RECONNAISSANCE LEVEL INVESTIGATION OF SALT-WATER INTRUSION ON KUTTU ISLAND, SATAWAN ATOLL, TRUK STATE

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INTRODUCTION

A salt-water intrusion problem was investigated on Kuttu Island, Satawan Atoll (Figure 1). Salt-water intrusion into portions of the island of Kuttu, Satawan Atoll, caused a general reduction in taro productivity and a rise of salinity levels in a number of household wells. In addition to reduced taro production, other food items such as breadfruit were severely affected by the increased salinity of groundwater. At least part of the problem was related to drought conditions that prevailed over the Western Pacific region. However, it does appear that salt-water intrusion into the taro patch was caused by two additional factors: (1) seasonal changes in the level of the surrounding ocean; and (2) subsurface conditions of relatively higher permeability (i.e., conditions that allow the free movement of brackish groundwater).

The taro patch, located in the central portion of the island, occupies approximately half of the land area of Kuttu (Figure 2). Enlargement of the patch over the years has placed the boundary, at some locations, within a hundred feet of the shoreline. Areas within the taro patch severely affected by salty groundwater are associated with this boundary. Here, taro plants do not grow normally and usually die after a short period of exposure. Salty groundwater causes the plant leaves to turn yellow and wither and the root system to decay. About one-fourth of the taro patch has been significantly affected by salt-water intrusion.

Objectives and Scope of the Study

The primary objectives of the study were to determine the major factors that influence salt-water intrusion into the area of taro cultivation and to make recommendations for the effective control of the problem. In order to achieve these objectives, a number of field and laboratory activities were conducted. These activities are outlined below.

Field Activities

1. A general (in situ) water-quality survey was conducted for 30 household wells and 8 taro patch sites.

2. Water samples collected from 30 household wells were analyzed in the field for temperature, pH, specific conductance, carbon dioxide, chloride concentration, and relative salinity.

3. Additional water samples from selected household wells (primary drinking water wells) were collected and taken to the WERI water-quality laboratory for further analyses.

4. A seismic-refraction survey consisting of 11 forward-reverse lines was conducted.

5. Vertical electrical soundings (earth-resistivity measurements) were made at seven stations.

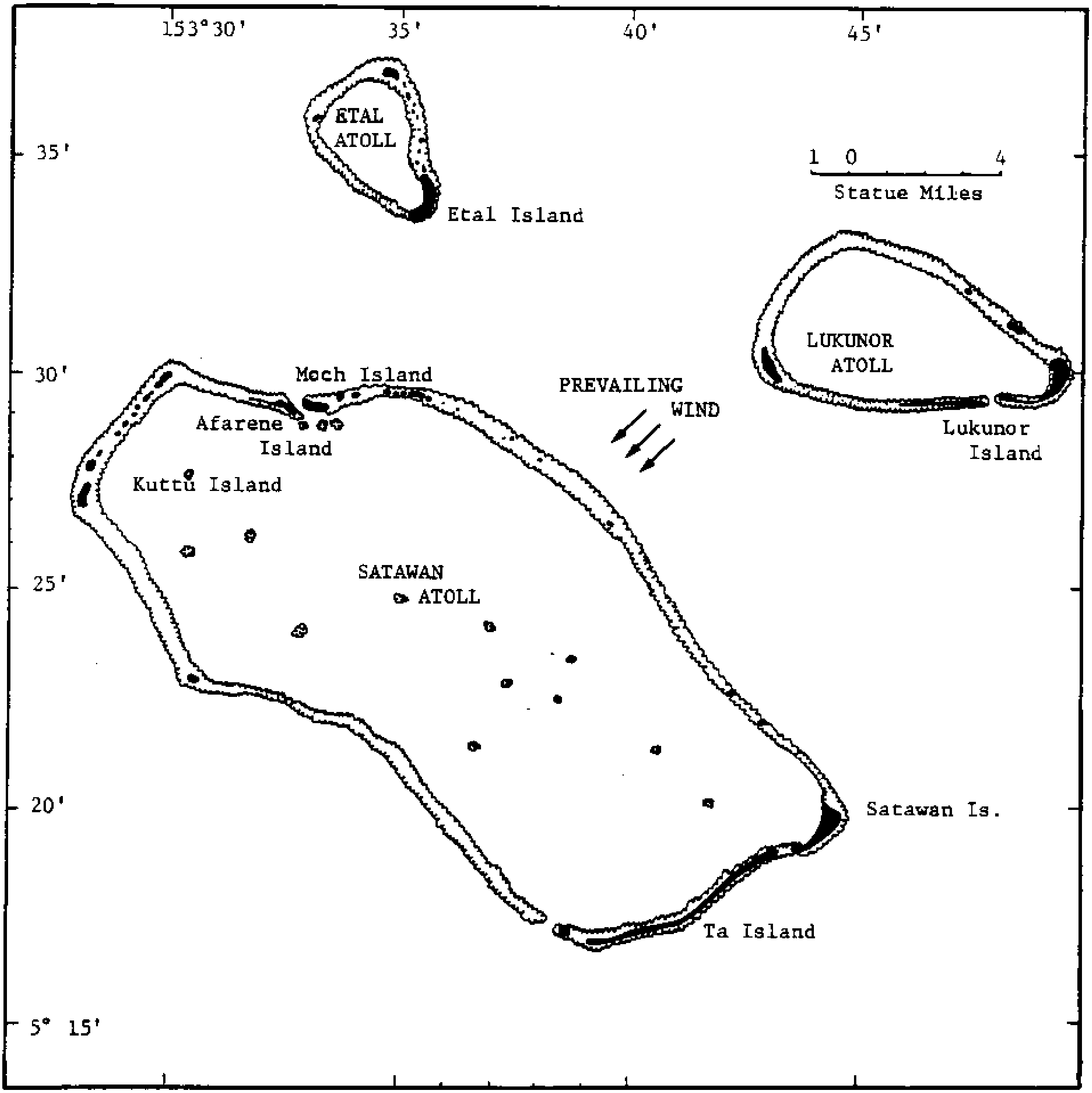


Figure I. Kuttu Island in Satawan Atoll.

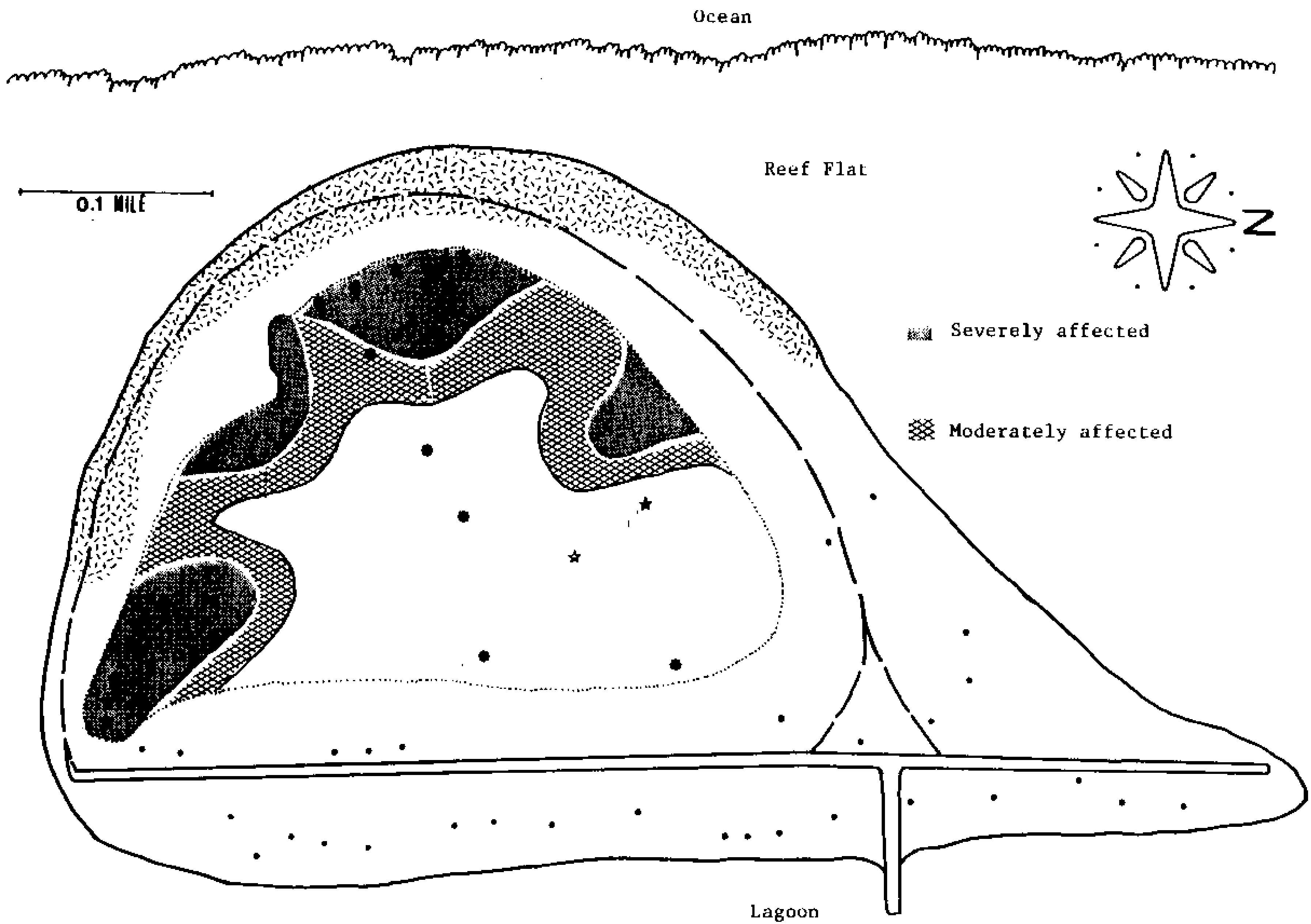


Figure 2. Distribution of areas within the taro patch affected by salt-water intrusion.

6. Several auger holes were hand drilled to shallow depths in and around the taro patch.

7. A questionnaire was administered to 31 community members.

Laboratory Activities

1. Analyses of water samples for chloride concentration, alkalinity, total hardness, calcium hardness, total phosphorus, nitrate nitrogen, nitrite nitrogen, and chloride concentration.

2. Analysis of seismic-refraction data.

3. Analysis of earth-resistivity data.

4. Compilation of questionnaire responses.

5. Interpretation of study results and preparation of the completion report.

The field trip to Kuttu took place during the latter part of May 1983. All field activities were completed within a three-day period.

Location and Description of the Study Area

Satawan Atoll is located approximately 190 miles southeast of Truk in a group known as the Mortlock Islands (Figure 1). The atoll platform is roughly elliptical in shape with the long axis oriented along a northwest-southeast line. The total area of the platform is about 148 mi^2. Forty-nine low-lying islands are situated on the platform margin; these islands occupy only 1.76 mi^2 of land area.

The island of Kuttu is located at the northwestern end of the atoll platform (Figure 1). Kuttu is about 3200 feet long and 1900 feet wide and is somewhat lobate in shape. The island is composed of carbonate sediments derived from the reef and lagoon environments. Sediment in the size range of cobbles to boulders forms a relatively high ridge along most of the ocean shoreline (Figure 3). This very coarse grained material grades rapidly inland to gravel and coarse sand. On the lagoon side, sediment in the sand-size range forms a low ridge. Within the central portion of the island, the land surface is flat and is the site of active taro cultivation (Figure 2). Much of this area has been artificially produced; that is, the original physiographic feature has been expanded and greatly modified by the practice of taro growing.

All of the community members (population of 700 to 800) live along the lagoon shoreline and the northern end of the island. This part of the island is preferred mainly because of (1) availability of fresh groundwater beneath the area and (2) the protection from storms offered by the lagoon and its enclosing reef.

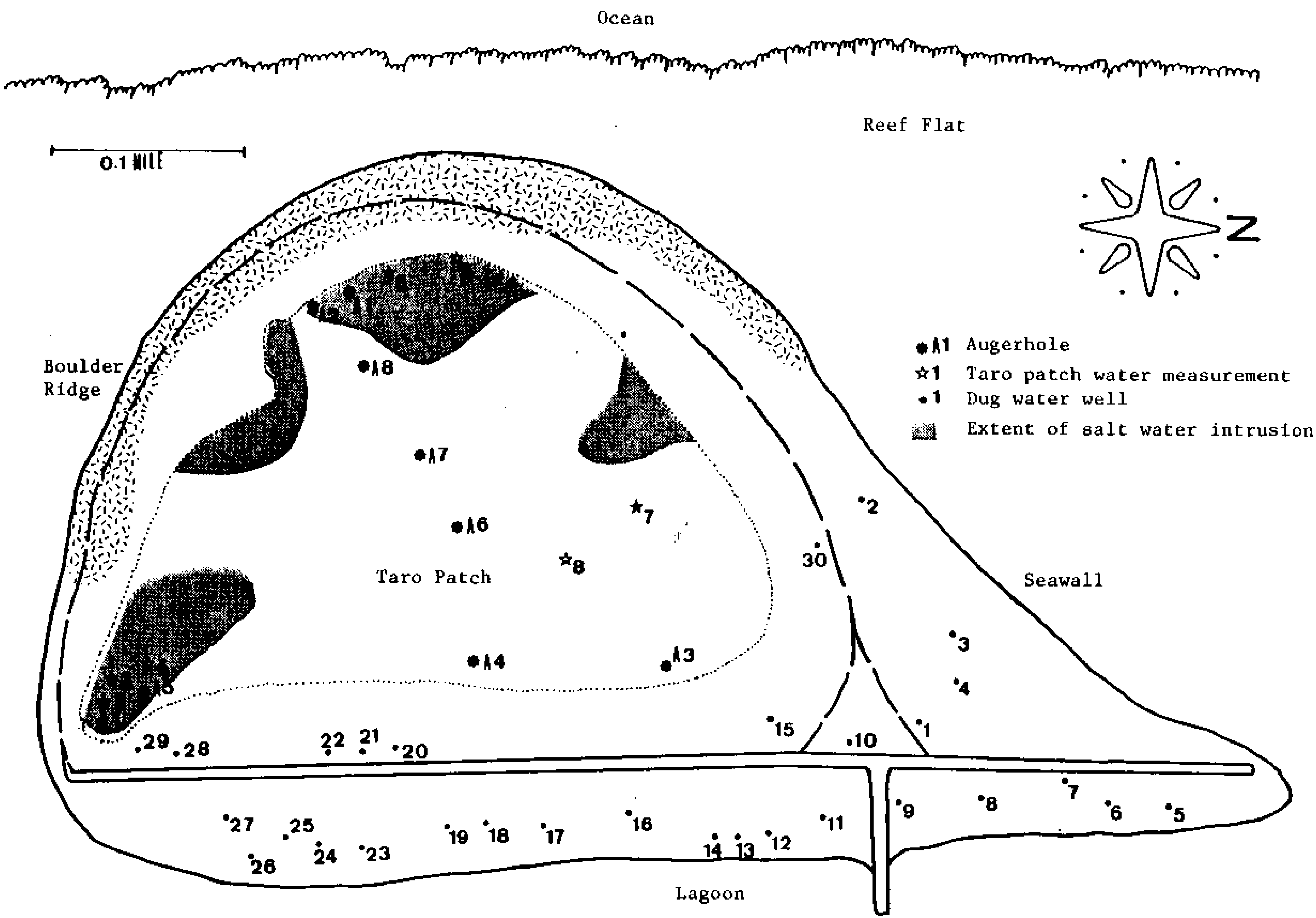


Figure 3. Location of dug wells, auger holes, taro patch water measurement sites and extent of damaged taro by salt water intrusion on Kuttu Island.

Freshwater is acquired by two methods. These are (1) the collection of rainwater from roofs either off buildings or those over catchment tanks and (2) from hand-dug household wells. Rainwater is greatly preferred for drinking, however groundwater is used during those times when rainfall is not adequate to provide sufficient quantities of potable water. The general practice is to boil the well water prior to consumption.

