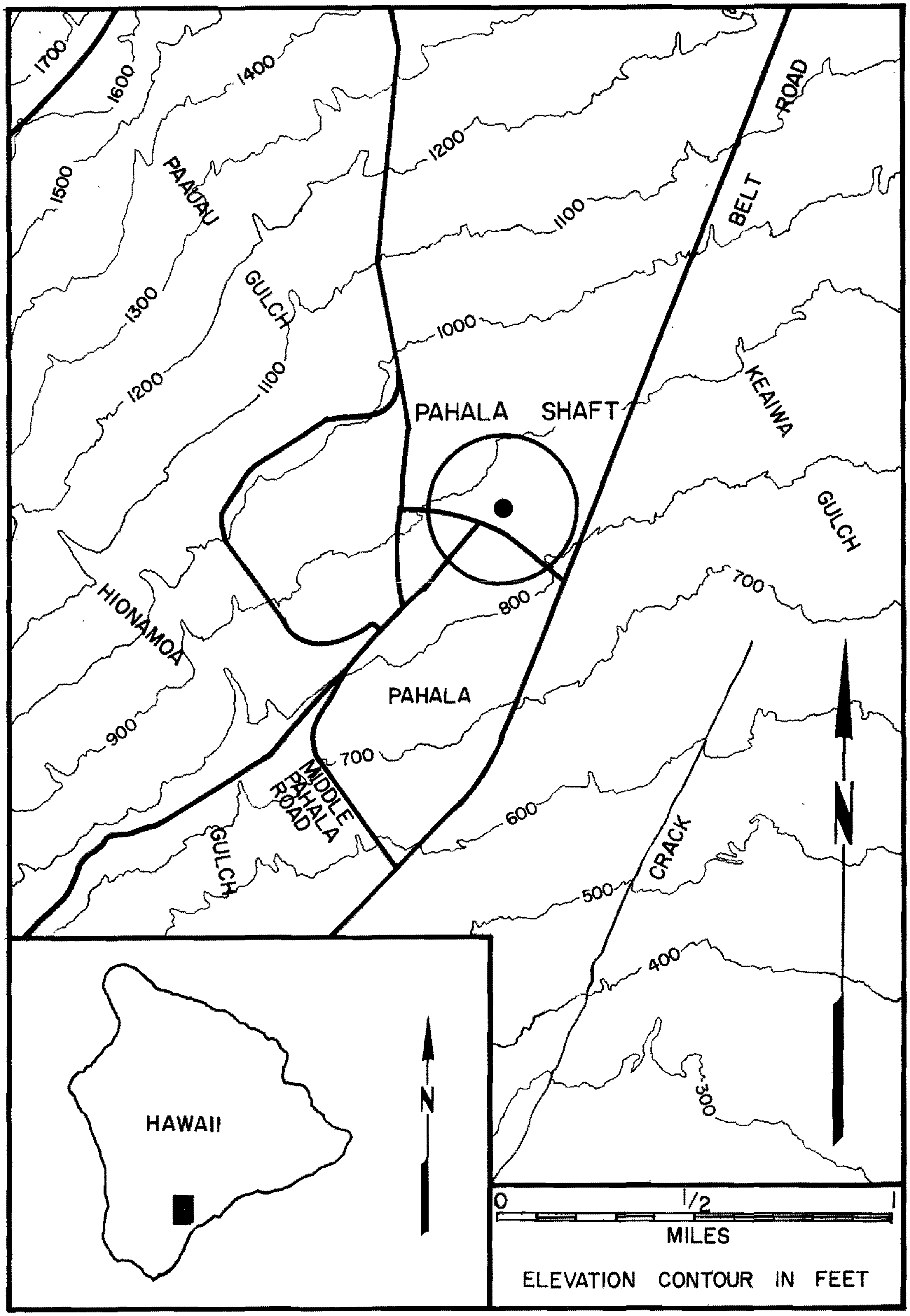

FIGURE 3. LOCATION MAP OF THE ISLAND OF HAWAII SHOWING THE PAHALA SHAFT (FROM ADAMS, MATHUR, AND HUBER, 1970).

the object of considerable geological and geophysical study. Throughout its length, the shaft passes through basalt lava flows from Mauna Loa. The Pahala shaft taps a high-head reservoir that was discovered in 1946. The top of the reservoir is approximately 220 feet above sea level. The occurrence of this reservoir has been attributed by Adams, Mathur, and Huber (1970) to the damming of ground water by the Kolea barrier and the Pahala-dump barrier.

Studies on the geology and water resources of Hawaii and especially the Pahala area has been published by Stearns and Macdonald (1946) and Davis and Yamanaga (1966). Considerable study of the water table configuration has been conducted by the Water Resources Research Center at the University of Hawaii and is reported by Hussong (1967), Hussong and Cox (1967), Adams, Mathur, and Huber (1970), and Huber (1970).

SURVEY METHODS USED IN THE WELL SHAFTS

Prior to this study, control adequate for a gravity survey did not exist within any of the three shafts. Therefore an elevation survey was conducted in each of the shafts using a modified stadia technique. The stations were selected and the distances between them were chained. A transit was located halfway down the shaft and adjusted so that it was fixed at an angle 30 degrees above or below a level plane (Fig. 4). The stadia rod was then placed at each station and a reading taken. The elevation difference between any station, calculated by using the expression in Figure 4, can be determined by summing the increments between any two stations.

In the vertical well on Maui, the elevation increments were determined by extending a chain down the shaft and noting the distance between stations.

In the case of the surveys on Maui and Hawaii, the elevation profiles were related to known bench marks and the elevations above sea level were then determined. The elevation data for all wells are reported as vertical distances from the surface or the first station at the top of the shaft.

The gravity surveys were made using Lacoste-Romberg gravity meters Nos. 19 and 93. Readings were obtained in the inclined shafts by

