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# CHANGE IN BATHYMETRIC CONFIGURATION, KANEOHE BAY, OAHU, 1882-1969

By

KENNETH J. ROY

OCTOBER 1970

Prepared under the
National Science Foundation
SEA GRANT PROGRAM
(Grant No. GH-28 I)

**HAWAII INSTITUTE OF GEOPHYSICS**

UNIVERSITY OF HAWAII

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Approved by Director

George P. Woollard

Date: 30 October 1970

UNIVERSITY OF HAWAII
Department of Oceanography

To the people of the State of Hawaii, and other interested parties:

The following report entitled "Changes in the Bathymetric Configuration, Kaneohe Bay, Oahu, 1882-1969," by Dr. Kenneth Roy, was prepared through the support of the Sea Grant Program.

The report presents:

1. The detailed bathymetry of the Bay, as of 1969, as measured by 175 miles of continuous fathometer recording. (Figure 1.)

2. Geological and biological causes for the present bathymetry of the Bay. These are largely a remnant erosional topography formed at a lower stand of sea level (Figures 14 and 20), coral growth, and wave erosion.

3. Changes in the bathymetry of the Bay over an 87-year period, and the causes of these changes. The Bay changed very little between 1882 and 1927 (Figure 19). Since 1927 the lagoon, between the barrier reef and the shore, became shallower an average of 5.4 feet as a result of increased reef erosion and increased run-off from land (Figure 18). The rate of this infilling is impossible to determine because it is not known when it started. If it started in 1927 the Bay might last several hundred years. If it started recently, the Bay might last less than 100 years.

The increase rate of lagoon filling is undoubtedly the result of man's activities along the shore. This must be controlled or we will lose one of the beauty spots of our beautiful island.

Aloha!

K. E. Chave

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## INTRODUCTION

Kaneohe Bay, on the northeast shore of Oahu, Hawaii, is in part an estuary, and as such, its expected lifetime is relatively short. The bay is the only large sheltered body of water along the windward coast of Oahu. Therefore important questions are: how long will the bay remain more or less the way it is, in terms of depth and general configuration, and what are the factors that are effecting change.

The work for this report was begun in 1968 in conjunction with the Coral Reef project (Sea Grant GH-28). A major concern of the Coral Reef project is the $CaCO_3$ budget in Kaneohe Bay. The configuration of the bay and the sediment depositional rates are needed to work out the budget.

This report has three main objectives:

1. to examine the present bathymetric configuration of Kaneohe Bay in terms of type and origin;
2. to determine changes in depth due to infilling or to erosion during the periods 1882 to 1927, and 1927 to 1969; and,
3. to examine sedimentation in the bay in terms of the nature of the sediment and the mechanisms and rates of sediment deposition.

## FIELD AND LABORATORY METHODS

### Bathymetric survey

One hundred seventy-five miles of continuous fathometer tracks were run in Kaneohe Bay using a small boat and a portable fathometer (two fathometers were used; Ratheyon Model DE-119B, Chart width - 1 in.= 10 ft. and Bendix model 23, chart width - 1 in.= 60 ft.) The base map used was prepared from aerial photographs enlarged to a scale of 1:6000. Positioning in the survey was done by means of sextant fixes. Features on land that could be located on the aerial photographs were used as reference points. Care was taken to choose reference points that were as close to sea level as possible.

Location error includes sextant reading and sighting error, plotting error, and boat drift. In areas where the true position could be determined from the configuration of the bottom, as seen on the aerial photographs, the accuracy of the locations was determined. Inshore of a line between Kekepa and Mokolii islands, the plotted locations are estimated to be within 100 ft. of the true locations. All errors increase offshore, so locations seaward of the Kekepa-Mokolii line probably have a ±200 ft. maximum error in location associated with them.

Depths were determined every 100 ft. along the survey tracks, plotted on the base map, and contoured (see Fig. 1). Interpolation of contours between areas of bathymetric control was done using the bottom detail seen on the aerial photographs.

The area of the lagoon and of individual patch reefs in the lagoon was measured by planimetry of the bathymetric map (see Table 2). Hypsographic data were obtained by planimetry of the 1927 and 1969 bathymetric maps (see Table 18).

Measurement of the dimensions of the dredged patch reefs was done on the 1927 map which shows the predredging configurations. The remaining reefs were measured on the enlarged aerial photographs. The measurements included maximum dimension of the patch reefs (the major axis), and maximum dimension perpendicular to the major axis (the minor axis) (see Table 2). The azimuth of the major axis of elongate simple reefs was also measured (see Table 2 and Fig. 6) (see p. 6 for explanation of simple reef). Distance between patch reefs and their nearest neighbor reef (side to side distance) as well as the minimum center to center distance between patch reefs was measured (see Table 2 and Figs. 10 and 11). Distances were recorded to the nearest 10 ft.