METHODS

A number of field techniques and laboratory procedures were employed during the course of the investigation. These methods included (1) collection and chemical analysis of water samples, (2) application of geophysical surveys, and (3) administration of a questionnaire to selected members of the community. Details of the study methods are presented below.

Water-Quality Analysis

Determinations of water quality are important aspects of any groundwater investigation. The most obvious benefit of such studies is the assessment of the resource in terms of its potability or fitness for human consumption and domestic use. However, water-quality data also can be used to evaluate natural processes within the subsurface hydrologic environment, such as the degree of mixing between fresh groundwater and seawater in the case of an insular setting or identifying sources of natural or artificial contamination in more general situations. Although no comprehensive program of water quality assessment was undertaken for this study, the methods outlined below were employed in order to obtain at least a general concept of water chemistry within the lens beneath Kuttu Island.

Water-quality data were obtained from (1) a general survey of household wells and selected sites specific conductance meter, (2) field analyses of samples from household wells, and (3) laboratory analyses of samples collected from selected household wells. In the latter case, the wells were selected on the basis of location relative to either the shoreline or the taro patch and on customary usage (primarily those used as a source of drinking water). Figure 3 shows a map of Kuttu Island with the location of water sampling sites and auger hole test sites.

Water samples collected within the study area were subjected to both field and laboratory analyses in order to determine temperature, specific conductance, relative salinity, chloride-ion concentration, and, in some cases, pH. Additional analyses included alkalinity, calcium hardness, total hardness, carbon dioxide, total phosphorus, nitrate-nitrogen, and ammonia-nitrogen. Field measurements were performed utilizing portable instruments and testing kits while laboratory analyses followed standardized procedures (American Public Health Association, 1980).

Geophysical Measurements

Two geophysical field methods were employed by the study. Specifically, these methods were (1) seismic-refraction profiling and (2) earth-resistivity soundings. These methods were used in an attempt to determine the subsurface structure and, to a certain extent, the thickness of the fresh-water lens. Several measurement stations were established within the study area; their locations are shown on the map of Figure 4.

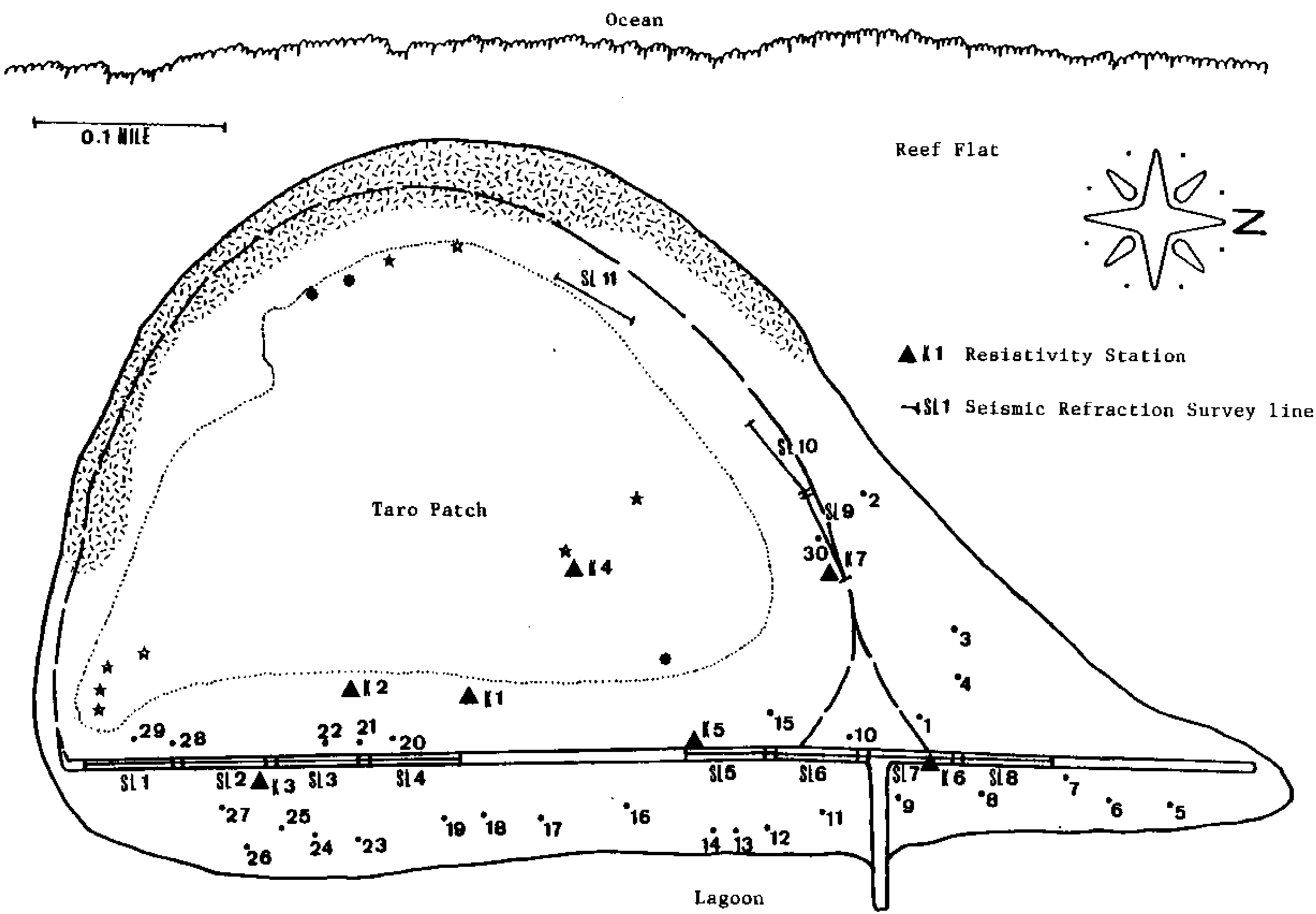


Figure 4. Seismic refraction survey lines and earth resistivity stations on Kuttu Island.

Seismic-Refraction Profiling

Seismic-refraction methods have been used in a wide variety of investigations involving the determinations of subsurface structure. Among these investigations are numerous applications of the method in groundwater-related studies. The object of refraction seismology is to obtain a time-distance graph from the first arrival of sound waves generated by an energy source. From time-distance graphs, seismic velocities can be calculated and depth determination can be made.

Detection of refracted sound waves generated by controlled energy sources (e.g., hammer striking a steel plate, weight drop, or explosion) usually produces a seismic-record indicating one or more events that are caused by the change in velocity of the wave front. Seismic energy is transmitted through solid material as elastic waves. Abrupt changes in the elastic properties of the medium through which these waves are propagated will cause the waves to be refracted or bent. The degree to which the wave paths are refracted is related to Snell's Law, that is, the sine of the angle of incidence is equal to the sine of the angle of refraction. Another way of expressing this law is by the following equation:

$$\frac{\sin i}{\sin r} = \frac{V_1}{V_2}$$

where

i = angle of incidence,

r = angle of refraction

V_1 = velocity of transmission of the elastic wave in the incidence medium, and

V_2 = velocity of transmission of the elastic wave in the refraction medium.

A primary concept in refraction work is that of the critical angle. Where r is equal to 90°, sin i is equal to V_1/V_2. Here, the incident wave path or ray strikes the interface at the critical angle and the refracted wave travels parallel to the interface. A refracted wave front acts as a first arrival when its travel time from the source through the refraction medium to the detector is equal to or greater than the time required for the direct wave to travel from the source to the same detector. The path that first-arrival waves take is dependent upon the depth to the reference interface and the distance between the first detector and the energy source (Telford et al., 1976; Zohdy et al., 1974).

When first-arrival times derived from seismograms are plotted on a time-distance graph, a break in slope of the curve will occur where the time taken for both direct and refracted waves to travel from the energy source to the detector is the same. Seismic velocities are obtained from the slope on the time-distance curve (i.e., velocity is the inverse of the slope).

The most widely used of all field techniques in refraction work is profile shooting. To obtain the necessary time-distance, data, shot points and detectors or geophones are laid out on long lines and repeated shots are taken at various positions at the ends and middle of the geophone spread. If successive spreads are necessary, the lines are overlapped by at least one or two geophones.

During field operations, a total of 11 seismic-refraction lines or spreads were established within the study area. Each line was shot in both the forward and reverse order; several lines were shot at the midpoint of the spread. The energy source used in the refraction work was a sledge hammer striking a steel plate. The geophone spread consisted of 12 detectors spaced at 25-foot intervals connected to a McSeis-1300 (model 1191) Signal Enhancement Seismograph. A permanent record was produced on light-sensitive paper.

Although a number of analytical approaches are available (see, for example, Telford et al., 1976; Dobrin, 1976), the least time-consuming method utilizes computer processing of the time-distance data. The computer program used to process the Kuttu data was first published by the U.S. Bureau of Mines (Scott, 1972). The program generates a two-dimensional model representing a layered-earth depth interpretation. Travel times are picked from the seismogram by the user. These times, together with shot point and geophone locations and refraction layer control information, are used as program input. A first approximation delineation for each refraction interface is obtained by a computer adaptation of the delay-time method. The approximation is then tested and improved by the computer through the use of a ray-tracing procedure in which ray travel times computed for the model are compared to field data. The model is subsequently adjusted in an interative manner such that the discrepancy between computed and measured travel times is minimized. Seismic velocities and depths to refractor interfaces, among other information, are printed as the final step.

Earth-Resistivity Sounding

In addition to the application of seismic-refraction profiling in groundwater investigations, earth-resistivity measurements are widely used in the determination of subsurface characteristics and, in many cases, water quality. Essentially, the method involves measuring the electrical resistivity of earth materials by introducing an electrical current into the ground and monitoring the potential field developed by that current. In most earth materials, electricity is conducted electrolytically by the interstitial fluid, and resistivity is controlled more by porosity, water content, and water quality than by the resistivities of the matrix (Zohdy et al., 1974). Clay minerals, however, are capable of conducting a current electronically, and the electrical flow in a clay unit is both electronic and electrolytic.

In conducting earth-resistivity soundings, a commutated direct current or very low frequency (<1 Hz) current is introduced into the ground through two electrodes (Zohdy et al., 1974). The potential difference is measured between a second pair of electrodes; the current and potential measurements are used to calculate apparent resistivity.

The most commonly used electrode configuration for vertical electrical soundings, and the one used in this study, is the Schlumberger array. Four electrodes are placed along a straight line on the ground surface such that the outside current electrode distance ($\overline{AB}$) is equal to or greater than 5 times the inside potential electrode distance ($\overline{MN}$). For any linear, symmetric array AMNB of electrodes, the apparent resistivity is given by (Zohdy et al., 1974):

$$\rho_a = \frac{(\overline{AB}/2)^2 - (\overline{MN}/2)^2}{\overline{MN}} - \frac{\Delta V}{I}$$

where

ΔV = measured potential difference, and
I = electrical current

A Soiltest R-60 resistivity unit was used to conduct the soundings. The unit utilizes dry-cell batteries as a power source with a maximum output of 810 volts and 1.0 amps. Seven resistivity stations were established at various sites around and, in one case, within the taro patch (Figure 4) all soundings utilized the Schlumberger electrode configuration with a maximum current electrode ($\overline{AB}/2$) spacing of 100 feet (except station 6 where $\overline{AB}/2$ equalled 50 feet).

Resultant data generated during the resistivity survey were analyzed by a trial-and-error procedure of curve matching. The first step was to plot the data on a graph of apparent resistivity versus electrode spacing ($\overline{AB}/2$) for each station and smooth the vertical electrical sounding (VES) curve to remove the discontinuities produced by the method of measurement (see, for example, Zohdy et al., 1974). Next, an appropriate layer model is selected as a first approximation to the field VES curve. Layer thickness or depth and resistivity values are used as input to a computer program (Zohdy, 1974) which calculates the model VES curve. This model VES curve is then compared to the field VES curve for goodness of fit (usually a qualitative comparison). If necessary, the input values are adjusted and the program rerun. This procedure is continued until a reasonable match is achieved between the model and field curves.

As discussed by Zohdy (1974), for a given earth model composed of horizontally stratified, laterally homogeneous, and isotropic layers, the computer program calculates the Schlumberger apparent resistivity in two parts. First, the total kernel function $T = f(h,e,\lambda)$ is calculated for an n-layer model using Sundi's recurrence formula which is given by

$$T_i = (h,\rho,\lambda) = [1-Q_i e^{-2\lambda h_i}]/[1+Q_i e^{-2\lambda h_i}]$$

$$= \quad Q_i = [\rho_i - \rho_{i+1} Q_{i+1}]/[\rho_i + \rho_{i+1} Q_{i+1}]$$

$$T_{n-1}(h,\rho,\lambda) = [1 - Q_{n-1} e^{-22h_{n-1}}]/[1 + Q_{n-1} e^{-2\lambda h_{n+1}}]$$

$$Q_{n-1} = [\rho_{n-1} - \rho_n]/[\rho_{n-1} + \rho_n]$$

where

ρ_i = Resistivity of the i $\underline{th}$ layer, and

h_i = thickness of the i $\underline{th}$ layer.

The second part in the calculation of the Schlumberger apparent resistivity is based on convolving the inverse filter coefficients (Ghosh's coefficients) with the computed total kernel function curve. The convolution is made twice and six apparent resistivity values per logarithmic cycle are obtained. The abscissas of the computed points are logarithmically equally spaced, with

$$(\overline{AB}/2)_{i+1}/(AB/2)_i = 1.468$$

where $\overline{AB}/2$ is the Schlumberger electrode spacing.

Questionnaire Administration

The purpose of administering a questionnaire as part of the field activities was to collect background information related to the salt-water intrusion problem. In addition, the questionnaire addressed the subject of problem solution in terms of what a number of the community members felt could be done to improve the taro production. A total of 31 people were interviewed.

RESULTS

The following is a presentation of the relevant findings of the study. These include a number of general observations, results of water-quality analyses, interpretation of geophysical data (seismic-refraction surveys and vertical electrical soundings), and compilation of questionnaire responses. The implication of these findings are discussed in the next section.

General Observations

A number of general observations made during the course of the field work warrant consideration. These observations are listed below.

1. The taro patch has been extended oceanward to within a hundred feet of the shoreline in some locations.

2. In those areas affected by salt-water intrusion, the ditches in and around the taro patch exhibit large changes in salinity from point to point.

3. Healthy taro plants are located within the lagoonward half of the taro patch.

4. Numerous crab burrows are present within the taro patch in addition to evidence of damage to plants by the crabs.

5. Insect damage to plants is evident by partially eaten leaves and bored holes in the taro leaf stem.

6. From the results of auger drilling and probing, there appears to be a distinct gradation in size of the sediment directly beneath the soil layer of the taro patch. This gradation is from cobbles and coarse gravels on the ocean side to coarse sand on the lagoon side.

7. During the augering and probing within the taro patch a strong hydrogen sulfide odor was noted. The odor is associated with the saturated portion of the organic soil layer overlying the sediments.

Water-Quality Analyses

As indicated above, water samples were collected from various sample sites at different times and analyzed both in the field and in the laboratory. Results of the analyses for the three data sets (conductance meter survey, field analysis of water from household wells, and laboratory analysis of selected wells) are presented in Tables 1, 2, and 3.

Of the constituents determined in the field and laboratory, specific conductance and chloride concentration are the most useful. These measurements are indicative of the amount of mixing between fresh groundwater and seawater that has occurred in the subsurface. From the results listed in the tables, the amount of mixing in the wells ranges from

Table 1. General water quality of household wells and taro patch surface water, May 23, 1983.