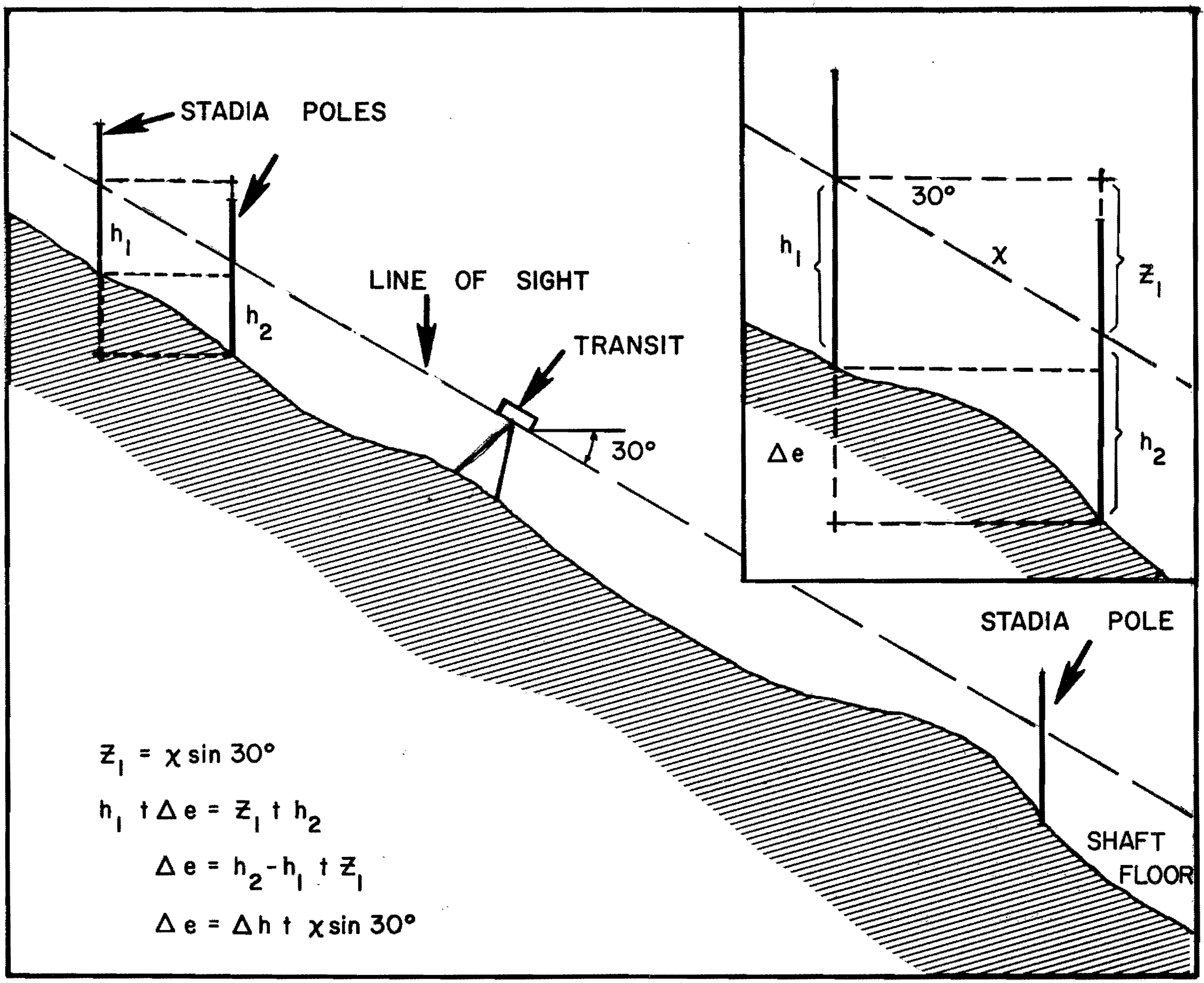

FIGURE 4. SURVEY CONFIGURATION AND GEOMETRY USED IN THE INCLINE SHAFTS.

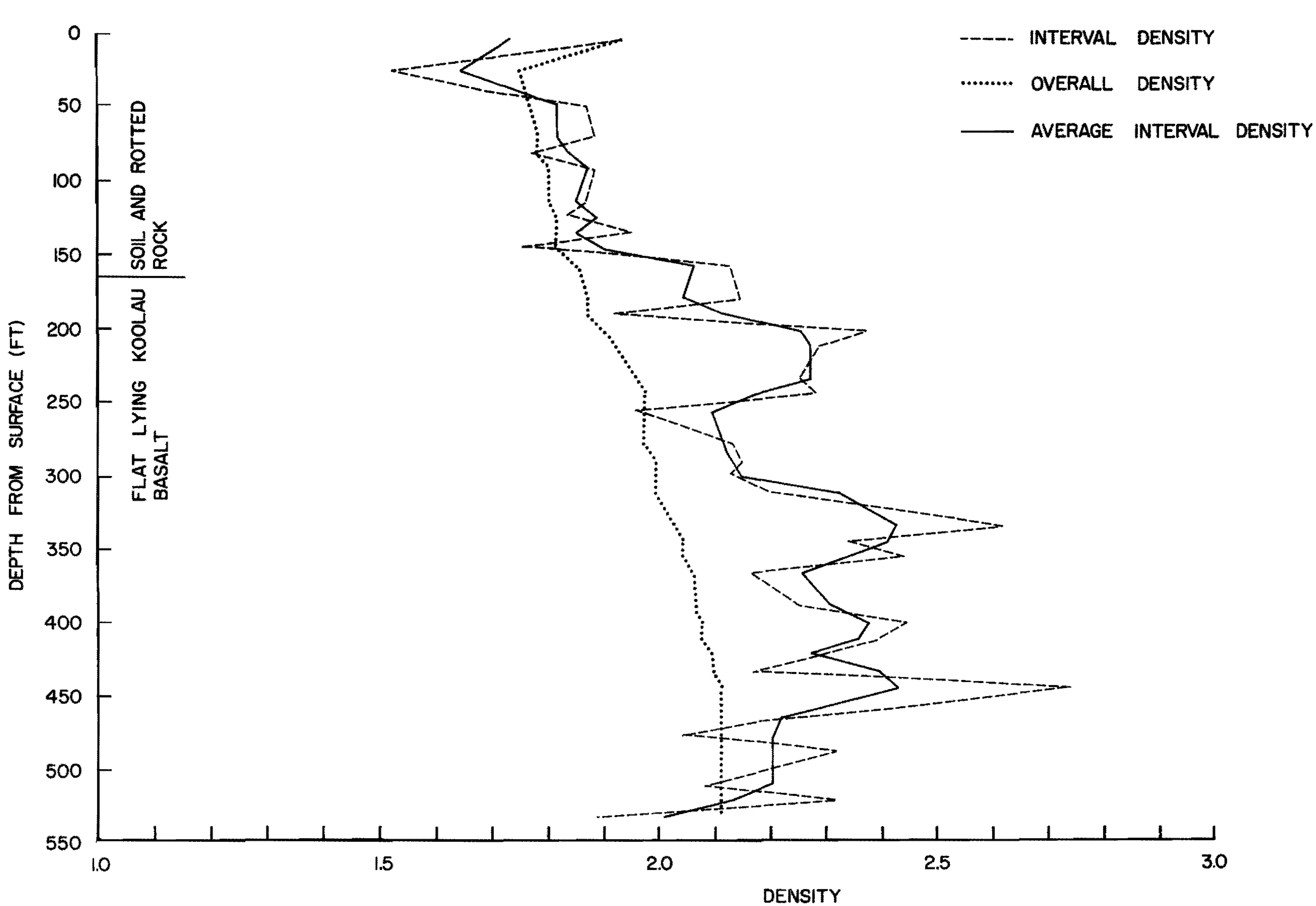

FIGURE 5. DENSITY LOG FOR THE SCHOFIELD SHAFT.