Slopes of the fringing, patch, and barrier reefs were calculated from data obtained from fathometer traces. Slopes of passage bottoms were obtained from the bathymetric map.

Data concerning the nature of the bottom were collected as incidental observations while diving on benthic surveys related to the overall Sea Grant project.

## Bay Infilling

THE PERIOD 1927-1969. The U.S. Army Corps of Engineers and the U.S. Coast and Geodetic Survey did detailed bathymetric surveys with sounding lines in Kaneohe Bay during 1927 and 1933. These data were contoured and their configuration was compared to that of the 1969 survey.

To obtain data on change of depth with time, 18 transect lines, each about 4,000 ft. long, were chosen so as to cover the bay in as uniform a pattern as possible (see Fig. 18). The position of the transect lines was governed by the location of the 1969 survey tracks. The lines were located on those tracks, and where possible were picked to also correspond with the 1927-1933 tracks. However, correspondence was generally not possible, so the 1927-1933 depth values were interpolated to the sample lines. However, because the sample locations on the 1969 lines were chosen randomly, the 1969 values are also the result of interpolation.

The 1927-1933 data points are generally not more than 200 ft. apart. The 1969 data points as marked on the survey tracks, are 100 ft. apart. The distance of interpolation is about the same for both data sets, so the interpolation error is assumed to be the same for both surveys. From examination of the data, the possible error due to interpolation is seen to be generally not more than the error associated with the survey precision--about 1.5 ft. (see Table 7).

One depth-deviation sample was collected for each 378 ft. of line at a location. This uneven factor is a result of using divisions of 0.5 in. on the 1927 chart, which has a scale of 1:50,000. Of the 18 transects, 16 have 11 samples, one has 10, and one 8 (see Table 9). Random positions were selected for each depth determination at a location. At the selected positions, both the 1969 and 1927-1933 depths were determined, and the difference calculated (see Table 9). The sets of random positions were different from location to location.

Physical problems related to bathymetric surveys done from small boats can lead to large survey errors. Because of the relatively small changes in depth during the time between the surveys, knowledge of the precision and relative accuracy of the surveys is required before realistic evaluation of depth change can be made. Survey precision for both the 1969 and the 1927-1933 surveys (see Table 7) was determined by using the differences in depth that were recorded where the tracks of a survey crossed one another.

Accuracy is also a problem. The comparison of depths found in 1969, 1927, and 1882 is complicated by two factors; possible differences in reference datums, and differences in survey methods. The 1969 survey was done with a fathometer, the others were done with sounding lines. Prior to the 1969 survey, the fathometer was calibrated with a sounding line. After the survey was made, sounding-line depths were taken at 11 locations in the lagoon to determine the relative accuracy of the 1969 and 1927 surveys. The 11 locations were 100 to 200 ft. from data locations on the two surveys. Differences due to interpolation in the comparison of the 1969 sounding line and fathometer data should be about the same as those expected in comparison of the overall 1969 and 1927 surveys. The data are given in Table 8.

Various statistical tests were done on the depth-deviation data, the survey-precision data, and the accuracy data in order to determine if the observed variations are significant. These tests will be discussed.

THE PERIOD 1882-1927. In 1882 G. Jackson did a bathymetric survey of Koolau-Kaneohe Bay for the Hawaiian government. Soundings were taken on various tracks in the bay and depths were recorded to a quarter of a fathom. The 1882 and 1927-1933 charts were compared for depth changes at 8 locations (Fig. 19). The methods used and the problems of precision and accuracy are the same as described above for the 1927-1969 comparison.

Inadequate coverage in the 1882 survey precludes analysis of precision and relative accuracy. It is assumed because both surveys were done with sounding line, that the relative accuracy is the same in the 1882 survey as in the 1927 survey. It is also assumed that the precision is no worse than the 1969 survey. These are reasonable assumptions, particularly in the lagoon, where local bottom relief is relatively minor.

### Sediment analysis

Eleven sediment samples were selected to represent open-lagoon floor sediments (Fig. 17). The samples were taken with a small van Veen-type grab sampler, and are representative of the upper 6 inches of the sediment.

Splits of the samples were washed with fresh water, dried, and ground. Four gasometric analyses for $CaCO_3$ were done on each sample (after the method of Hülsemann, 1966), and the average weight percent $CaCO_3$ was calculated for each sample (Table 4). Splits of the samples were also dissolved in 2.3 normal hydrochloric acid, and filtered through preweighed Whatman no. 1 paper filters. The weight percent of the sample soluble in hydrochloric acid was calculated (Table 4).