Well No.	Well Owner	Specific Conduc (umhos/cm) Top	Bottom	Chloride (mg/1) Top	Bottom	Water Depth (ft)	Depth to Water (ft)
1	Luela	3000	3000	810	810	2	---
2	Diofil	1175	1175	40	40	1.5	---
3	Kapino	3400	3400	975	975	1.5	---
4	Kos	6500	6500	2290	2290	1.5	8.0
5	Masuo	16000	16000	6305	6305	1.5	4.0
6	Elias	10250	10250	3870	3870	1.5	4.0
7	Daniel	3900	3900	1190	1190	1.5	4.5
8	Roman	3300	3475	935	1010	2.0	4.5
9	Ernest	3250	3250	910	910	1.0	5.0
10	Her	1400	1425	130	140	2.0	6.0
11	Rafino	2350	2350	530	530	1.0	4.0
12	Akostih	2000	2000	385	385	1.0	3.5
13	Istino	5000	5250	1650	1760	2.0	3.0
14	Eriper	5000	5000	1650	1650	1.5	3.0
15	Tasiuo	1375	1375	120	120	2.0	3.0
16	Atalifus	3350	3350	955	955	2.0	3.0
17	Akira	2250	2250	490	490	1.0	3.0
18	Sami	2100	2100	430	430	2.0	3.0
19	Daifis	1200	1150	46	30	2.0	2.5
20	Daniel	1400	1400	130	130	2.0	2.0
21	Tarech	1400	1400	130	130	2.0	4.0
22	Epel	1150	1150	30	30	1.5	4.0
23	Berman	1750	1750	280	280	2.0	4.0
24	Dofer	2475	2475	585	585	2.0	3.5
25	Sam	1750	1750	280	280	2.0	3.0
26	Achum	1550	1575	195	205	2.0	3.5
27	Asauo	1150	1150	30	30	1.5	3.0
28	Kutper	1625	1625	225	225	1.5	3.0
29	Santer	1800	1800	300	300	2.0	2.5
30	Michael	---	---			---	---
Taro 1		8000		3000			
Taro 2		13000		5000			
Taro 3		24000		9700			
Taro 4		58000		19000			
Taro 5		7250		2600			
Taro 6		8000		3000			
Taro 7		1650		250			
Taro 8		1250		100			

Table 2. General water quality of household wells water, May 25, 1983.

Well No.	Well Owner	Sample Time	Water Depth (ft)	Temp. (°C)	Field pH	Specific Conduc[1]	CO_2 (mg/l)	Chloride[2] (mg/l)	Salinity (0/100)
1	Luela	0755	1.0	28.1	6.70	3350	131	747	---
2	Diofil	0735	1.5	27.8	6.95	1350	94	84	---
3	Kapino	0750	1.5	27.7	6.74	3375	77	807	---
4	Kos	0805	1.5	27.7	6.85	6750	107	2011	1
5	Masuo	1245	1.5	27.4	6.70	11500	150	6000	4
6	Elias	1255	1.5	27.8	6.40	10250	128	4144	3
7	Daniel	1300	2.0	28.2	6.71	4200	94	1478	---
8	Roman	1020	2.5	27.7	6.63	3650	97	1083	---
9	Ernest	1305	1.0	27.8	6.57	3050	101	885	---
10	Her	0810	1.5	27.7	6.94	1450	74	115	---
11	Rafino	0820	1.0	27.4	7.06	2575	58	641	---
12	Akostih	0830	1.5	28.0	7.10	2575	56	542	---
13	Istino	0835	2.0	27.4	7.14	5500	101	1498	---
14	Eriper	0840	1.5	28.8	6.86	5000	92	1438	---
15	Tasiuo	0845	1.0	28.7	6.85	1450	81	108	---
16	Atalifus	0855	2.0	27.4	7.00	3650	62	1201	---
17	Akira	0900	1.0	26.8	7.01	2100	70	510	---
18	Sami	0905	2.0	27.4	6.73	2200	93	491	---
19	Daifis	0908	2.0	27.3	7.00	1250	52	147	---
20	Daniel	0910	2.5	28.3	6.67	1450	90	112	---
21	Tarech	0920	1.0	28.0	6.67	1500	98	167	---
22	Epel	0925	2.0	27.4	6.88	1175	64	60	---
23	Berman	0930	2.0	27.1	6.86	1900	83	328	---
24	Dofer	0940	1.5	27.1	6.73	2600	102	570	---
25	Sam	0945	2.0	27.1	6.73	1800	67	281	---
26	Achum	0950	2.0	26.8	7.00	1150	68	266	---
27	Asauo	0955	1.5	27.8	6.73	1200	62	96	---
28	Kutper	1000	1.0	28.4	6.67	1700	72	218	---
29	Santer	1005	1.0	28.4	6.45	1900	146	234	---
30	Michael	0725	2.0	27.6	7.24	1250	95	72	---

[1] Specific conductance, umhos/cm (@ field temperature).

[2] Chloride determined with specific ion probe.

Table 3. Water quality of selected household wells sampled May 25, 1983.

Well No.	Well Owner	Field pH	Field CO_2	Alkalinity[1] (mg/l)	Total[2] Hardness (mg/l)	Calcium[3] Hardness (mg/l)	TH/CA[4] (%)	Total Phosphorus (mg/l)	Nitrate-Nitrogen (mg/l)	Nitrite-Nitrogen (mg/l)	Chloride[5] (mg/l)	Spec.[6] Conduc. umhos/cm
2	Diofli	6.95	94	395	400	340	85	1.051	0.20	> .001	100	1245
8	Roman	6.63	97	365	730	400	55	1.576	48.08	0.075	850	3495
10	Her	6.94	74	435	530	370	70	1.323	4.94	0.014	150	1390
11	Rafino	7.06	68	300	550	330	60	0.097	6.39	0.033	530	2470
15	Tasiuo	6.85	81	360	500	450	90	0.547	2.66	> .001	130	1355
19	Daifis	7.00	52	310	430	310	72	0.168	1.55	0.048	190	1200
20	Daniel	6.67	90	410	630	410	65	0.318	7.54	> .001	130	1355
22	Epel	6.88	64	420	610	370	61	0.230	0.12	> .001	80	1125
23	Berman	6.86	83	415	650	370	57	0.108	0.08	> .001	300	1820
27	Asauo	6.73	62	375	610	350	57	0.063	1.55	0.011	110	1150
28	Kutper	6.67	72	345	650	350	54	0.081	11.75	0.032	220	1595
30	Michael	7.24	95	430	590	370	63	0.306	1.71	> .001	80	1200

1 potentiometric, pH 4.5.

2 hardness (EDTA) as mg $CaCO_3$ / ℓ

3 hardness (EDTA) as mg $CaCO_3$ / ℓ

4 percent calcium hardness of total hardness

5 Mercuric-nitrate titration method

6 Specific conductance, umhos/cm @ 25°C

relatively fresh to moderately brackish (i.e., from about 60 mg/l to about 6000 mg/l chloride). Except for the brackish wells (those above 1000 mg/l chloride), the chloride-ion concentration averaged about 350 mg/l at the time of sampling. Chloride-ion concentrations at the 8 sites within the taro patch ranged over a wider degree with values between 100 mg/l (very fresh) to those of unmixed seawater. The highest concentrations were measured in the southernmost sector of the taro patch. This portion of the patch is also nearly barren of plants (Figure 2).

From the results of the laboratory analyses it appears that, in general terms, the quality of water from the sampled wells is good although total hardness is rather high (Table 3). Notable exceptions are those wells where the total phosphorus is many times higher than the 0.20 mg/l standard used by the Trust Territory Environmental Protection Board (Territorial Register, 1978). The probably source of the contamination is soap from the common practice of bathing and clothes washing near the well. Nitrate concentration in two wells also exceeds safe drinking water standards (greater than 10 mg/l) and may be unsafe for consumption by infants one year or less in age (may cause methemoglobinemia; Lewis et.al, 1980, p.6). The source of the nitrate is not known but warrants further study.

Geophysical Measurements

Results from the application of the geophysical field technique of seismic-refraction profiling and earth-resistivity sounding are presented in detail in Appendices A and B and summarized below.

Seismic-Refraction Profiling

From the computer study of seismic data, two types of information were obtained (1) velocity values for various subsurface layers and (2) depths to the top of the layers beneath each geophone. Seismic velocities are listed in Table 4 and the layer depths are illustrated in Figures 5 and 6 and presented in Appendix A.

A number of relevant points can be made with regard to the computer results. These points are summarized below.

1. Interpretation of seismic data from those lines established along the lagoon side of the island (spreads 1-8) indicate that the near surface structure is composed of three layers.

2. Interpretation of seismic data from spreads 9 and 10 established on the ocean side indicate that the near surface structure is composed of two layers.

3. Velocities of layers 1 and 2 appear not to vary across the island, suggesting no significant change in composition or internal structure (i.e., intra-layer construction). There is, however, distinct differences between the two layers.

4. Layer 3 appears to underlie only that portion of the island along the lagoon shoreline. It should be noted however that the

Table 4. Layer velocities determined by the seismic-refraction survey.

Line		Layer 1 (ft./sec)	Layer 2 (ft./sec)	Layer 3 (ft./sec)
1		1186	5485	6213
2		1500	5634	7747
3		1345	5222	6612
4		1103	5160	5968
5		1175	5540	8852
6		1500	5200	6612
7		1158	5370	9162
8		1272	5549	6894
	Mean value	1280	5395	7258
9		1192	6134	
10		1083	5847	
	Mean value	1138	5990	
*1-4		1201	5388	6472
*5-8		1207	5419	7361
	Mean value	1204	5404	6916

*Note: Results from the computer analysis of coupled lines.

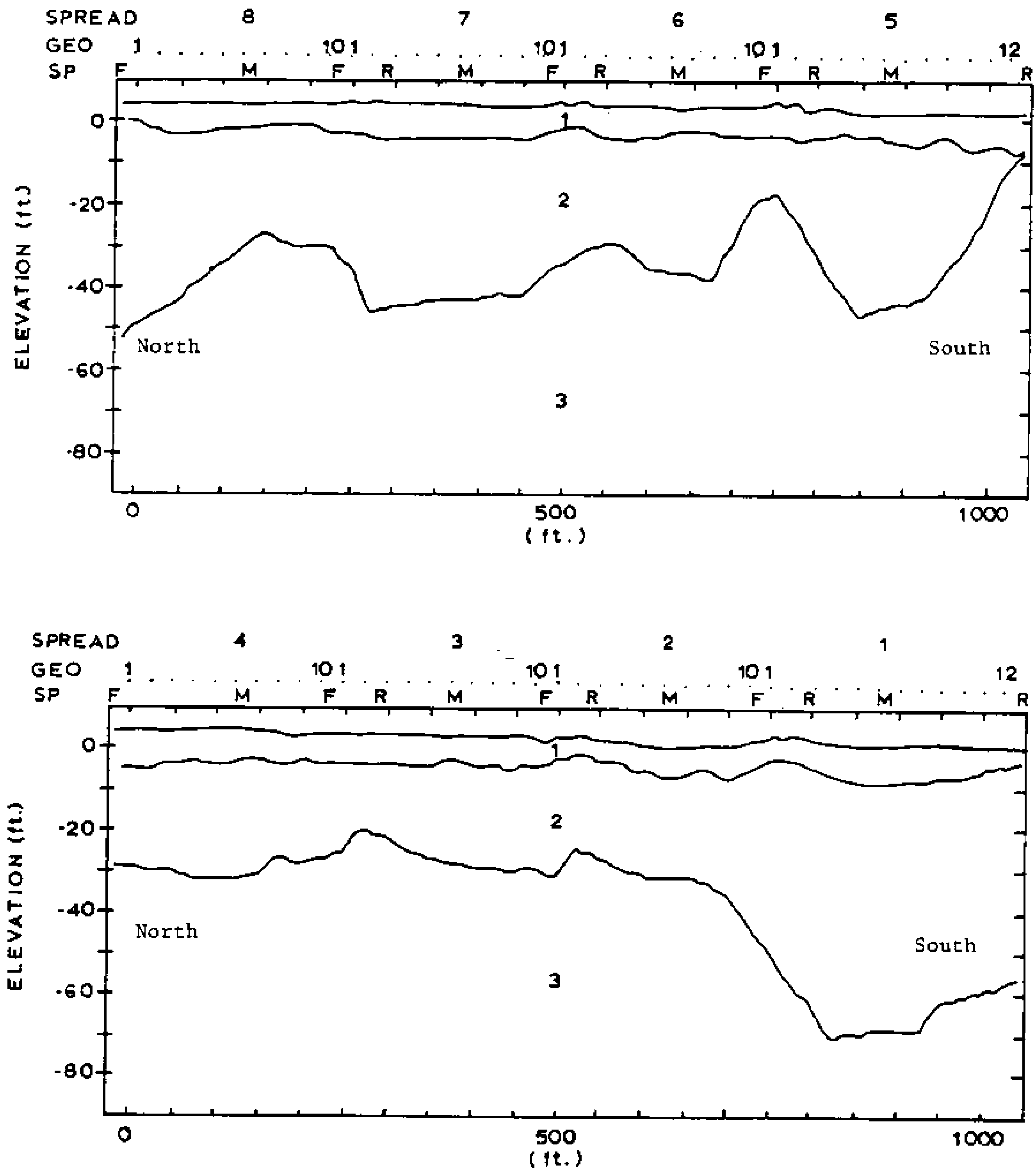


Figure 5. Layer depths for combined spreads 1-4 and 5-8.

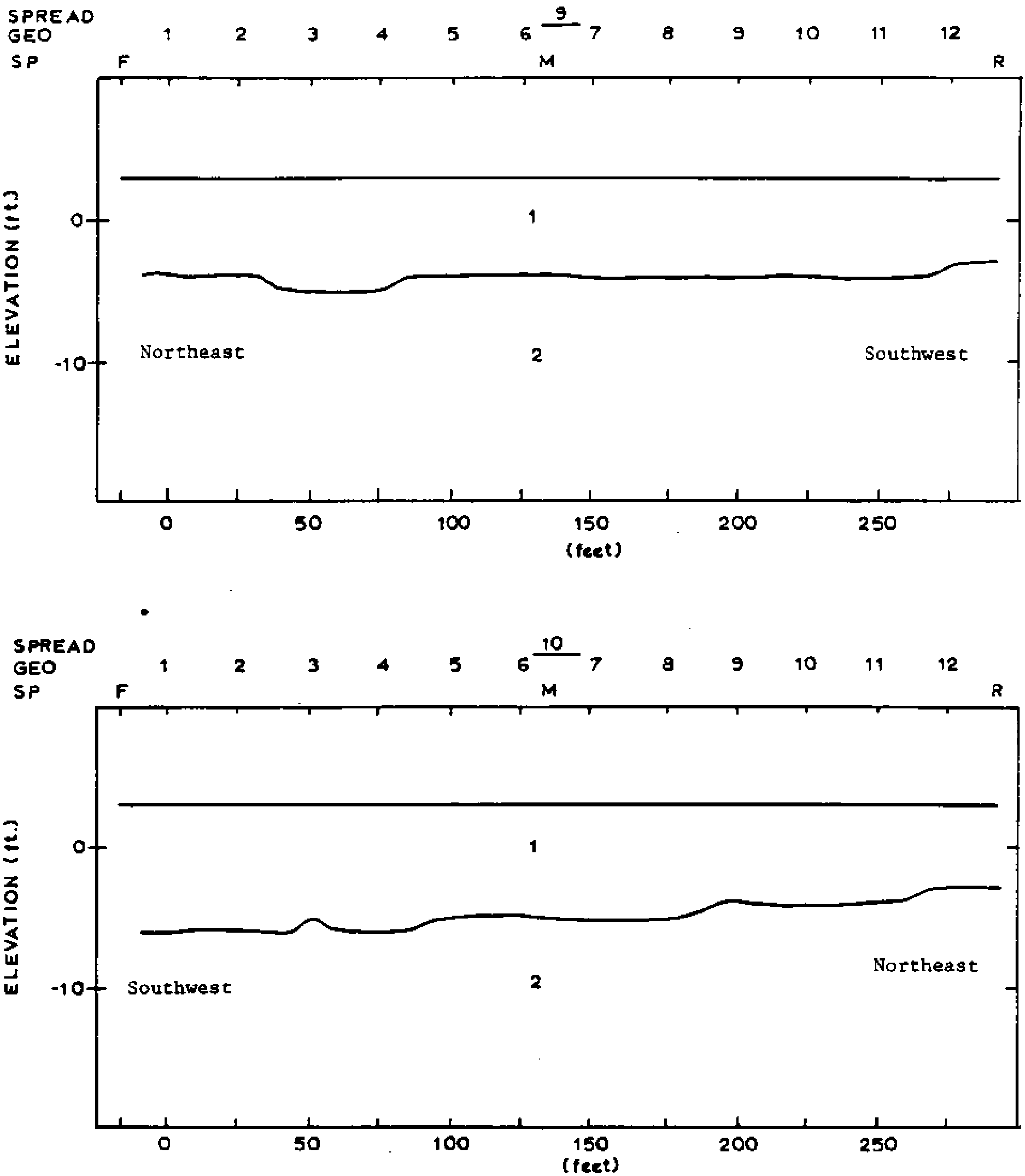


Figure 6. Layer depths for spreads 9 and 10.

seismic-line coverage is inadequate to verify the presence of layer 3 elsewhere.