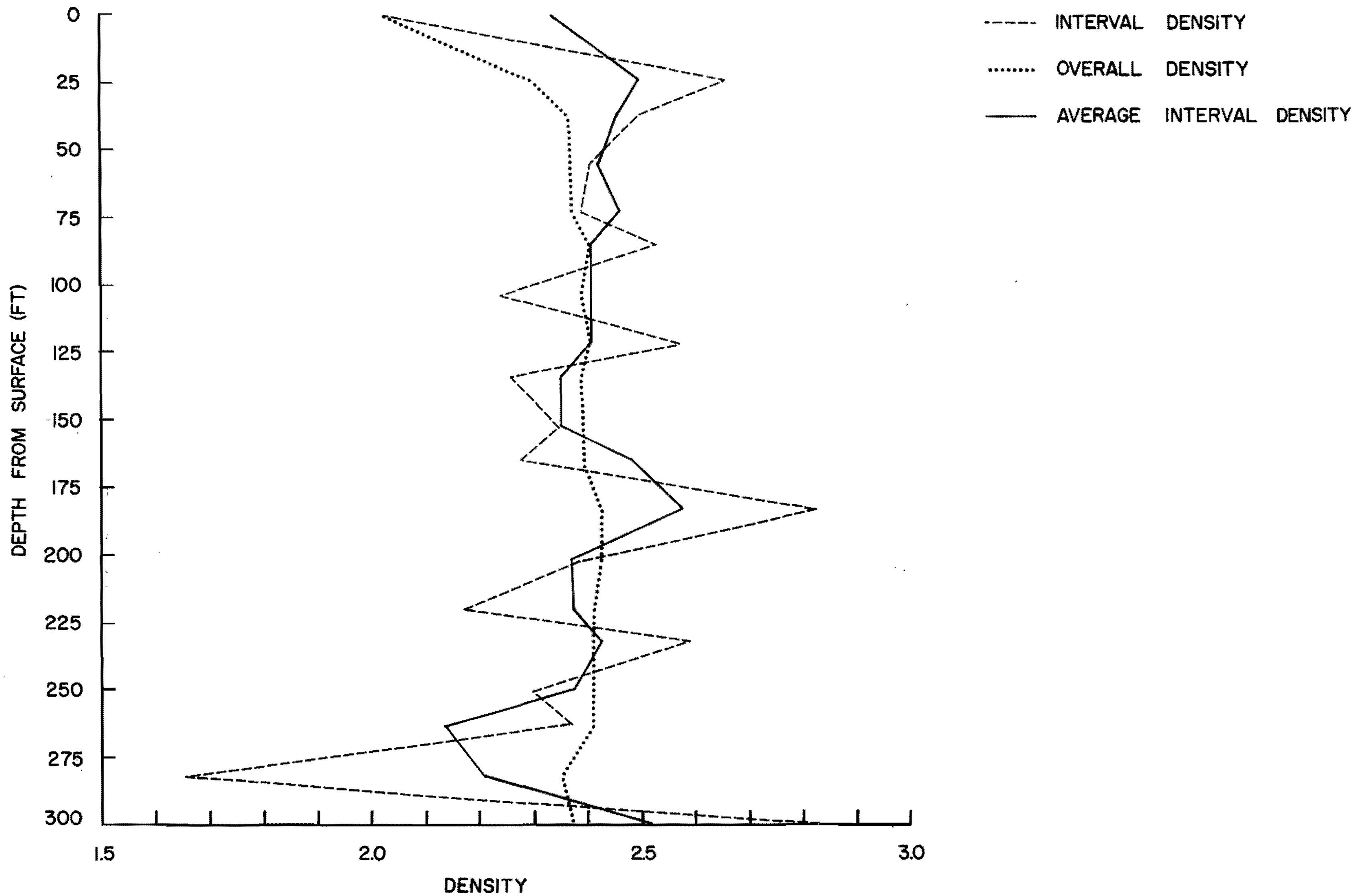

FIGURE 6. DENSITY LOG FOR THE KIHEI 3 MAUI SHAFT.

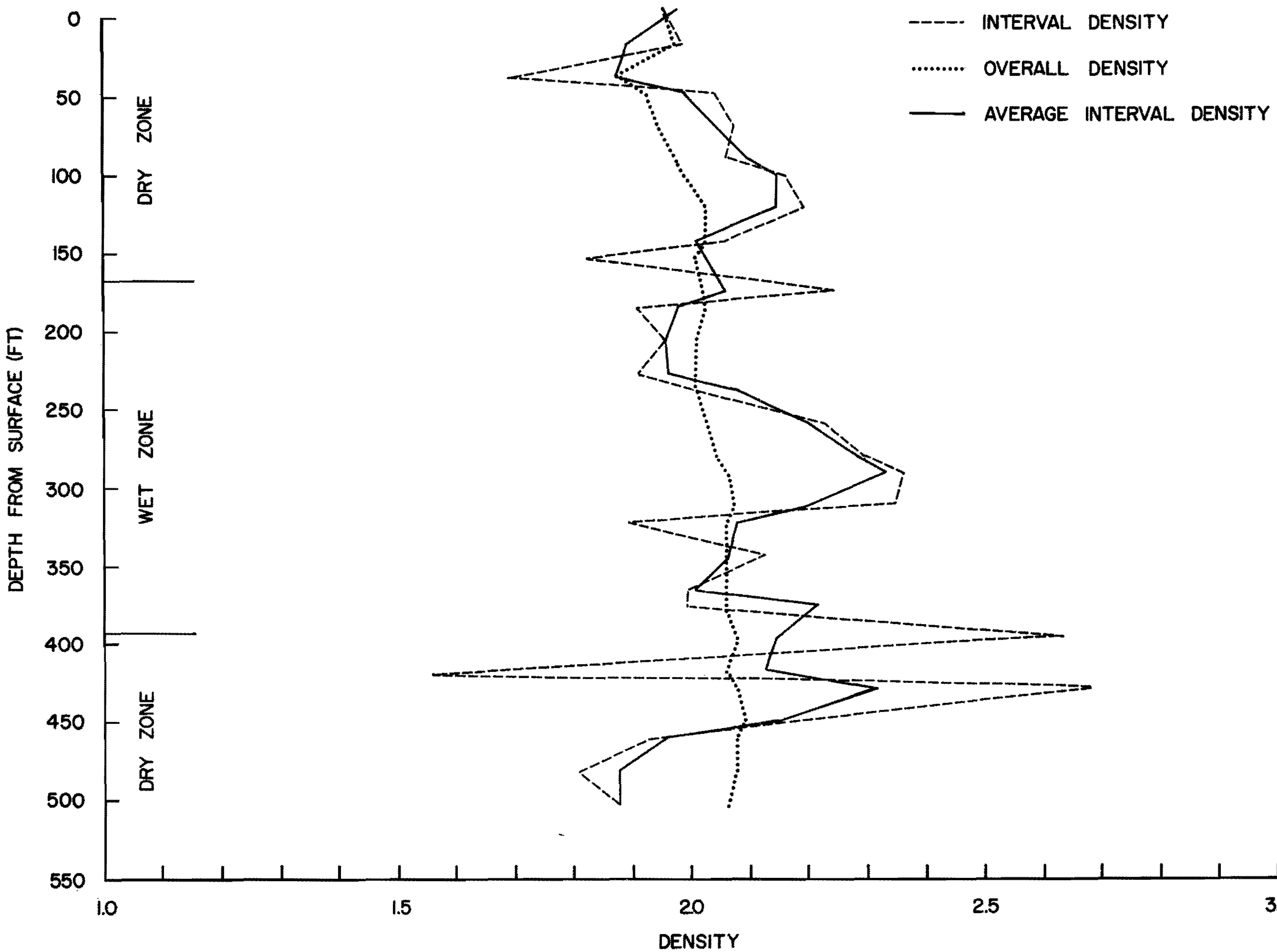

FIGURE 7. DENSITY LOG FOR THE PAHALA SHAFT.