5. The top of layer 2 displays relatively little relief and is located at an average depth of 6.6 feet below the surface.

6. The top of layer 3 is very irregular with a relief of about 20 feet to 25 feet beneath spreads 5 to 8 and about 10 feet to as much as 40 feet for spreads 1 to 4. It is noteworthy that the surface of layer 3 is greatly depressed beneath spread 1; this location also corresponds to an area of severe damage by salt-water intrusion.

7. The average depth to the top of layer 3 is roughly 40 feet beneath spreads 5 to 8 and 35 feet beneath spreads 1-4 except for spread 1. Here the top of layer 3 exceeds a depth of 60 feet.

Earth-Resistivity Soundings

Results from the curve matching procedure are listed in Table 5. All relevant information produced during the course of resistivity data analysis are presented in Appendix B (field curves matched ves curves, and program input and output).

Analytical results indicate that at the time of measurement the fresh-water column probably was 10 to 12 feet in the thickest part of the lens. On the average, the transition zone or zone of mixing between fresh groundwater and the underlying seawater may be on the order of 12 feet thick, or about the same thickness as the fresh-water nucleus near the center of the lens. These values are subject to about a ±15% error; however, they do serve as a first approximation of water availability. It should be noted that any geophysical field method, especially earth resistivity, should be checked by drilling and water sampling.

Questionnaire Responses

The questions and their corresponding responses are given in Appendix C. A total of the 31 people interviewed, 30 were male. Seven people were in the age range of 18-29, eleven were in the range of 30-49, and fourteen were 50 years of age or older. Apparently, all of the people interviewed have experienced problems with salt-water intrusion into their respective plots. Figure 7 shows the distribution of taro plots owned and/or worked by the people interviewed.

Table 5. Fresh-water lens and associated transition zone thicknesses derived from earth-resistivity data.

Station	Lens Thickness (ft.)	Transition Zone Thickness (ft.)
K-1	6	14
K-2	10	8
K-3	8	12
K-4	12	8
K-5	8	12
K-6	6	12
*K-7	15	10

* Field curve may be distorted due to lateral inhomogeneties; curve matching results are therefore tentative.

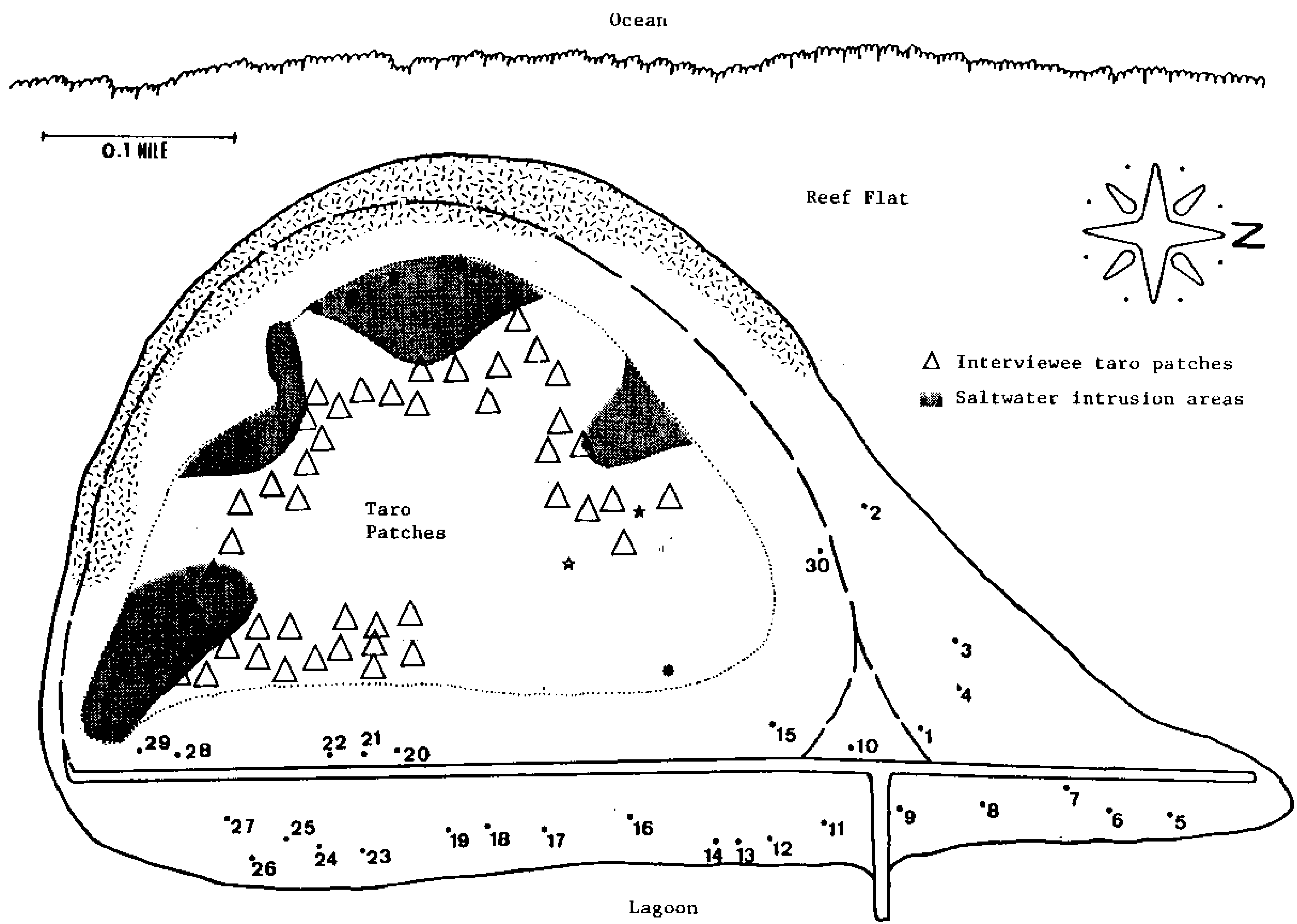


Figure 7. Distribution of interviewee taro patches on Kuttu Island.

DISCUSSION

The following discussion of the study results is based on the interpretation of water-quality data and geophysical information combined with the general observations and questionnaire responses. Three main topics are addressed, these are (1) the geologic framework of the island, (2) the occurrence and distribution of fresh and brackish groundwater, and (3) the problem of salt-water intrusion and its possible control.

Geologic Framework

The geologic framework of Kuttu can be deduced from the results of the seismic-refraction survey and, in part, from general observations. Three distinct, more or less, horizontal layers make up the structural components of the near surface portion of the island (Table 6). The surface layer has an average thickness of about 6.5 feet and is composed of dry unconsolidated sands and gravels for the most part. Sediment sizes grade rapidly from the general composition of sand into cobbles and boulders as the ocean shoreline is approached. Seismic velocities within layer 2 are typical of those indicative of saturated unconsolidated to moderately consolidated sand and fine-grained gravel. The thickness of layer 2 varies from site to site because of the irregular surface of layer 3; a rough estimate, however, is about 30 to 35 feet. Velocities determined for layer 3 are typical of well consolidated sand and gravel, although other types of material are possible.

The seismic profile determined from the computer analysis of data generated by spreads 1 to 4 (Figure 5) shows a distinct depression in the surface of layer 3 beneath spread 1. This depression (and necessarily thicker portion to layer 2) corresponds to a portion of the taro patch that is severely affected by salt-water intrusion. It is possible that this depression is somehow related to the problem. One explanation might be that this depressed surface represents a former channel that cut across the reef flat prior to the development of the island. If this is the case, the channel may be partially filled with very coarse-grained material and thus would be higher in permeability relative to other portions of layer 2. This higher permeability would allow a greater degree of mixing between fresh groundwater and the underlying seawater and result in very high salinity values within the coarse-grained material. This, of course, is only speculation and needs verification by further study.

Groundwater Occurrence and Water Quality

Kuttu is underlain by a substantial fresh-water lens as shown by the chloride-ion concentration map of Figure 8. The map was constructed with data from Tables 1 and 2 and the results indicate that approximately one-third of the island is underlain by a fresh-water nucleus which contains water of 250 mg/l chloride or less. Interpretation of resistivity data suggests that the fresh-water nucleus, at the time of measurement, may be 10 to 12 feet at the thickest part of the lens. The associated transition zone is probably around 12 feet thick beneath most of the nucleus.

Table 6. Possible types of geologic material comprising the near-surface portion of Kuttu.

Layer	Average Velocity (ft/s)	Layer Composition
1	1280	Dry, unconsolidated sand and gravel
2	5395	Saturated, unconsolidated to consolidated sand and/or fine gravel
3	7258	Saturated, well consolidated sand and/or gravel

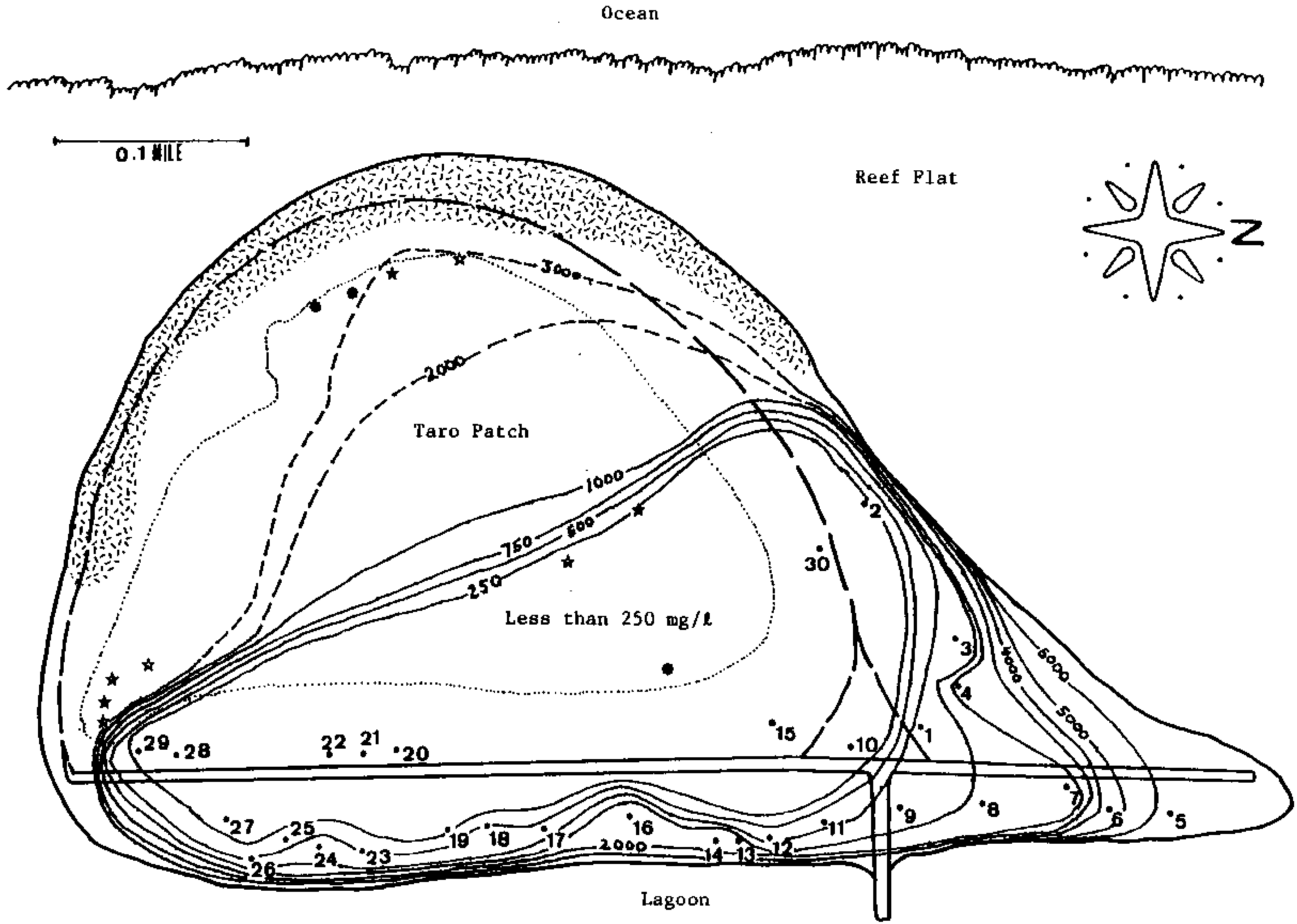


Figure 8. Chloride ion concentration contour map of Kuttu Island. The contour interval is by 250 mg/ℓ to the 1000 mg/ℓ contourline and by 1000 mg/ℓ to the maximum shown interval of 6000 mg/ℓ.

One additional point with regards to lens characteristics is its position. As seen by the map of Figure 8, the fresh-water nucleus is situated, more or less, along the lagoon side of the island. The location of the lens is probably related to the hydrogeologic characteristics of layer 2. It is suspected that near the ocean, the sediment comprising layer 2 is composed of mostly gravel, cobbles, and boulders derived from the reef environment and transported by storm waves. Evidence that this activity occurs is the boulder ridge along the ocean shoreline of Kuttu which was deposited during typhoon Pamela in 1976. Permeability in such a deposit would be necessarily high and thus allow considerable mixing of freshwater and seawater in the subsurface, in addition to allowing free movement of this water inland. The overall results would be highly saline groundwater inland of the ocean shoreline.

The water-quality map of Figure 9 was also constructed from the data in Table 3. The map indicates the distribution of nitrate-nitrogen in the groundwater. It appears that nitrate is present in significant concentrations (two areas exceed the safe drinking water limit of 10 mg/l set by the Trust Territory Environmental Protection Board) to warrant concern. Nitrate concentration in excess of the recommended limit may be hazardous to the health of infants one year or less in age and therefore should not be used. Nitrate has been associated with the disease methemoglobinemia (infantile cyanosis; Lewis et al., 1980, p.6). The acute toxicity of nitrate occurs as a result of its reduction to nitrite within the body. The nitrite ion formed oxidizes iron in the hemoglobin molecule. The resultant methemoglobin is incapable of reversibly binding oxygen, and consequently anoxia or death may ensue if the condition is left untreated.

Sources of the nitrate have not been identified in Kuttu. The prime source, however, is animal and human waste. Nitrate is also a principal ingredient in chemical fertilizers and can be produced by certain plants. The problem of nitrate contamination may become more serious in the near future and therefore warrants a more comprehensive investigation than what has been done by this study.