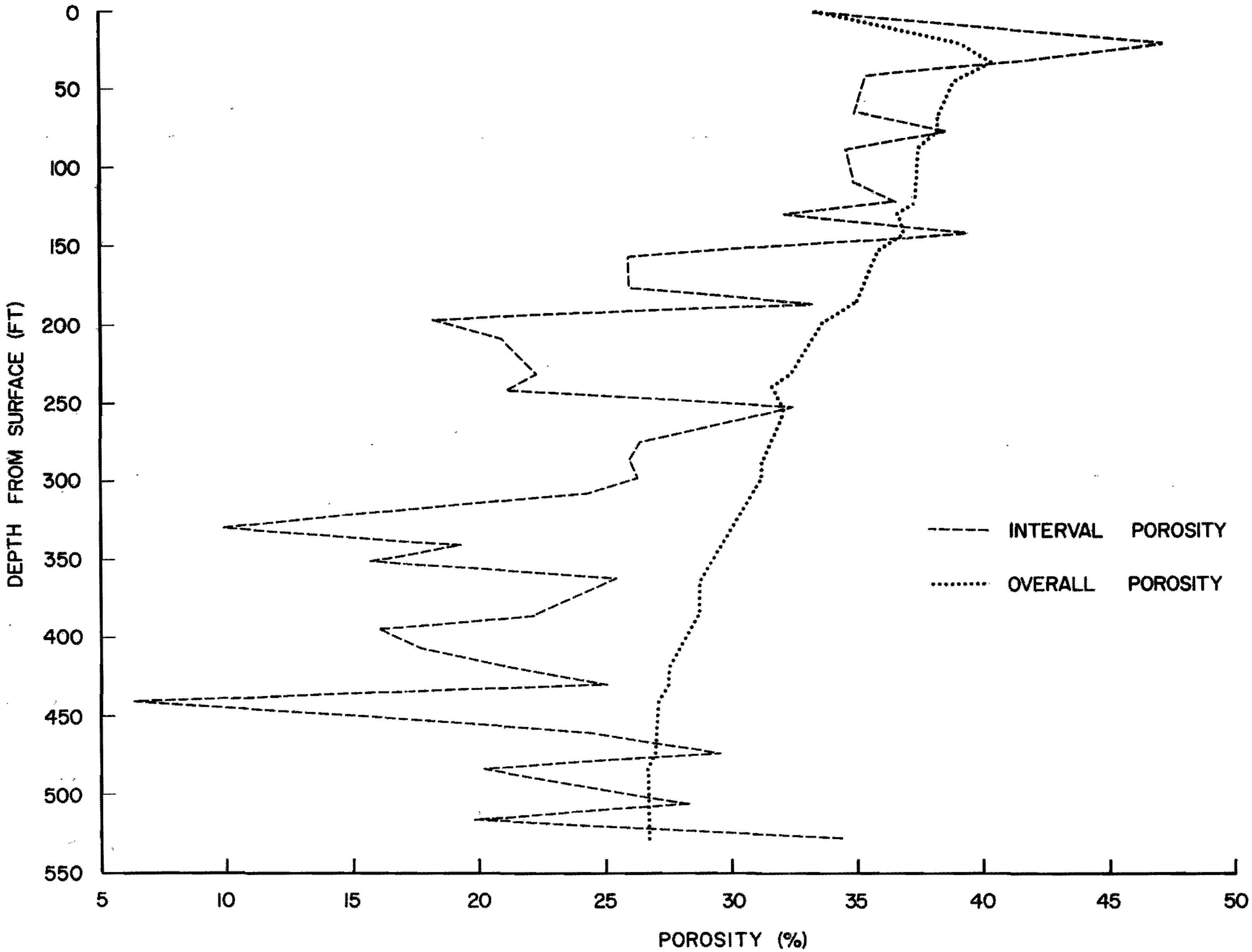

FIGURE 8. POROSITY LOG FOR THE SCHOFIELD SHAFT.

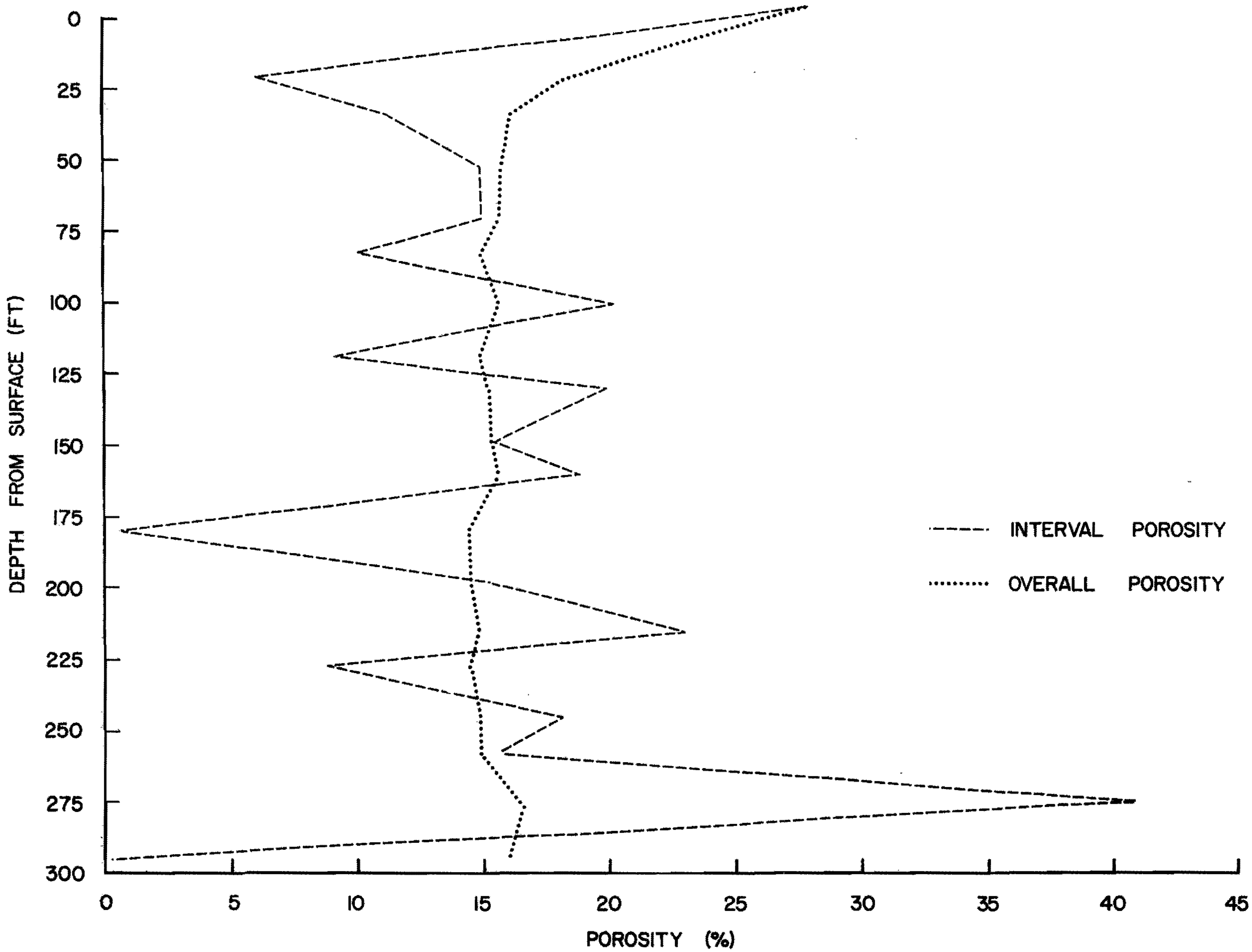

FIGURE 9. POROSITY LOG FOR THE KIHEI 3 MAUI SHAFT.

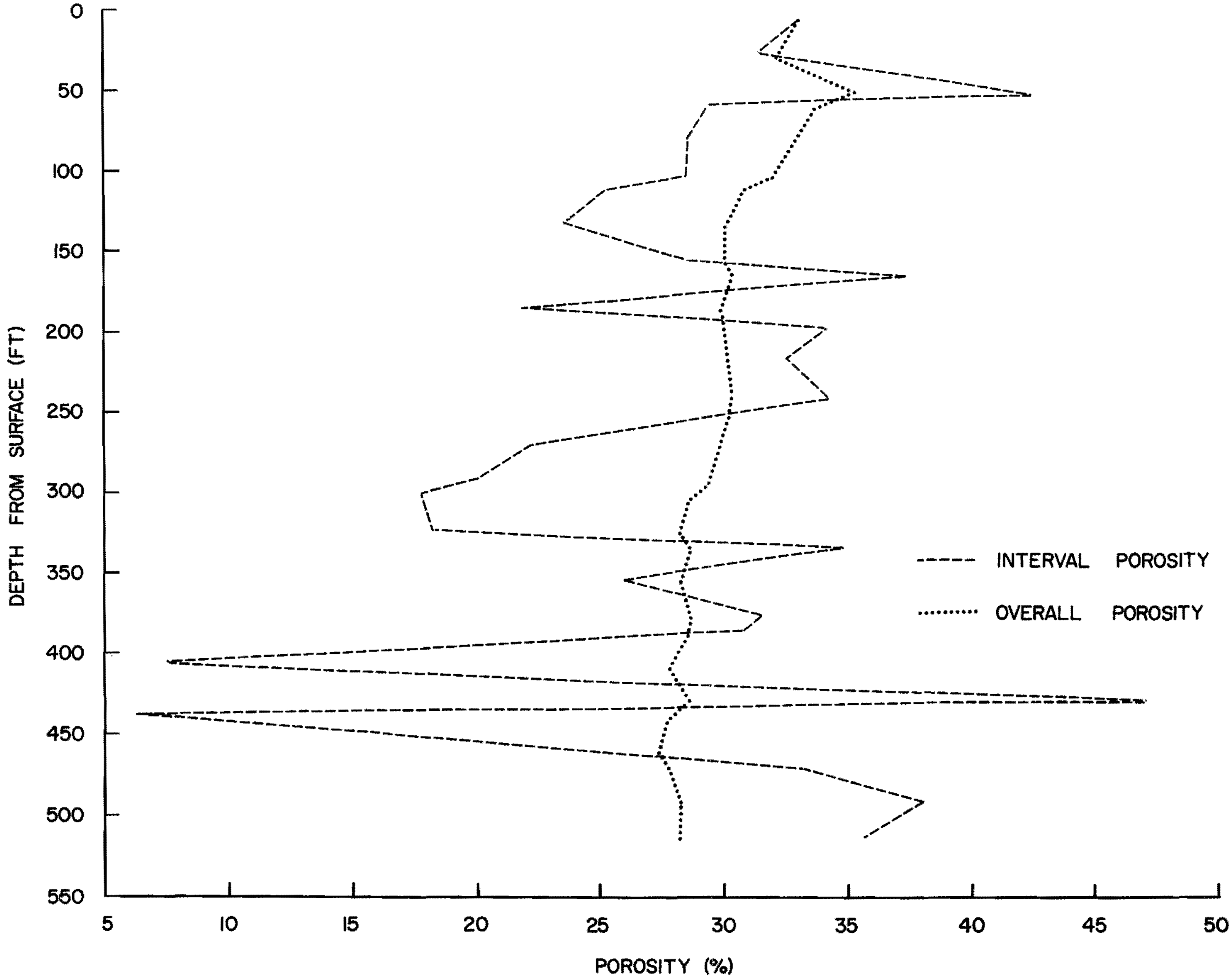

FIGURE 10. POROSITY LOG FOR THE PAHALA SHAFT.

mounting the meter upon a tripod which was firmly placed on the floor. Under these conditions, the pumps need not be shut down. In the vertical shaft, both the meter and observer were on platforms constructed on the steel girders of the elevator shaft. During the survey in the vertical shaft on Maui, the pumps were turned off. The observer and elevator operator restrict their movements to minimize vibrations during the observation. With these restrictions, satisfactory readings were possible.

During each gravity survey, a base station was resurveyed every hour to obtain accurate drift and earth-tide corrections.

DATA ANALYSIS

The data presented here has been changed from dial readings to milligals with corrections for drift and earth-tide effects. Because the measurements were made effectively at a single point on the surface, no regional correction was made. The elevation data was reduced in accord with the methods and equations listed in the previous section on SURVEY METHODS (p. 8). The data for the Schofield shaft on Oahu, Kihei Well No. 3 on Maui, and Pahala shaft on Hawaii are listed in Tables 1, 2, and 3, respectively. These data were used as input to the computer programs listed in Appendix B, from which density and porosity logs were calculated.

Figures 5, 6, and 7 present the density logs for the three shafts calculated by Equation (3). Each graph consists of three plots: the interval density -- the density for the layers occurring between gravity stations, a 3-point moving average of the interval density, and the density log for a single layer of increasing thickness (the layer formed between the uppermost station and each succeeding station), called the overall density.

Figures 8, 9, and 10 are porosity logs for the three shafts determined by using Equation (4). Each figure contains two plots: an interval porosity log corresponding to the interval density plot in Figures 5 to 7 and an overall porosity log corresponding to the overall density plot mentioned in the preceding paragraph.

TABLE 1. GRAVITY AND ELEVATION AND SUMMARY OF DENSITY AND POROSITY DATA FOR THE SCHOFIELD SHAFT, OAHU.