Another constituent of the groundwater that is of concern is phosphorus. As noted before, several wells were found to contain levels of total phosphorus that exceed the recommended limit of 0.20 mg/l set by the Trust Territory Environmental Protection Board (Territorial Register, 1978). Phosphorus, no doubt, is entering the wells via waste water from nearby clothes and dish-washing facilities. It was observed that the common practice is to conduct the washing adjacent to the well, primarily for convenience.

Concentration of phosphorus in excess of the recommended limit may cause irritation of mucous membranes. In addition, phosphorus combines with essential metals and renders them useless to the body.

Sources of phosphorus in addition to many washing and bathing soaps is chemical fertilizer. In fact, it is one of the three (nitrate, phosphorus, and potash) prime ingredients.

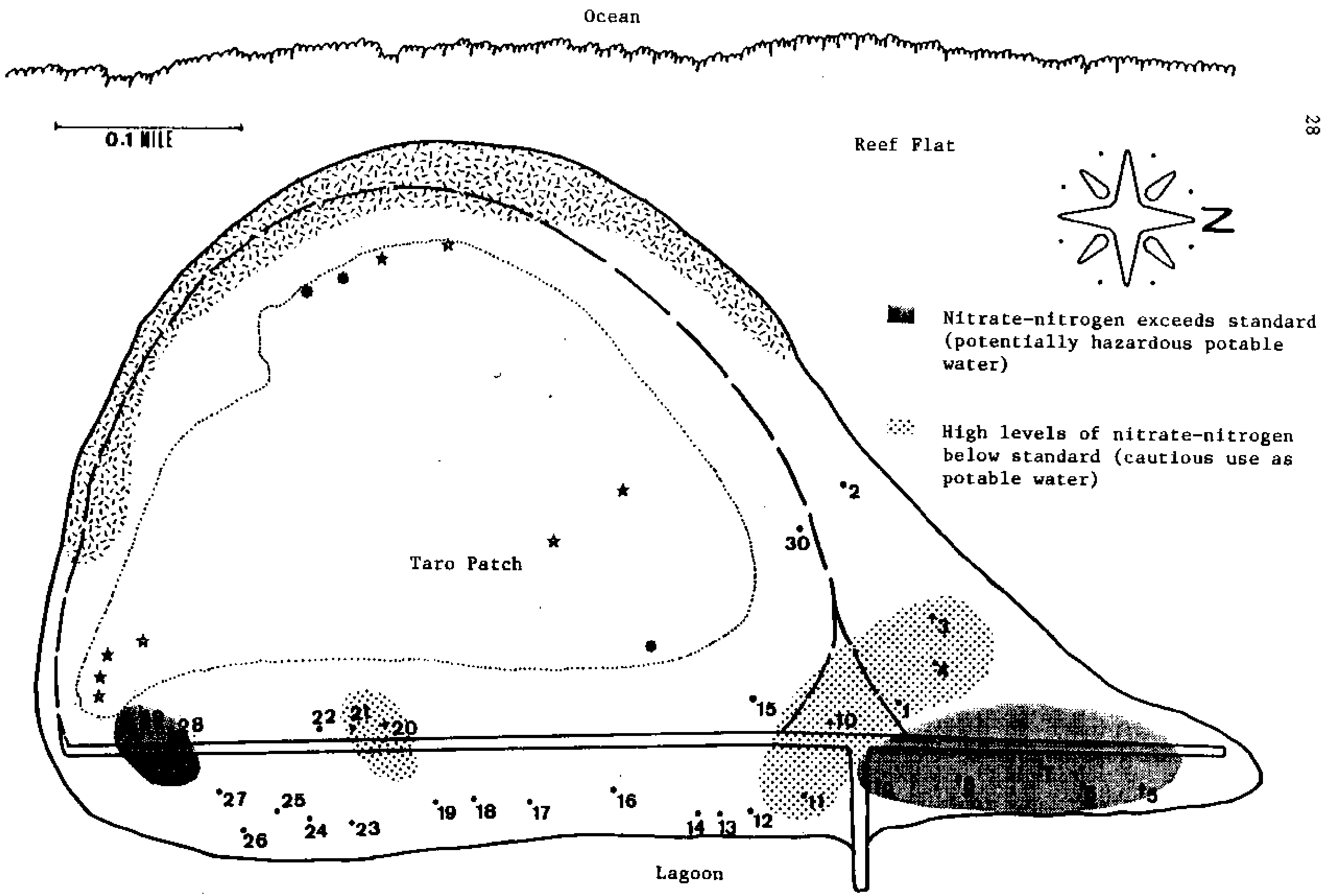


Figure 9. Areas where nitrate-nitrogen exceeds the TTPI water quality standards (10 mg/ℓ) and areas with high levels of nitrate-nitrogen on Kuttu Island.

Salt-Water Intrusion and Its Control

Taro production on Kuttu has been decreased due to salt-water intrusion into part of the region of cultivation. Slightly brackish to very brackish water underlies the oceanward half of the taro patch (see map of Figure 8). The photographs of Figure 10 were taken at opposing sides of the patch; the top photograph shows healthy taro growing within the lagoon half of the island and the bottom photograph shows the affects of brackish water within the root zone in an area near the ocean shoreline. The contrast between the two areas within the taro patch is obvious.

Another obvious contrast in terms of the affects of salty groundwater is depicted in the two photographs of Figure 11. The top photograph shows well 30 and healthy taro growing in the background. The chloride-ion concentration in the well water at the time of sampling was 72 mg/l. This water is probably representative of the groundwater beneath the healthy plants. The water in the ditch, shown in the foreground of the bottom photograph, contained a chloride-ion concentration of about 3000 mg/l. The affects of the salty groundwater present beneath the variety of taro planted in this region of the patch (site 6 on Figure 3) are readily seen. The bottom photograph also shows a thinner organic soil layer than is found elsewhere.

The current problem with taro production is not an isolated one. Apparently, salt-water intrusion into the ocean-side of the taro patch occurs during that time of the year when sea level is the highest (due to steric effects) and when the westerly winds have been established. This time of the year is between October and December or January, that is, toward the end of the wet season. The problem is occasionally compounded with heavy rains that cause flooding within the taro patch which allows salty water in the intruded areas to flow lagoonward into the region where healthy plants are located.

The major factor that has contributed to the problem of salt-water intrusion is the past practice of expanding the taro patch in an effort to grow more food. As a result, the patch has been extended over highly permeable sediments allowing direct access of brackish groundwater to the border areas and the boundary has been pushed nearly to the ocean shoreline. The size of the taro patch has exceeded the natural system's ability to maintain healthy conditions in which taro can be produced on a sustained yield basis.

Salty water that intrudes the ocean border areas appears to migrate inland by way of a number of ditches within the taro patch. The result is a larger affected area by the brackish water than otherwise would occur without the open conduits. These ditches should be partially filled to limit the movement of high chloride concentration water.

From the responses to the questionnaire, most of the people suggested lining the taro patch with a cement or plastic barrier and then refill the region with soil. It appears that this suggestion is in response to a comment that was made during the field work. The comment was related to

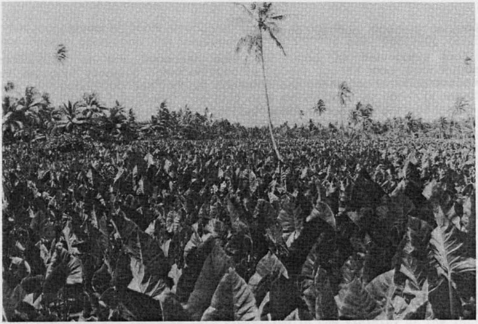


Figure 10. Comparison of unaffected (top) and affected (bottom) areas within the taro patch.

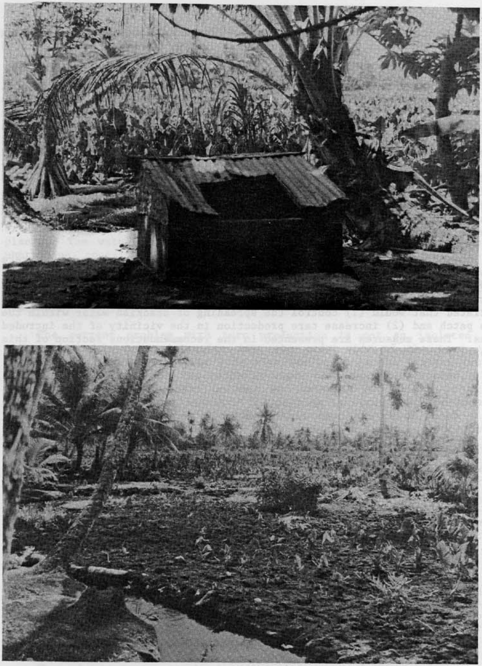


Figure 11. Comparison of areas within the taro patch underlain by fresh (top) and brackish (bottom) groundwater.

what is currently being discussed in Yap State as a means of controlling salt-water intrusion. No construction activities have yet been initiated however.

This suggested means of salt-water intrusion control has several disadvantages that by far outweigh any benefits. The major drawback is that the fresh-water lens would not receive enough recharge (derived from rainfall) because of the artificial barrier to infiltrating water and thus the lens could not maintain itself. The fresh-water nucleus would soon become extremely brackish. The result, of course, is that freshwater would not be available for consumption during the later part of the dry season or during droughts. Other disadvantages include (a) improper development of soil due to poor drainage, (b) total loss of taro production during the installation of the impermeable membrane and refilling operation, and finally (c) enormous cost of the project, especially considering the large area of the taro patch on Kuttu.

In terms of a solution to the problem of salt-water intrusion, there appears to be none. The taro patch has been enlarged to a point that the border areas along the ocean shoreline are always going to be subjected to intruding seawater. There are, however, effective measures that can be initiated that would (1) control the spreading of brackish water within the taro patch and (2) increase taro production in the vicinity of the intruded areas. These measures are presented in the recommendations section of this report.

SUMMARY AND RECOMMENDATIONS

Summary

The following is a summary of the results and conclusions of this study.

1. The geologic structure of Kuttu consists of three distinct, more or less, horizontal layers. The thickness of the surface, on the average, is 6.6 feet and is composed of sand and gravel which grades rapidly to cobbles and boulders as the ocean shoreline is approached. Underlying the surface layer is a unit which varies in thickness from 10 to as much as 40 feet. This unit appears to be composed of saturated consolidated sands and gravels. The third unit displays an irregular surface at an average depth of about 40 feet. The unit may be composed of well cemented material.

2. Groundwater beneath Kuttu appears to occur as a fresh-water lens with an associated mixing zone. The lens is situated within layer 2 and along the lagoon portion of the island. The maximum thickness of the lens is probably around 10 feet as determined from resistivity measurements.

3. Water quality within the freshest part of the lens is relatively good, except for high hardness in general and high nitrate and total phosphorus in some areas. The source of the nitrate is not known, however, the phosphorus contamination is no doubt related to the common practice of clothes and dish washing and bathing near the well.

4. The past practice of expanding the taro patch in order to produce more food appears to be the major contributing factor to the problem of salt-water intrusion. The taro patch has been extended over what may be a highly permeable unit (layer 2) which allows a greater mixing of fresh and salty water in the subsurface. This brackish water intrudes the border areas of the taro patch through the permeable unit.

5. The intruded brackish water appears to flow inland toward unaffected areas through the numerous ditches within the taro patch.

6. Although the problem of salt-water intrusion appears to be a permanent occurrence, there are measures that can be initiated to control the spread of brackish water within the taro patch and to increase the yield of taro in areas underlain by brackish groundwater.

Recommendations

The following recommendations are suggested as a means of improving the current situation on Kuttu. These recommendations are based on the findings of this study.

1. Further expansion of the taro patch will probably lead to increased salinity problems and therefore should be discouraged.

2. To inhibit the migration of brackish water from intruded areas, any ditch in the vicinity should be partially filled such that only short sections (no more than 25 feet) are left open.

3. Thin soil layers in intruded areas should be refilled to as thick as possible in order to raise the taro roots above the underlying brackish water.

4. A mulching machine would greatly speed up the process of soil rebuilding by producing small-sized fill material which would decay quickly.

5. Salt tolerant varieties of taro such as cystosperma (2000-3000 mg/l chloride tolerant) could be planted in those areas were higher salinity is expected. An alternative is to plant fast-growing taro (variety known by Ponape Agricultural Station) in areas seasonally affected by salt-water intrusion. This variety could be harvested annually prior to the seasonal occurrence of the problem.

6. An expert should be consulted on the effective control of land crabs and insects that are currently damaging taro plants.

7. To decrease further contamination of the fresh groundwater resource (1) washing and bathing should not be done in the vicinity of the household well (suggested minimum distance is 30 feet from the well) and (2) utilization of chemical fertilizer should be discouraged.

8. A more comprehensive water-quality study (including fecal coliform) should be conducted in the very near future.

9. Further hydrogeologic study is needed to define the subsurface conditions that promote the intrusion of salty groundwater.

ACKNOWLEDGMENTS

This study was conducted at the request of the government of the Federated States of Micronesia and funded by the Trust Territory Environmental Protection Board and the South Pacific Commission. The Water and Energy Research Institute extends its appreciation to those individuals that cooperated in the study effort. Specifically, we thank Mr. Nachsa Siren, Director of the Department of Rural Health and Community Development, and Mr. Misauo Petrus, Governor's Representative, for their invaluable help in the organization of the field trip and for their logistic support. We also extend appreciation to Mr. Ermer Siales, Community Development Officer, Department of Public Affairs, for administrating the questionnaire. We also thank the people of Kuttu for their generosity and hospitality during our brief visit to their island.

LITERATURE CITED

American Public Health Association, 1980. Standard Methods for the Examination of Water and Wastewater. 15th ed. American Public Health Association, Washington D.C., 1193 pp.

Ayers, J. F., 1981. Estimate of recharge to the freshwater lens of northern Guam. Water Resources Research Center, Univ. of Guam, Tech. Rept. No. 21, 20 pp.

Davis, S. N., and R. J. M. DeWiest, 1966. Hydrogeology. John Wiley and Sons, Inc., New York, 463 pp.

Dobrin, M. B., 1976. Introduction to Geophysical Prospecting. McGraw Hill, Inc., 630 pp.

Scott, J. H., B. L. Tibbetti, and R. G. Burdich, 1972. Computer analysis of seismic refraction data. U.S. Dept. of Interior, Bureau of Mines Report of Investigation RI-7595, 95 pp.

Telford, W. M., L. P. Geldart, R. E. Sheriff, and D. A. Keys, 1976. Applied Geophysics. Cambridge University Press, New York, 860 pp.

Tracey, J. I., S. O. Schlanger, J. T. Stark, D. B. Doan, and H. G. May, 1964. General geology of Guam. U.S. Geol. Surv. Prof. Pap. No. 403-A, 104 pp. Rept. No. 74-010, 11 pp.

U.S. Environmental Protection Agency, 1979. Methods for chemical analysis of water and wastes. U.S. E.P.A. Publication EPA-600/4-79-020.

Zohdy, A. A. R., 1974. A computer program for the calculation of Schlumberger sounding curves by convolution. U. S. Geol. Serv. Open File.

Zohdy, A. A. R., G. P. Eaton, and D. R. Mabey, 1974. Application of surface geophysics to ground-water investigations. U.S. Geol. Surv. Techniques of Water-Resources Investigation, Book 2, Chapter D1, 116 pp.