GRAVITY (MGALS)	DEPTH BELOW SURFACE (FT)	DENSITY (G/CC)		POROSITY (%)	
		INTERVAL	OVERALL	INTERVAL	OVERALL
2600.94	0.0	1.950	1.950	32.8	32.8
2601.71	15.76	1.532	1.770	47.2	39.0
2602.42	27.69	1.685	1.739	41.9	40.0
2603.29	43.33	1.885	1.771	35.0	38.9
2603.90	55.41	1.894	1.800	34.7	37.9
2604.74	72.12	1.782	1.797	38.5	38.0
2605.34	83.41	1.902	1.814	34.4	37.5
2606.13	99.19	1.890	1.822	34.8	37.2
2606.76	111.69	1.841	1.825	36.5	37.1
2607.54	126.80	1.977	1.838	31.8	36.6
2608.14	139.26	1.754	1.831	39.5	36.9
2608.84	152.26	2.154	1.862	25.7	35.8
2609.55	168.53	2.159	1.883	25.5	35.1
2610.09	180.94	1.939	1.886	33.1	35.0
2610.65	192.34	2.390	1.925	17.6	33.6
2611.26	208.55	2.313	1.945	20.2	32.9
2611.71	219.92	2.276	1.968	21.5	32.1
2612.37	236.20	2.308	1.984	20.4	31.6
2612.82	247.53	1.971	1.983	32.0	31.6
2613.61	263.88	2.152	1.900	25.8	31.4
2614.13	275.78	2.156	1.999	25.6	31.1
2614.82	291.61	2.153	2.005	25.8	30.9
2615.32	303.06	2.215	2.016	23.6	30.5
2616.01	319.45	2.636	2.040	9.1	29.6
2616.42	332.53	2.361	2.054	18.6	29.2
2617.00	347.65	2.468	2.067	14.9	28.7
2617.39	358.59	2.17	2.072	25.0	28.6
2618.10	375.06	2.270	2.078	21.7	28.4
2618.59	387.10	2.456	2.088	15.3	28.0
2619.00	398.51	2.404	2.101	17.1	27.6
2619.61	414.87	2.303	2.107	20.6	27.3
2620.11	427.42	2.185	2.109	24.7	27.3
2620.60	438.85	2.752	2.126	5.1	26.7
2620.94	450.83	2.201	2.129	24.1	26.6
2621.61	466.61	2.056	2.127	29.1	26.7
2622.16	478.53	2.336	2.134	19.5	26.4
2622.80	494.93	2.087	2.132	28.0	26.5
2623.37	507.50	2.346	2.139	19.1	26.3
2623.96	522.73	1.907	2.132	34.2	26.5
2624.75	538.55				
	AVERAGE	2.13		26.4	

TABLE 2. GRAVITY AND ELEVATION AND SUMMARY OF DENSITY AND POROSITY DATA FOR THE MAUI SHAFT (KIHEI NO. 3), MAUI.

GRAVITY (MGALS)	ELEVATION (FT)		DENSITY (G/CC)		POROSITY (%)	
	ABOVE SEA LEVEL	BELOW SURFACE	INTERVAL	OVERALL	INTERVAL	OVERALL
2513.63	303.43	0.0	2.056	2.056	29.1	29.1
2515.57	383.06	20.37	2.716	2.347	6.4	19.1
2515.04	267.03	36.40	2.556	2.410	11.9	16.9
2515.57	251.16	52.27	2.444	2.418	15.7	16.6
2516.15	235.16	68.27	2.443	2.423	15.8	16.5
2516.73	219.17	84.26	2.592	2.450	10.6	15.5
2517.25	203.16	100.27	2.287	2.428	21.1	16.3
2517.89	187.26	116.17	2.615	2.450	9.8	15.5
2518.40	171.26	132.17	2.300	2.434	20.7	16.1
2519.04	155.23	148.20	2.440	2.435	15.9	16.0
2519.62	139.27	164.16	2.322	2.425	19.9	16.4
2520.25	123.26	180.17	2.885	2.466	0.5	14.9
2520.70	105.26	198.17	2.443	2.465	15.8	15.0
2521.28	89.28	214.15	2.196	2.446	24.3	15.7
2521.96	73.30	230.13	2.640	2.459	9.0	15.2
2522.46	57.30	246.13	2.346	2.452	19.1	15.5
2523.08	41.30	262.13	2.419	2.450	16.6	15.5
2523.67	25.30	278.13	1.665	2.402	42.6	17.2
2524.68	7.30	296.13	2.899	2.408	0.0	17.0
2524.76	4.06	299.37				
		AVERAGE	2.43		16.0	

TABLE 3. GRAVITY AND ELEVATION AND SUMMARY OF DENSITY AND POROSITY DATA FOR THE PAHALA SHAFT, HAWAII.

GRAVITY (MGALS)	ELEVATION (FT)		DENSITY (G/CC)	
	ABOVE SEA LEVEL	BELOW SURFACE	INTERVAL	OVERALL
2533.40	753.50	0.0	1.966	1.966
2534.18	737.40	16.10	2.011	1.989
2534.97	720.70	32.80	1.707	1.889
2535.95	702.90	50.60	2.061	1.934
2536.76	685.30	68.20	2.087	1.965
2537.54	668.10	85.40	2.081	1.985
2538.35	650.30	103.20	2.179	2.012
2539.09	633.10	120.40	2.219	2.039
2539.85	615.00	138.50	2.079	2.044
2540.62	598.10	155.40	1.838	2.023
2541.53	580.50	173.00	2.260	2.044
2542.23	563.40	190.10	1.929	2.035
2543.05	546.80	206.70	1.977	2.031
2543.84	530.40	223.10	1.926	2.023
2544.76	511.80	241.70	2.029	2.023
2545.57	494.50	259.00	2.250	2.038
2546.32	476.30	277.20	2.311	2.053
2546.97	459.90	293.60	2.378	2.071
2547.63	442.50	311.00	2.361	2.087
2548.29	425.30	328.20	1.905	2.078
2549.15	408.10	345.40	2.149	2.081
2549.89	391.20	362.30	1.999	2.077
2550.68	374.60	378.90	2.015	2.074
2551.52	356.80	396.70	2.652	2.098
2552.04	340.00	413.50	1.575	2.076
2553.08	322.20	431.30	2.694	2.099
2553.57	305.80	447.70	2.175	2.102
2554.32	288.40	465.10	1.948	2.096
2555.20	270.40	483.10	1.816	2.086
2556.12	252.80	500.70	1.884	2.079
2557.06	234.20	519.30		
		AVERAGE	2.07	

DISCUSSION OF THE RESULTS

All the plotted logs have a high variability in the density (porosity) from one layer to the next. Visually the density changes smoothly with depth and not as sharply as the density logs indicate, although a rather large density contrast exists between different lava flows observed in Hawaii. The variability observed in these logs is probably related to the inaccurate assumption in the theory of a constant density layer.

That the logs are generally similar and yield similar values for density and porosity suggest that the general trends of the logs are real and accurate. These values could be said to represent "average" density and porosity values.

Oahu

The density and porosity logs for the Schofield shaft, displayed in Figures 5 and 8, show a distinct density contrast that coincides with the interface between the soil and basalt zones. Above the contrast, the soil zone has a density range between 1.7 and 1.9 gm/cc and a porosity range of 30 to 40 percent. Below the contrast, there are "high" density zones at depths of 208 feet, 329 feet, and 395 feet, with relative lows in between. The approximate average density for these zones is 2.3 gm/cc. The approximate average porosity for this zone is 22 percent.

The interval density appears to increase linearly to a depth of 400 feet below the surface and then decrease. This decrease is probably due to the neglected terrain correction for the excavated pumping shaft. With terrain considered, the interval density, to a first approximation, increased linearly with depth from 1.7 gm/cc at the surface to 2.4 gm/cc at 340 feet and remained constant at 2.4 gm/cc throughout the extent of the shaft. The porosity then decreased from 42 percent at the surface to 18 percent at 340 feet and remained constant at 18 percent throughout the extent of the shaft.