APPENDIX A

LAYER DEPTHS DETERMINED BY SEISMIC-REFRACTION SURVEY

Spread 1 Smoothed position of layers beneath shotpoints and geophones

SP[1]	Position	Surf Elev	Layer 2 Depth (ft)	Layer 2 Elev	Layer 3 Depth (ft)	Layer 3 Elev
F	-15.0	2.5	2.6	-0.1	66.5	-64.0
M	137.5	2.0	9.6	-7.6	59.0	-57.0
R	290.0	2.0	4.4	-2.4	53.5	-51.5
GEO[2]						
1	0.0	2.5	3.5	-1.0	65.8	-63.3
2	25.0	2.5	5.4	-2.9	64.8	-62.3
3	50.0	2.5	6.3	-3.8	63.7	-61.2
4	75.0	2.0	8.1	-6.1	62.2	-60.2
5	100.0	2.0	10.4	-8.4	61.1	-59.1
6	125.0	2.0	9.9	-7.9	59.7	-57.7
7	150.0	2.0	9.3	-7.3	58.2	-56.2
8	175.0	2.0	9.4	-7.4	56.9	-54.9
9	200.0	2.0	8.5	-6.5	56.4	-54.4
10	225.0	2.0	8.0	-6.0	56.0	-54.0
11	250.0	2.0	6.5	-4.5	55.0	-53.0
12	275.0	2.0	5.0	-3.0	53.9	-51.9

[1] SP - Shot Point: F, Forward; M, Middle, R, Reverse.

[2] GEO - Geophone Spacing

Spread 2 Smoothed position of layers beneath shotpoints and geophones

SP[1]	Position	Surf Elev	Layer 2 Depth (ft)	Layer 2 Elev	Layer 3 Depth (ft)	Layer 3 Elev
F	-15.0	2.0	3.9	-1.9	34.2	-32.2
M	137.5	1.0	9.5	-8.5	66.4	-65.4
R	290.0	2.5	5.7	-3.2	46.2	-43.7
GEO[2]						
1	0.0	2.8	5.5	-2.7	38.1	-35.3
2	25.0	2.8	5.7	-2.9	55.9	-53.1
3	50.0	2.5	7.3	-4.8	60.9	-58.4
4	75.0	2.0	7.7	-5.7	65.1	-63.1
5	100.0	1.0	8.6	-7.6	64.2	-63.2
6	125.0	1.0	9.7	-8.7	66.4	-65.4
7	150.0	1.0	9.2	-8.2	66.4	-65.4
8	175.0	1.0	8.5	-7.5	68.9	-67.9
9	200.0	1.0	10.2	-9.2	64.6	-63.6
10	225.0	2.0	9.0	-7.0	59.2	-57.2
11	250.0	2.5	7.0	-4.5	52.0	-49.5
12	275.0	2.5	6.2	-3.7	48.9	-46.4

1 SP - Shot Point: F, Forward; M, Middle; R, Reverse.

2 GEO - Geophone Spacing

Spread 3 Smoothed position of layers beneath shotpoints and geophones

SP[1]	Position	Surf Elev	Layer 2 Depth (ft)	Layer 2 Elev	Layer 3 Depth (ft)	Layer 3 Elev
F	-15.0	2.5	5.8	-3.3	35.0	-32.5
M	137.5	3.0	6.8	-3.8	38.9	-35.9
R	290.0	2.8	4.1	-1.3	4.1	-1.3
GEO[2]						
1	0.0	2.5	5.9	-3.4	35.5	-33.0
2	25.0	2.5	6.2	-3.7	35.9	-33.4
3	50.0	2.5	7.2	-4.7	38.5	-36.0
4	75.0	3.0	6.9	-3.9	40.4	-37.4
5	100.0	3.0	6.8	-3.8	40.3	-37.3
6	125.0	3.0	6.7	-3.7	39.1	-36.1
7	150.0	3.0	7.0	-4.0	38.7	-35.7
8	175.0	3.0	7.3	-4.3	36.4	-33.4
9	200.0	3.0	8.1	-5.1	31.5	-28.5
10	225.0	3.0	7.1	-4.1	26.5	-23.5
11	250.0	2.8	7.0	-4.2	14.1	-11.3
12	275.0	2.8	4.3	-1.5	4.3	-1.5

[1] SP - Shot Point: F, Forward, M, Middle; R, Reverse.

[2] GEO - Geophone Spacing

Spread 4 Smoothed position of layers beneath shotpoints and geophones

SP[1]	Position	Surf Elev	Layer 2 Depth (ft)	Layer 2 Elev	Layer 3 Depth (ft)	Layer 3 Elev
F	-15.0	4.0	7.2	-3.2	12.4	-8.4
M	137.5	3.5	5.8	-2.3	24.4	-20.9
R	290.0	2.5	5.5	-3.0	24.7	-22.2
GEO[2]						
1	0.0	4.0	7.1	-3.1	13.7	-9.7
2	25.0	4.0	7.3	-3.3	15.8	-11.8
3	50.0	4.0	7.0	-3.0	16.7	-12.7
4	75.0	4.0	6.2	-2.2	18.7	-14.7
5	100.0	4.0	6.7	-2.7	22.0	-18.0
6	125.0	3.5	5.8	-2.3	24.6	-21.1
7	150.0	3.5	5.8	-2.3	24.2	-20.7
8	175.0	3.5	6.2	-2.7	25.5	-22.0
9	200.0	3.0	5.1	-2.1	29.5	-26.5
10	225.0	3.0	5.6	-2.6	28.9	-25.9
11	250.0	2.5	5.3	-2.8	23.7	-21.1
12	275.0	2.5	5.4	-2.9	24.6	-22.1

[1] SP - Shot Point: F, Forward; M, Middle; R, Reverse.

[2] GEO - Geophone Spacing

Spread 5 Smoothed position of layers beneath shotpoints and geophones

SP[1]	Position	Surf Elev	Layer 2 Depth (ft)	Layer 2 Elev	Layer 3 Depth (ft)	Layer 3 Elev
F	-15.0	4.0	6.7	-2.7	95.7	-91.7
M	137.5	3.0	7.3	-4.3	62.8	-59.8
R	290.0	3.0	8.3	-5.3	24.9	-21.9
GEO[2]						
1	0.0	4.0	6.7	-2.7	92.7	-88.7
2	25.0	4.0	7.5	-3.5	86.5	-82.5
3	50.0	3.5	6.6	-3.1	79.7	-76.2
4	75.0	3.5	6.0	-2.5	73.4	-69.9
5	100.0	3.0	5.9	-2.9	72.4	-69.4
6	125.0	3.0	6.6	-3.6	66.2	-63.2
7	150.0	3.0	7.9	-4.9	59.4	-56.4
8	175.0	3.0	8.2	-5.2	53.7	-50.7
9	200.0	3.0	6.0	-3.0	41.7	-38.7
10	225.0	3.0	8.8	-5.8	32.7	-29.7
11	250.0	3.0	8.1	-5.1	27.1	-24.1
12	275.0	3.0	8.3	-5.3	29.0	-26.0

[1] SP - Shot Point: F, Forward; M, Middle; R, Reverse.

[2] GEO - Geophone Spacing

Spread 6 Smoothed position of layers beneath shotpoints and geophones

SP[1]	Position	Surf Elev	Layer 2 Depth (ft)	Layer 2 Elev	Layer 3 Depth (ft)	Layer 3 Elev
F	-15.0	4.0	5.5	-1.5	38.4	34.4
M	137.5	3.0	6.2	-3.2	34.6	-31.6
R	290.0	3.0	7.9	-4.9	7.9	-4.9
GEO[2]						
1	0.0	4.0	5.7	-1.7	38.3	-34.3
2	25.0	4.0	5.9	-1.9	37.3	-33.3
3	50.0	4.0	7.3	-3.3	36.3	-32.3
4	75.0	4.0	8.7	-4.7	35.4	-31.4
5	100.0	4.0	7.7	-3.7	36.1	-32.1
6	125.0	4.0	7.2	-3.2	37.3	-33.3
7	150.0	4.0	7.1	-3.1	33.9	-29.9
8	175.0	4.0	6.9	-2.9	30.3	-26.3
9	200.0	4.0	8.5	-4.5	26.5	-22.5
10	225.0	4.0	8.4	-4.4	18.6	-14.6
11	250.0	4.0	7.7	-3.7	10.9	-6.9
12	275.0	4.0	8.7	-4.7	9.3	-5.3

[1] SP - Shot Point: F, Forward; M, Middle, R, Reverse.

[2] GEO - Geophone Spacing

Spread 7 Smoothed position of layers beneath shotpoints and geophones

SP[1]	Position	Surf Elev	Layer 2 Depth (ft)	Layer 2 Elev	Layer 3 Depth (ft)	Layer 3 Elev
F	-15.0	4.0	6.5	-2.5	109.8	-105.8
M	137.0	3.5	6.9	-3.4	52.9	-49.4
R	290.0	4.0	8.0	-4.0	37.9	-33.9
GEO[2]						
1	0.0	4.0	6.6	-2.6	104.6	-100.6
2	25.0	4.0	7.9	-3.9	96.8	-92.8
3	50.0	4.0	7.9	-3.9	88.9	-84.9
4	75.0	4.0	7.8	-3.8	81.1	-77.1
5	100.0	3.8	7.3	-3.5	73.0	-69.1
6	125.0	3.5	7.0	-3.5	59.5	-56.0
7	150.0	3.5	6.9	-3.4	46.4	-42.9
8	175.0	3.5	7.3	-3.8	27.9	-24.4
9	200.0	4.0	7.9	-3.9	34.4	-30.4
10	225.0	4.0	8.1	-4.1	37.3	-33.3
11	250.0	4.0	7.9	-3.9	38.5	-34.5
12	275.0	4.0	8.0	-4.0	38.1	-34.1

[1] SP - Shot Point: F, Forward; M, Middle, R, Reverse.

[2] GEO - Geophone Spacing

Spread 8 Smoothed position of layers beneath shotpoints and geophones

SP[1]	Position	Surf Elev	Layer 2 Depth (ft)	Layer 2 Elev	Layer 3 Depth (ft)	Layer 3 Elev
F	-15.0	3.5	4.3	-0.8	40.3	-36.8
M	137.5	3.8	6.2	-2.4	31.9	-28.1
R	290.0	4.0	6.6	-2.6	40.9	-36.9
GEO[2]						
1	0.0	3.5	4.4	-0.9	39.5	-36.0
2	25.0	3.5	6.4	-2.9	38.5	-35.0
3	50.0	3.5	7.1	-3.6	37.5	-34.0
4	75.0	3.5	7.3	-3.8	36.1	-32.6
5	100.0	3.8	6.3	-2.5	35.0	-31.2
6	125.0	3.8	6.4	-2.6	32.6	-28.8
7	150.0	3.8	6.0	-2.2	31.1	-27.3
8	175.0	3.8	5.5	-1.7	34.4	-30.6
9	200.0	3.8	5.4	-1.6	37.1	-33.3
10	225.0	4.0	6.9	-2.9	39.0	-35.0
11	250.0	4.0	6.4	-2.4	39.5	-35.5
12	275.0	4.0	6.5	-2.5	39.9	-35.9

1 SP - Shot Point: F, Forward, M, Middle; R, Reverse.

2 GEO - Geophone Spacing

Spread 9 Smoothed position of layers beneath shotpoints and geophones

SP[1]	Position	Surf Elev	Layer 2 Depth (ft)	Layer 2 Elev
F	-15.0	3.0	6.8	-3.8
M	137.5	3.0	6.9	-3.9
R	290.0	3.0	6.3	-3.3
GEO[2]				
1	0.0	3.0	6.8	-3.8
2	25.0	3.0	7.2	-4.2
3	50.0	3.0	7.7	-4.7
4	75.0	3.0	7.6	-4.6
5	100.0	3.0	7.1	-4.1
6	125.0	3.0	7.0	-4.0
7	150.0	3.0	6.8	-3.8
8	175.0	3.0	7.1	-4.1
9	200.0	3.0	6.9	-3.9
10	225.0	3.0	7.4	-4.4
11	250.0	3.0	7.1	-4.1
12	275.0	3.0	6.4	-3.4

[1] SP - Shot Point: F, Forward; M, Middle; R, Reverse.

[2] GEO - Geophone Spacing

Spread 10 Smoothed position of layers beneath shotpoints and geophones

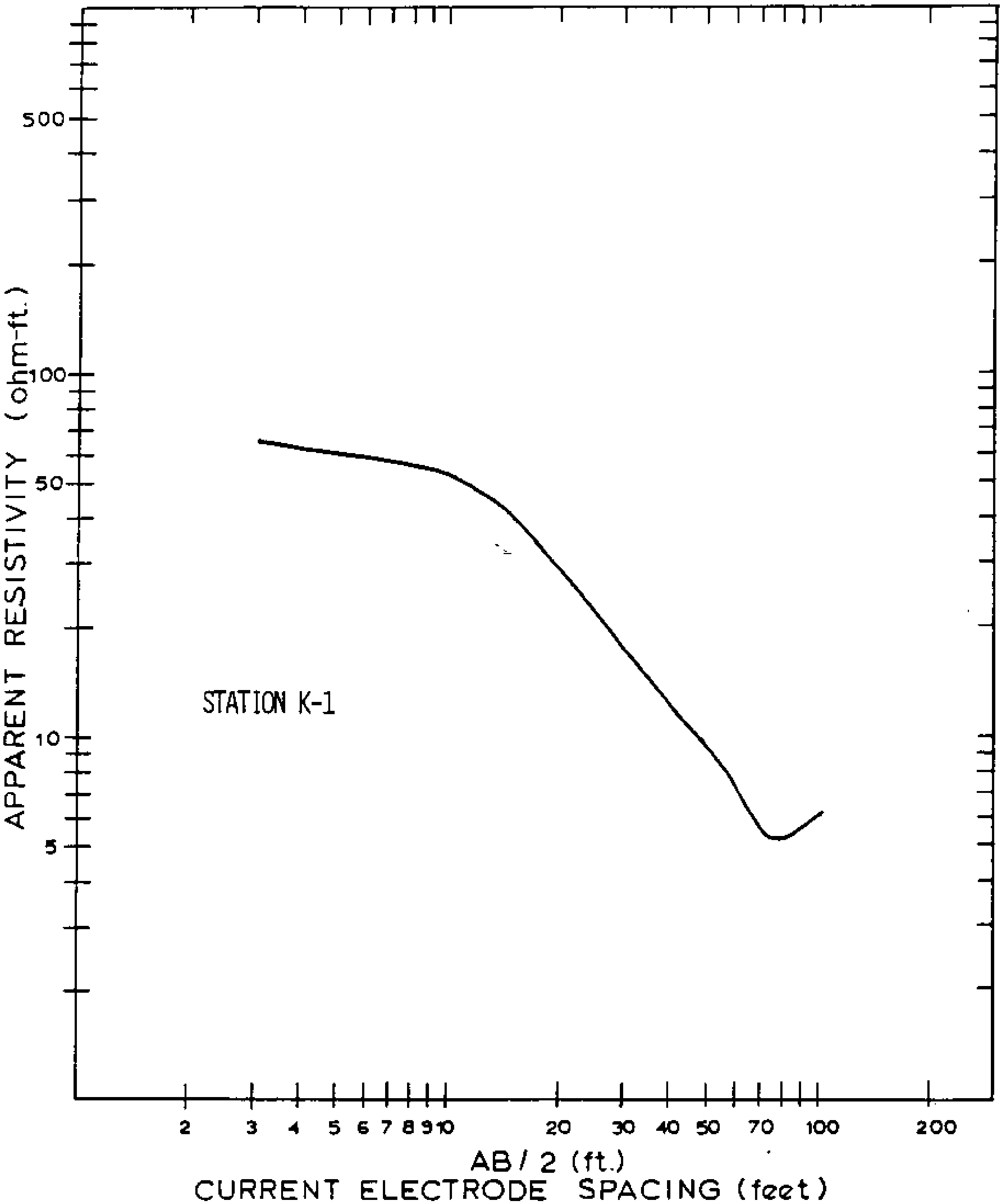
SP[1]	Position	Surf Elev	Layer 2 Depth (ft)	Layer 2 Elev
F	-15.0	3.0	8.8	-5.8
M	137.5	3.0	8.1	-5.1
R	290.0	3.0	6.1	-3.1
GEO[2]				
1	0.0	3.0	8.7	-5.7
2	25.0	3.0	8.6	-5.6
3	50.0	3.0	8.5	-5.5
4	75.0	3.0	8.7	-5.7
5	100.0	3.0	8.2	-5.2
6	125.0	3.0	8.2	-5.2
7	150.0	3.0	8.1	-5.1
8	175.0	3.0	8.1	-5.1
9	200.0	3.0	7.2	-4.2
10	225.0	3.0	6.6	-3.6
11	250.0	3.0	6.7	-3.7
12	275.0	3.0	6.3	-3.3