Maui

The density and porosity logs for Kihei No. 3 shaft are shown in Figures 6 and 9. The interval density plot in this case indicates a constant density trend with depth and appears to be approximately independent of depth. Throughout the extent of the shaft the interval density averages about 2.4 gm/cc. The terrain effect of the pump shaft appears to be negligible in this case. Similarly, porosity remains constant at about 17 percent.

Hawaii

The density and porosity logs for the Pahala shaft, shown in Figures 7 and 10, are similar to those for the Maui shaft: the interval density plot, appears to be approximately independent of depth and remains constant at about 2.0 gm/cc throughout the entire length of the shaft. The corresponding porosity for this constant trend is about 27 percent.

CONCLUSIONS

The use of gravity measurements to determine a density log has been shown to be accurate (McCulloh, 1965) provided 1) adequate corrections are made to the gravity measurements and 2) the area in which the method is being used satisfies the assumptions made in the development of the theory. In applying the gravity method to the current study, terrain corrections were ignored; consequently, the calculated densities retain some error. In addition, the assumption of constant density layers is not accurate for Hawaiian basaltic aquifers as the high incidence in the variation of density logs indicate. Despite these limitations, these surveys provide a first-order approximation of an *in situ* vertical density and porosity logs for rocks in Hawaii. These values, summarized in Table 4, were determined from the visual trends of the density logs and should represent average density and porosity values for Hawaiian besaltic aquifers.

TABLE 4. DENSITY AND POROSITY FOR HAWAIIAN ROCKS.

TYPE ROCK	DENSITY (GM/CC)	PERCENT POROSITY
SOIL	1.7 - 1.9	42 - 32
WEATHER BASALT	1.9 - 2.4	32 - 17
BASALT	∿ 2.4	17
FRESH BASALT	∿ 2.0	27

ACKNOWLEDGEMENTS

The cooperation and assistance provided by the Army Engineering Corps at Schofield Barracks, Oahu; East Maui Irrigation Company on Maui, and the Hawaii Agricultural Company on Hawaii in granting access to the respective wells are gratefully acknowledged. In addition, the field assistance of R. Ching, R. Cassidy, J. Ing, and C. Marsh in conducting the various surveys and the critical technical review by Dr. Frank L. Peterson are appreciated.

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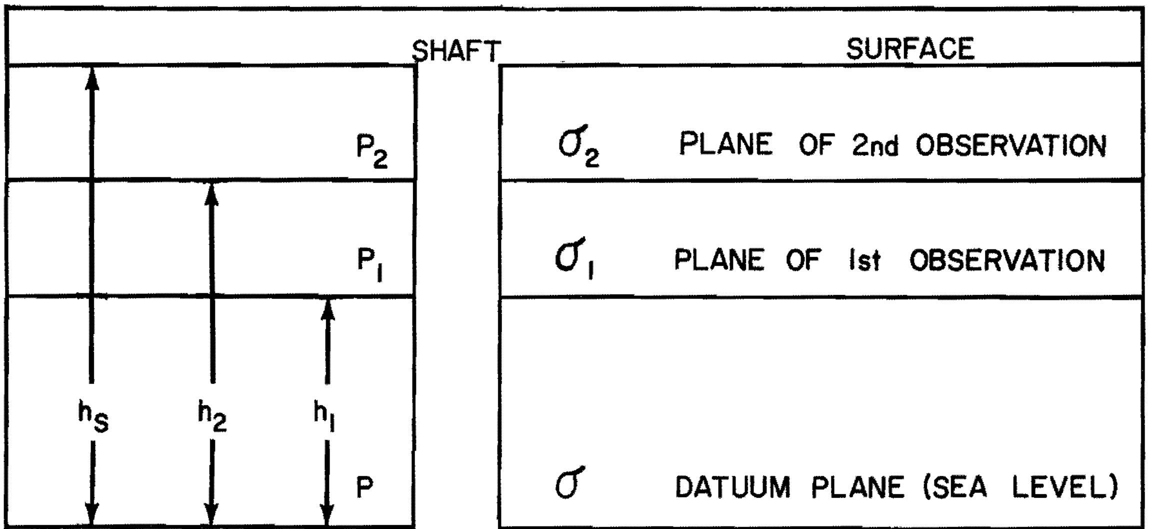
APPENDICES

APPENDIX A. DETERMINATION OF DENSITY AND POROSITY FROM GRAVITY OBSERVATIONS IN A WELL.



σ	=	DENSITY OF LOWER LAYER
σ_1	=	DENSITY OF MIDDLE LAYER
σ_2	=	DENSITY OF UPPER LAYER
γ	=	GRAVITATIONAL CONSTANT (6.670×10^{-8} $cm^3/g \cdot s^2$)
π	=	PI (3.15...)
h_1	=	HEIGHT OF OBSERVATION 1 ABOVE DATUUM
h_2	=	HEIGHT OF OBSERVATION 2 ABOVE DATUUM
h_S	=	HEIGHT OF SURFACE ABOVE THE DATUUM
g_{SL}	=	GRAVITATIONAL ACCELERATION OBSERVED AT THE DATUUM

Case (1)

Assume a uniform density between the surface and the datuum. Then

$$\sigma_1 = \sigma_2 = \sigma$$

The gravitational acceleration experienced at P_2 is

$$g_2 = g_{SL} - \underline{F}\, h_2 + \underline{B}\, \sigma h_2 - L_2 - T_2$$

where F $\equiv$ Free air gradient

$B \equiv 2\pi\gamma$

$L_2 \equiv B\sigma\ (h_s - h_2)$ which is the gravitational attraction of the layer above point P_2.

$T_2 \equiv$ terrain correction at P_2.

The gravitational acceleration at point P_1 is

$$g_1 = g_{SL} - F\ h_1 + B\ \sigma h_1 - L_1 - T_1$$

where F and B are the same as before.

$L_1 = B\sigma\ (h_s - h_1)$ which is the gravitational attraction of the layer above point P_1.

$T_2 \equiv$ terrain correction at P_1.

The difference in the measured gravity between points P_1 and P_2 is

$$g_1 - g_2 = \Delta g = F(h_2 - h_1) - B\sigma(h_2 - h_1) + (L_2 - L_1) + (T_2 - T_1)$$

or

$$\Delta g = F(h_2 - h_1) - B\sigma(h_2 - h_1) - B\sigma(h_2 - h_1) + \Delta T$$

or

$$\Delta g = F\ \Delta h - 2B\sigma\Delta h + \Delta T\ .$$

This equation may be solved for σ

$$\sigma = \frac{F}{2B} - \frac{1}{2B}\ \left(\frac{\Delta g\ -\ \Delta T}{\Delta h}\right)$$

Case (2)

Assume non-uniform density between the surface and the datuum. Then

$$\sigma_1 \neq \sigma_2 \neq \sigma$$

The gravitational attraction at point P_2 is

$$g_2 = g_{SL} - Fh_2 + B\sigma h_1 + B\sigma_1\ (h_2 - h_1) - BP_2\ (h_s - h_2) - T_2\ .$$

Similarly the attraction at point P_1 is

$$g_1 = g_{SL} - Fh_1 + B\sigma h_1 - B\sigma_1\ (h_2 - h_1) - B\sigma_2\ (h_s - h_2) - T_1\ .$$

The difference in measured gravity between the stations is

$$\Delta g = g_1 - g_2 = F(h_2 - h_1) - 2B\sigma_1\ (h_2 - h_1) + \Delta T$$

The gravity difference from this equation is only dependent on the density

(σ_1) of the layer between the points of observation. Solving for this density,

$$\sigma_1 = \frac{F}{2B} - \frac{1}{2B}\left[\frac{\Delta g - \Delta T}{\Delta h}\right] .$$

Therefore this gravity method will uniquely determine the density of the layer between observations.