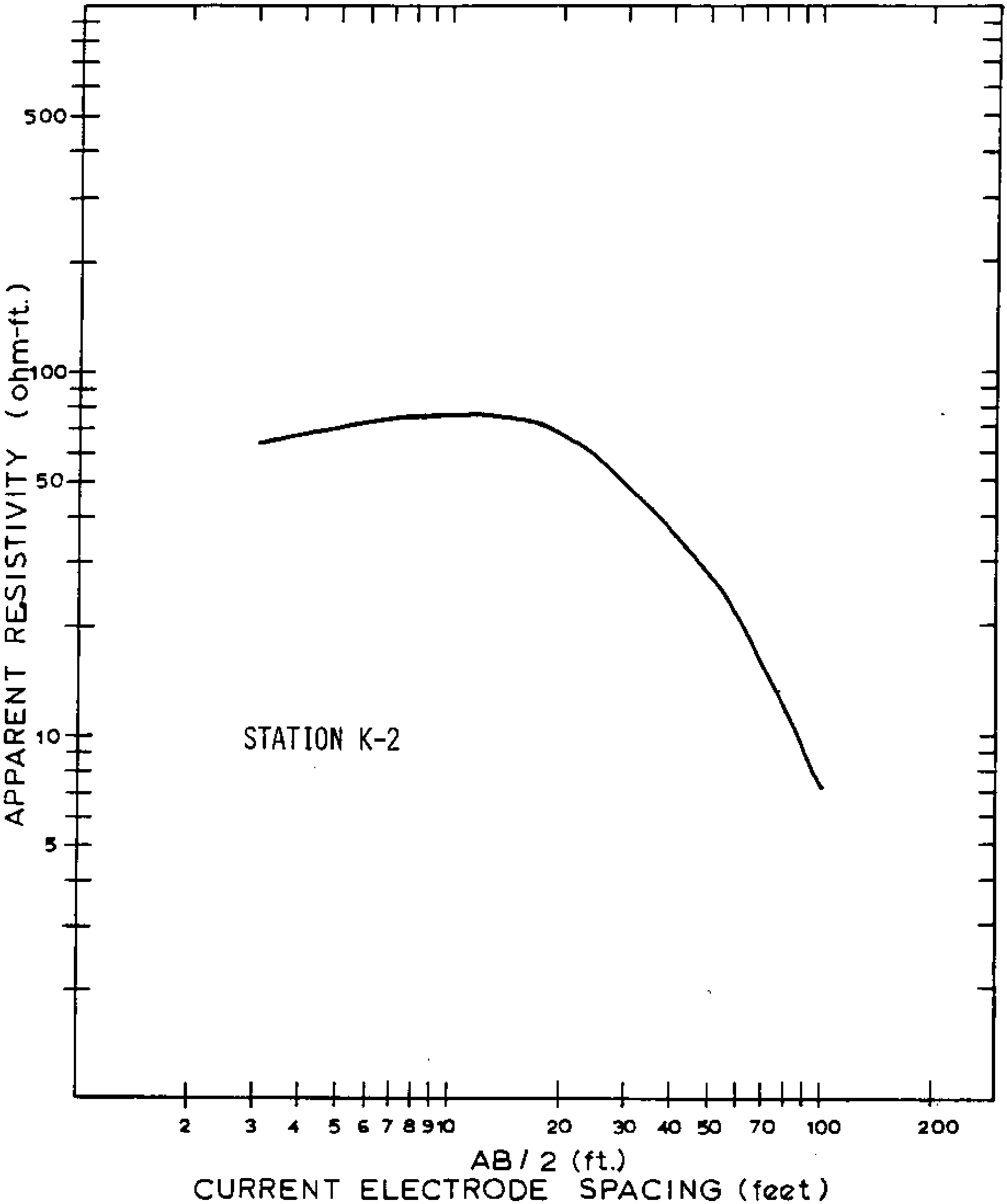
[1] SP - Shot Point: F, Forward; M, Middle; R, Reverse.

[2] GEO - Geophone Spacing

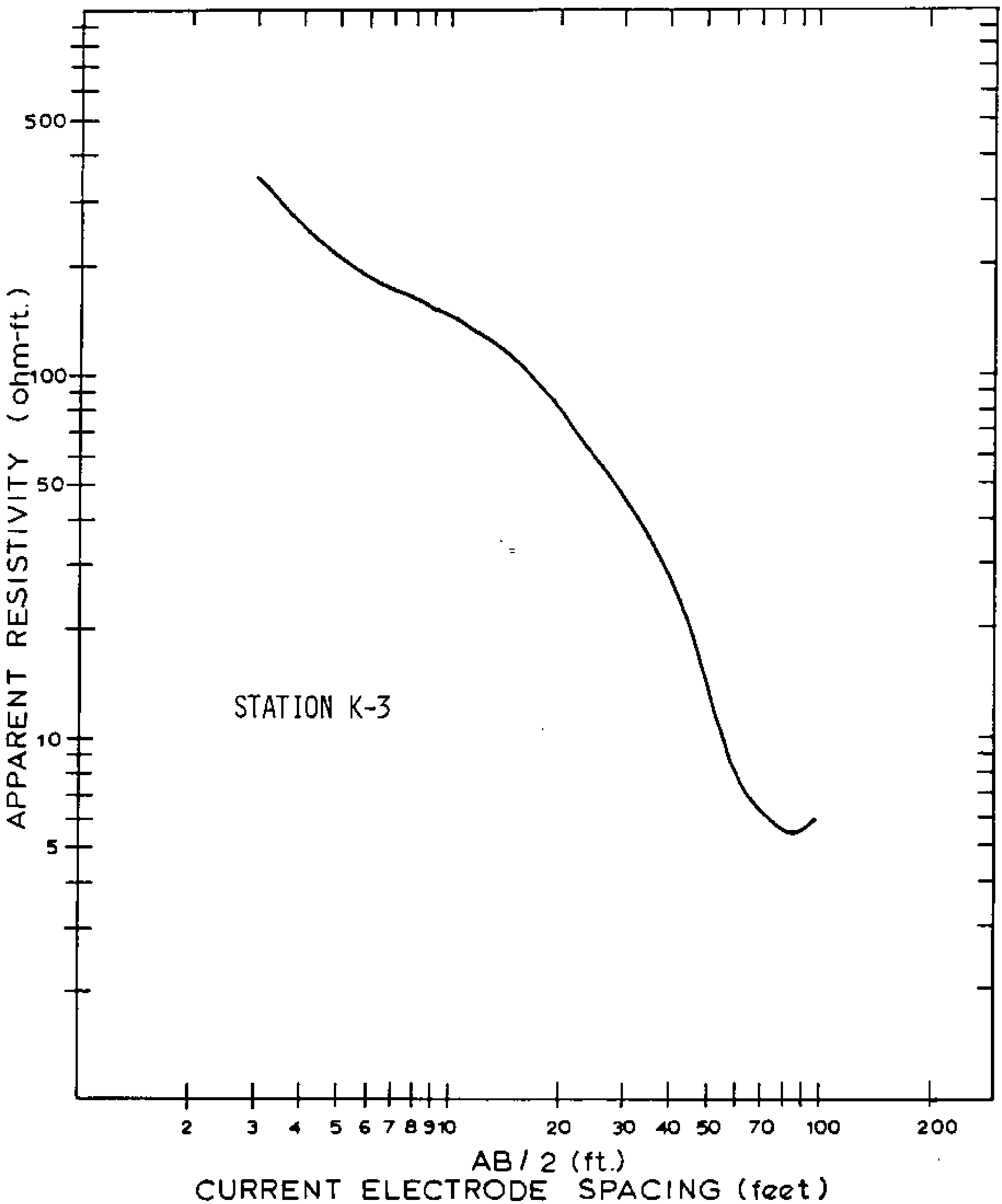
APPENDIX B

FIELD VERTICAL ELECTRICAL SOUNDING CURVES AND COMPUTER-GENERATED RESULTS

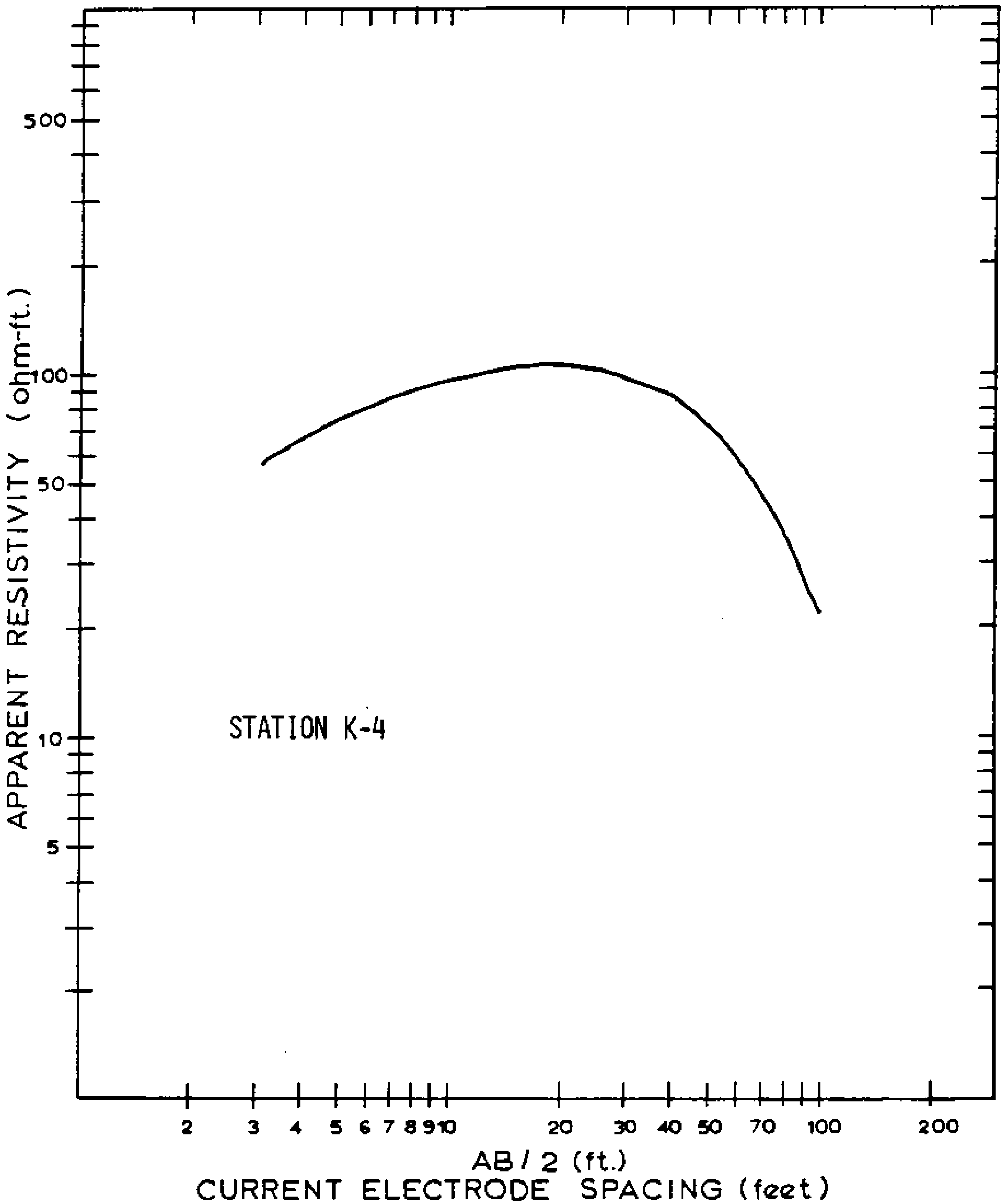

500
100
50
10
5
APPARENT RESISTIVITY (ohm-ft.)
STATION K-1
2
3
4
5
6
7
8
9
10
20
30
40
50
70
100
200
AB / 2 (ft.)
CURRENT ELECTRODE SPACING (feet)



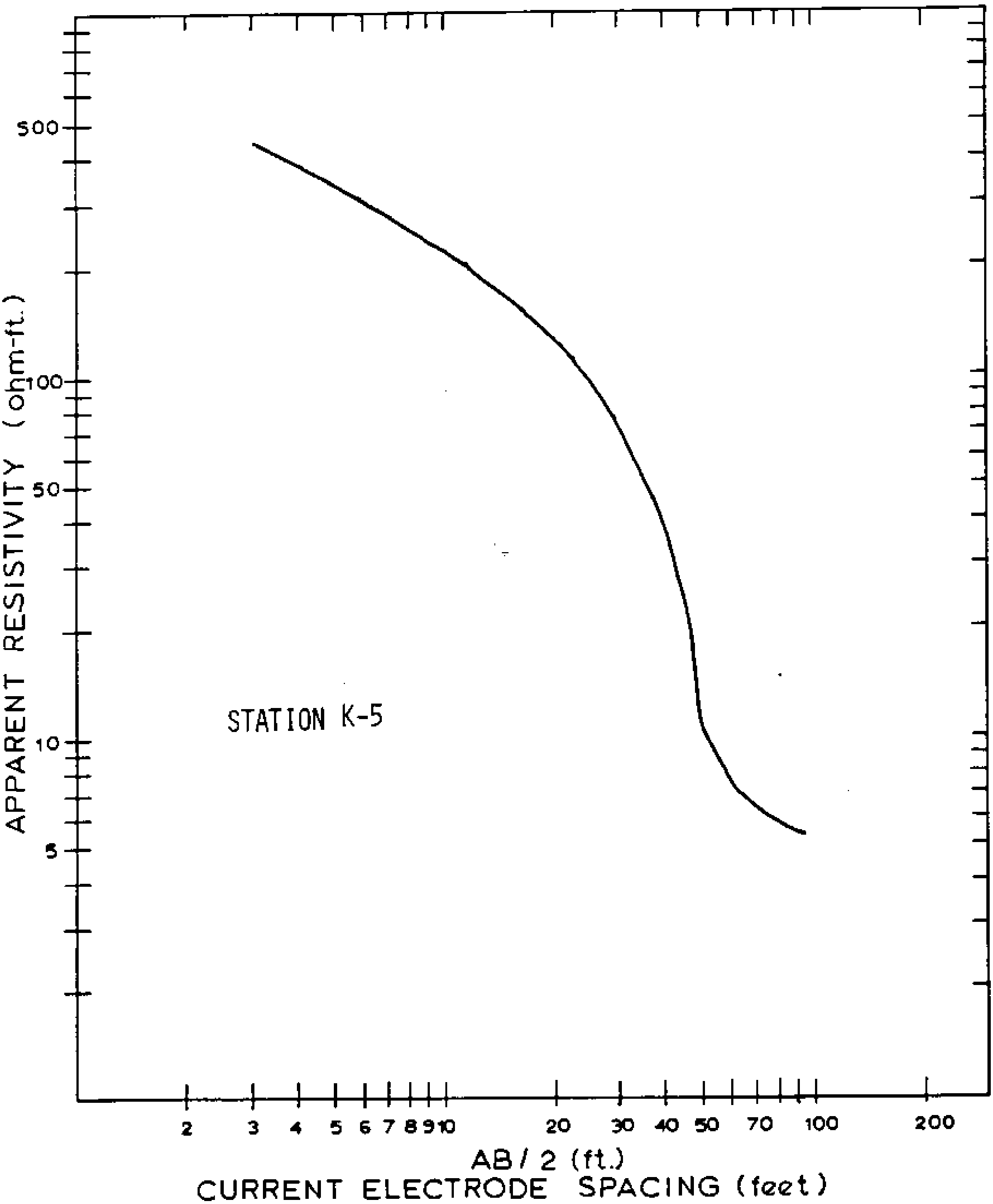
500
100
50
10
5
APPARENT RESISTIVITY (ohm-ft.)
STATION K-2
2
3
4
5
6
7
8
9
10
20
30
40
50
70
100
200
AB / 2 (ft.)
CURRENT ELECTRODE SPACING (feet)

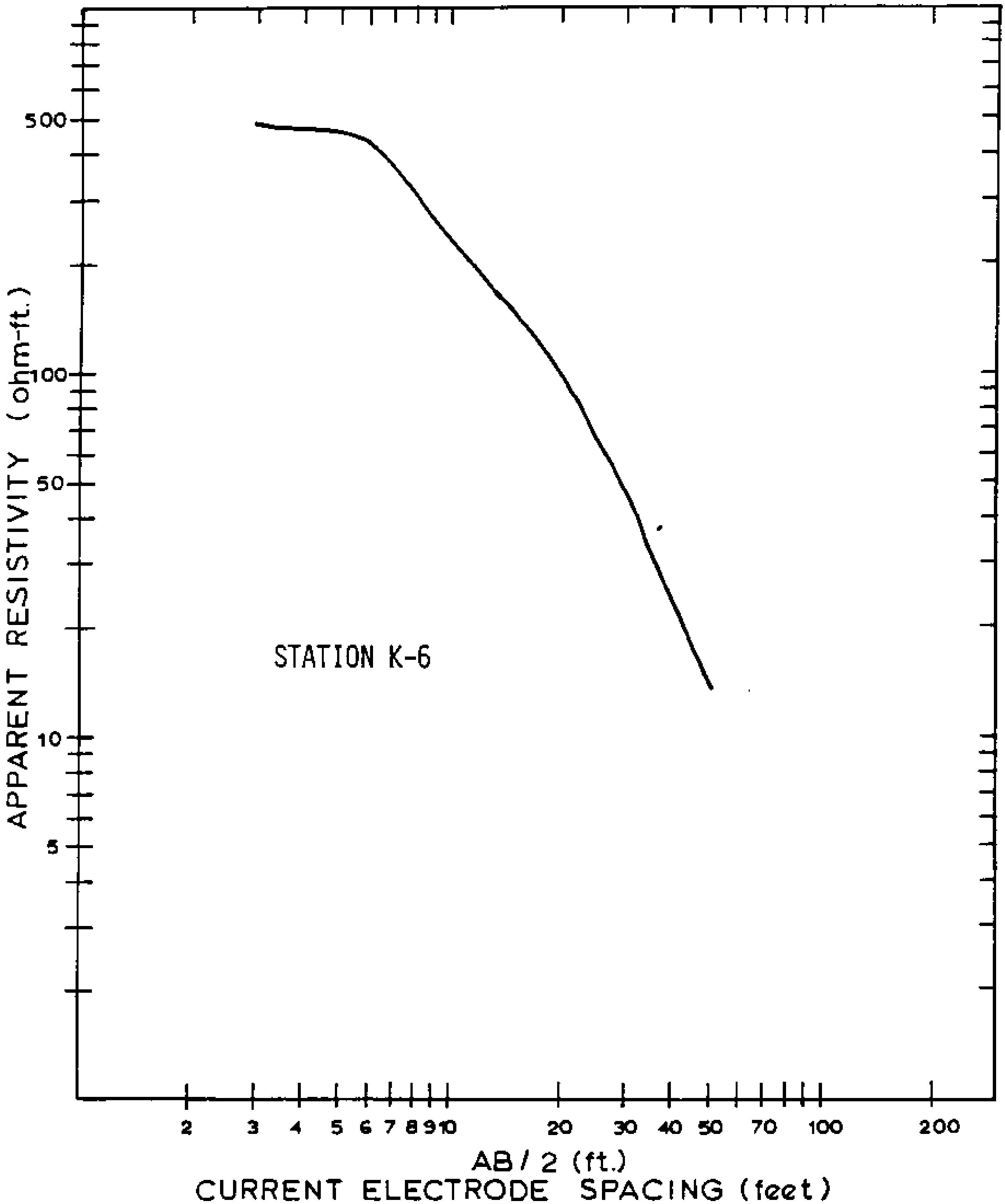


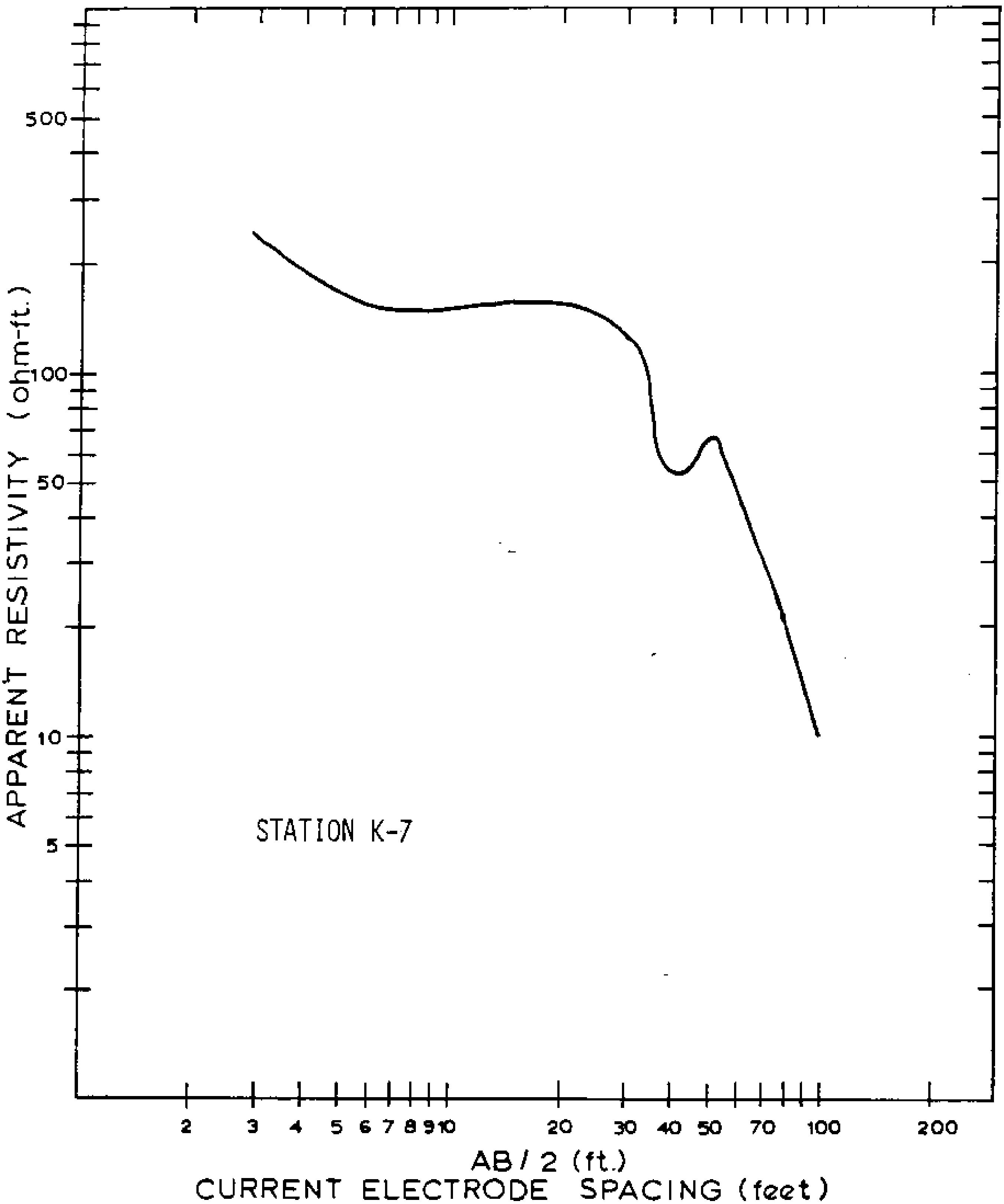
500
100
50
10
5
APPARENT RESISTIVITY (ohm-ft.)
STATION K-3
2
3
4
5
6
7
8
9
10
20
30
40
50
70
100
200
AB / 2 (ft.)
CURRENT ELECTRODE SPACING (feet)



APPARENT RESISTIVITY (ohm-ft.)
500
100
50
10
5
STATION K-4
2
3
4
5
6
7
8
9
10
20
30
40
50
70
100
200
AB / 2 (ft.)
CURRENT ELECTRODE SPACING (feet)


500
100
50
10
5
APPARENT RESISTIVITY (ohm-ft.)
STATION K-5
2
3
4
5
6
7
8
9
10
20
30
40
50
70
100
200
AB / 2 (ft.)
CURRENT ELECTRODE SPACING (feet)


500
100
50
10
5
APPARENT RESISTIVITY (ohm-ft.)
STATION K-6
2
3
4
5
6
7
8
9
10
20
30
40
50
70
100
200
AB / 2 (ft.)
CURRENT ELECTRODE SPACING (feet)


500
100
50
10
5
APPARENT RESISTIVITY (ohm-ft.)
STATION K-7
2
3
4
5
6
7
8
9
10
20
30
40
50
70
100
200
AB / 2 (ft.)
CURRENT ELECTRODE SPACING (feet)

STATION K-1

THICKNESS	DEPTH	RESISTIVITY
3.0	3.0	70.0
6.0	9.0	45.0
14.0	23.0	8.0
----	----	5.0

AB/2	VES
3.16	66.59
4.64	62.10
6.81	54.75
9.99	44.63
14.67	32.20
21.54	19.97
31.62	11.43
46.41	7.36
68.12	5.94
99.99	5.43

STATION K-2

THICKNESS	DEPTH	RESISTIVITY
4.0	4.0	60.0
10.0	14.0	100.0
8.0	22.0	8.0
----	----	5.0

AB/2	VES
3.16	61.21
4.64	63.37
6.81	66.97
9.99	70.89
14.67	71.10
21.54	61.98
31.62	42.92
46.41	22.49
68.12	9.95
99.99	5.83

STATION K-3

THICKNESS	DEPTH	RESISTIVTY
3.0	3.0	450.0
8.0	11.0	150.0
12.0	23.0	20.0
----	----	4.5

AB/2	VES
3.16	406.92
4.64	352.75
6.81	274.53
9.99	194.76
14.67	127.66
21.54	73.35
31.62	34.15
46.41	13.41
68.12	6.53
99.99	5.29

STATION K-4

THICKNESS	DEPTH	RESISTIVITY
2.0	2.0	45.0
12.0	14.0	150.0
8.0	22.0	40.0
----	----	15.0

AB/2	VES
3.16	57.71
4.64	69.65
6.81	83.99
9.99	97.33
14.67	105.35
21.54	101.97
31.62	83.17
46.41	54.98
68.12	31.20
99.99	19.38

STATION K-5

THICKNESS	DEPTH	RESISTIVITY
5.0	5.0	550.0
8.0	13.0	150.0
12.0	25.0	20.0
----	----	5.0

AB/2	VES
3.16	532.59
4.64	504.85
6.81	442.09
9.99	338.57
14.67	218.02
21.54	114.99
31.62	48.79
46.41	17.73
68.12	7.89
99.99	5.93

STATION K-6

THICKNESS	DEPTH	RESISTIVITY
4.5	4.5	550.0
6.0	10.5	125.0
12.0	22.5	20.0
----	----	6.0

AB/2	VES
3.16	525.17
4.64	486.34
6.81	405.06
9.99	284.18
14.67	160.20
21.54	71.81
31.62	27.88
46.41	12.47
68.12	8.16
99.99	6.84

STATION K-7

THICKNESS	DEPTH	RESISTIVITY
3.0	3.0	300.0
5.0	8.0	100.0
10.0	18.0	175.0
10.0	28.0	10.0
----	----	3.0

AB/2	VES
3.16	272.11
4.64	238.52
6.81	191.84
9.99	151.26
14.67	128.67
21.54	112.48
31.62	84.70
46.41	47.23
68.12	17.94
99.99	5.53

APPENDIX C

QUESTIONNAIRE RESPONSES

KUTTU QUESTIONNAIRE

A) DESCRIPTION OF TARO PROBLEM:

1. Has your family had any problems with their taro patch?

No		0
Yes		31
a)	salt water intrusion	31
b)	rotten taro roots	1
c)	crabs eating taro	2
d)	drought	3
e)	high tide in winter and spring time	17

2. How many times have you had this problem with the taro patch, as far back as you can remember? (Give number of times).

a)	twice	1
b)	almost every year	26
c)	after typhoon Pamela (1976)	5
d)	since 1981	1

What season?

a)	winter	31
b)	spring	31
c)	during the west wind period	1

B) INFORMATION ABOUT TARO PATCH:

3. Does your family own the plot they work in?

no		1
yes		30

Who is responsible for working in the taro patch?

a)	myself	30
b)	wife and myself	1
c)	in-laws	1

4. Who takes care of the taro patch if the one responsible for it is not there?

a)	brother	8
b)	sister	3
c)	mother/father	4
d)	in-laws	10
e)	wife	7
f)	aunt/niece	8
g)	none	3

5. Are there taro patches near you that are no longer being used?

no	29
yes	2

When were they last used?

a) after typhoon Pamela (1976)	2

Why did people stop using them?

a) rotten taro roots	2

C) 6. What is the weather like when there _is_ _no_ taro problems? (Please describe)

a) weather does not matter	30
b) good with low tide	1

What is the weather like when there _is_ a taro problem? (Please describe)

a) rough weather with westerly wind (oceanside), big waves and high tide	31

7. What is the ocean like when there _is_ _no_ taro problem? (Please describe)

a) calm and during summer	1
b) calm and low tide	2
c) calm (no big waves)	28

What is the ocean like when there _is_ a taro problem? (Please describe)

a) rough and big waves	11
b) rough, big waves, and high tides	20

8. Please list the foods that are usually eaten by you and your family?

a) USDA	1
b) Bananas	30
c) Breadfruit	31
d) Taro	30
e) Rice	30
f) Coconut	3

What 3 or 4 foods do you eat most often now?

a) Rice, limited taro, breadfruit	31

9. How well are other foods growing on the island (like breadfruit, yams, papaya)?

<u>Grows good</u>

a)	bananas	31
b)	papaya	30
c)	breadfruit	31
d)	sugar cane	1

<u>Does not grow</u>

a)	yams	31

D) 10. When Kuttu had problems with taro patches before, what was done to correct the problem? (Please give details)

a) built a seawall (when funding was provided) 31

What was most helpful?

a) the seawall was a little bit helpful in stopping overwashing waves (seawall did not stop high tide) 30

b) the seawall was not helpful to the problem 1

11. What do <u>you</u> believe causes the problem with the taro patches?

a)	salt water coming up through the ground	20
b)	intrusion from rocky areas (along seaward side)	2
c)	the coconut crab (making holes)	1
d)	wash-in over the land by high tide (which causes saltwater intrusion)	18

12. Do <u>you</u> think the problem can be solved?

yes 31

Why? (No responses)

13. What do <u>you</u> feel could be done to help correct this problem?

a) extend or make concrete wall deeper into ground (if funding is provided) 26

b) dig patch deeper and place concrete and/or plastic sheet (then refill soil) 30

14. Is there anything else you would like to tell me about the problem the island is having with the taro patches?

a)	coconut crabs (increased after Pamela, 1976)	30
b)	bad insects	1
c)	drought	1

15. Position within family of interviewee

a)	head of family	26
b)	on behalf of family	4
c)	unknown	1

16. Sex of interviewee

a)	male	30
b)	unknown	1

17. Approximate age of interviewee

a)	young adult (18-29)	7
b)	middle adult (30-49)	11
c)	older adult (50 and above)	14

18. Does house have:

a)	rooftop catchment system	29
b)	water well	17