APPENDIX B. COMPUTER PROGRAM FOR CALCULATING AND PLOTTING THE DENSITY AND POROSITY LOGS.

```
      DIMENSION G(40),H(40),RHO(40),RHOAVG(40),A(160),PERP(40),
     AAVPERP(40),B(160)
   19 READ(5,6) N
    6 FORMAT ( I2)
      IF(N.EQ.00) GO TO 20
      READ(5,1) (G(I),H(I),I = 1,N)
      WRITE(6,2)(G(I),H(I),I = 1,N)
      PERP(N) = 10.
      AVPERP(N) = 10.
      RHO(N) = 1.0
      RHOAVG(N) = 1.0
      IF(H(I)) 15,14,15
   15 TEMP = H(1)
      DO 13 I = 1,N
      H(I) = TEMP-H(I)
   13 WRITE(6,5) H(I)
    5 FORMAT(' ',F6.2)
   14 DO 10 I = 2,N
      DELG = ABS(G(I) - G(I-1))
      DELH = ABS( H(I) - H(I-1))
      RHO(I-1) = 3.865 - 39.20*(DELG/DELH)
      PERP(I-1) = 100.*(1.-RHO(I-1)/2.9)
      DELG = ABS(G(I) - G(1))
      DELH = ABS(H(I) - H(1))
      RHOAVG(I-1) = 3.865 - 39.20*(DELG/DELH)
      AVPERP(I-1) = 100.*(1.-RHOAVG(I-1)/2.9
   10 WRITE(6,3) RHO(I-1), RHOAVG(I-1),PERP(I-1),AVPERP(I-1)
      DO 11 I = 1,N
      B(I) = H(I)
   11 A(I) = H(I)
      NN = N-1
      K = N + 1
      M = 2*N
      KK = 2*N + 1
      MM = 3*N
      KKK = 3*N + 1
      MMM = 4*N
      DO 12 I = K,M
      B(I) = PERP(I-N)
   12 A(I) = RHO(I-N)
      DO 16 I = KK,MM
      B(I) = AVPERP(I-M)
   16 A(I) = RHOAVG(I - M)
      CALL RUNAVG(NN,RHO)
      DO 18 I = KKK,MMM
   18 A(I) = RHO(I-MM)
      CALL PLOT(001,A,N,4,0,0)
      CALL PLOT(002,B,N,3,0,0)
      GO TO 19
    1 FORMAT(   F6.2,F5.2)
    2 FORMAT(' ',F7.2,5X,F6.2)
    3 FORMAT(' ',F6.3,5X,F6.3,5X,F5.1,5X,F5.1)
   20 STOP
      END
```

```
      SUBROUTINE RUNAVG(N,D)
      DIMENSION D(1)
      DO 20 I = 1,N
      IF (I.EQ.1) TO TO 10
      IF(I.EQ.N) GO TO 11
      SUM = D(I-1) + D(I) + D(I+1)
      D(I) = SUM/3.0
      GO TO 20
   10 SUM = D(I+1) + D(I)
      D(I) = SUM/2.0
      GO TO 20
   11 SUM = D(I-1) + D(I)
      D(I) = SUM/2.0
   20 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE PLOT(NO,A,N,M,NL,NS)
      DIMENSION OUT(101),YPR(11),ANG(9),A(1)
    1 FORMAT (1H1,60X,7H CHART ,I3,//)
    2 FORMAT (1H , F11.4,5X,101A1)
    3 FORMAT (1H)
    5 FORMAT (10A1)
    7 FORMAT (1H , 16X,101H.          .         .         .         .
     1   .         .         .         .         .         .)
    8 FORMAT (1H0,9X,11F10.4)
C
C     ...............................................................
C
      NLL = NL
C
      IF(NS) 16, 16, 10
C
C     SORT BASE VARIABLE DATA IN ASCENDING ORDER
C
   10 DO 15 I = 1,N
      DO 14 J = 1,N
      IF(A(I) - A(J)) 14, 14, 11
   11 L = I-N
      LL = J-N
      DO 12 K = 1,M
      L = L+N
      LL = LL + N
      F = A(L)
      A(L) = A(LL)
   12 A(LL) = F
   14 CONTINUE
   15 CONTINUE
      KK = 2*N -1
      WRITE(6,4) (A(K),K = 1,KK)
    4 FORMAT(' ',F7.3)
C
C     TEST NLL
C
   16 IF(NLL) 20, 18, 20
   18 NLL = 50
C
C     PRINT TITLE
C
   20 WRITE(6,1) NO
C
C     DEVELOP BLANKS AND DIGITS FOR PRINTING
C
      READ( 5,5) BLANK,(ANG(I), I = 1,9)
      WRITE(6,5) BLANK,(ANG(I),I = 1,9)
C
C     FIND SCALE FOR BASE VARIABLE
C
      XSCAL = (A(N)-A(1))/(FLOAT(NLL-1))
```

```
C
C     FIND SCALE FOR CROSS-VARIABLES
C
      M1 = N+1
      YMIN = A(M1)
      YMAX = YMIN
      M2 = M*N
      DO 40 J = M1,M2
      IF(A(J)-YMIN) 28,26,26
   26 IF(A(J)-YMAX) 40,40,30
   28 YMIN = A(J)
      GO TO 40
   30 YMAX = A(J)
   40 CONTINUE
      YSCAL = (YMAX-YMIN)/100.0
      WRITE(6,9) XSCAL,YSCAL,YMIN,XMIN
    9 FORMAT(' ',F10.5,5X,F7.5,5X,F5.3,5X,F5.3)
C
C     FIND BASE VARIABLE PRINT POSITION
C
      XB = A(1)
      L = 1
      MY = M-1
      I = 1
   45 F = I-1
      XPR = XB + F*XSCAL
      IF(A(L)-XPR) 50,50,70
C
C     FIND CROSS-VARIABLES
C
   50 DO 55 IX = 1,101
   55 OUT(IX) = BLANK
      DO 60 J = 1,MY
      LL = L+J*N
      JP = ((A(LL)-YMIN)/YSCAL)+1.0
      OUT(JP) = ANG(J)
   60 CONTINUE
C
C     PRINT LINE AND CLEAR, OR SKIP
C
      WRITE(6,2) XPR,(OUT(IZ),IZ = 1,101)
      L = L + 1
      GO TO 80
   70 WRITE(6,3)
   80 I = I + 1
      IF(I-NLL) 45,84,86
   84 XPR = A(N)
      GO TO 50
C
C     PRINT CROSS-VARIABLES NUMBERS
C
   86 WRITE(6,7)
      YPR(1) = YMIN
```

```
      DO 90 KN = 1,9
   90 YPR(KN + 1) = YPR(KN) + YSCAL*10.0
      YPR(11) = YMAX
      WRITE(6,8) (YPR(IP),IP = 1,11)
      RETURN
      END
```