X-ray diffraction (Cu Kα radiation) was done to determine the calcite: aragonite ratio in the samples, and the mole percent Mg in the calcite (after Smith, 1970). The samples were prepared for X-ray analysis by grinding the sediment and making a smear slide. Two subsamples were taken from each sample, a slide was prepared from each subsample and each slide was X-rayed, reversed in the slide holder and X-rayed again. Analysis of variance was done on the percent aragonite data. Three samples were sieved to obtain the size distribution of the lagoon sediments.

Water samples were collected at six locations (Fig. 16), every 3 hours for 24 hours. The sampling was done in conjunction with a 24-hour study conducted by D. Klim. The water samples were filtered through 0.8μ Millipore® filters, and the filter cakes were X-rayed to determine mineral phases present.

### Seismic reflection survey

A sparker system was used from the R/V SALPA to do a seismic reflection survey in the bay. The survey and the data analysis were supervised by A. Malahoff. Tracks were run in the lagoon, in Kaneohe passage, and on the surrounding reef, and over the barrier reef between Kapapa and Mokolii islands, and in Mokolii passage. Only superfical analysis of the data has been done. The general basement configuration has been described.

## RESULTS AND DISCUSSION

### Present bathymetry

The bay can be divided into four physiographic provinces: fringing reef, lagoon, barrier reef, and passes (Fig. 2). The lagoon can be further divided into lagoon floor and patch reefs. For this study, the lagoon is defined as that area between the base of the fringing reef foreslope, and the base of the barrier reef backslope. For purposes of planimetry, the fringing-reef edge of the lagoon was defined by the 5-ft. isobath, and the barrier reef edge by the break in slope at the back of the barrier reef. The northern end of the lagoon was arbitrarily drawn across Mokolii passage at about the position of the sill prior to dredging in 1939.

FRINGING REEF. The fringing reef was not studied in detail. Usually depths were recorded only up onto the reef flat, and then the track was terminated. There is usually about 2 ft. of water on the reef flats, but they are exposed on extreme low tides. The top of the forereef slope is at a depth of about 3 ft. The reef front slopes at about 25° (Table 1), down to the lagoon floor, and levels off at about 30 to 35 ft. Living corals are present down to about 25 ft. in some parts of the bay. In places slumping of large blocks of the reef front has occurred. Generally at the top of the forereef slope there is a feature similar to an algal ridge. Inshore of this feature, the bottom is sand, rubble, and dead coral.

LAGOON FLOOR. On the scale examined by the fathometer, the lagoon floor appears very smooth in general, sloping gently downward from the fringing reef toward the barrier reef. The area of the lagoon floor, excluding both the existing and dredged patch reefs, is $187.7 \times 10^6$ sq. ft. (Table 15). (The British system of measurement has been used in this report because the published data as well as the fathometer charts were in feet.) The distribution of depth of the lagoon floor is shown in Figures 21 and 22. The median depth is 35 ft., and the mean depth is 33 ft. The depth frequency distribution is bimodal. The 5- to 20-ft. mode relates to delta-building and disposal of dredging spoils, and the 40- to 45-ft. mode to the flat bottom of the lagoon.

Moats up to 3 ft. deep and 100 ft. wide occur around the patch reefs. Similar moats are reported from Bikini by Emery et al. (1954), and by Lowenstam (1950, p. 472) around Niagran reefs. Both Emery et al. and Lowenstam attribute the moats to settlement of the reefs into the underlying compressible sediments. Emery et al. say that the currents around the reefs are too slow to have scoured out the moats.

In Kaneohe Bay some of the deepest areas in the lagoon are in narrow passes between patch reefs (Fig. 1). This relation is probably a result of increased current velocity through the reduced cross sections of the passes. The increased current velocity could cause a slower rate of deposition in the passes than in the more open parts of the lagoon, or, could cause erosion of the pass bottom. As the passes seem to have been filled in about the same amount as the rest of the lagoon during the period 1927-1969, it appears that a relative decrease in depositional rate is the cause of the deeper bottoms. The moats around the patch reefs may also have the same origin as a result of turbulence and current velocity increases related to the obstructive presence of the patch reefs.

PATCH REEFS. Patch reefs, sometimes called coral knolls, are small reefal masses that rise above the lagoon floor inside barrier reefs or atolls (Shepard, 1963, p. 351). In Kaneohe Bay there are 79 patch reefs of various sizes and structural complexity. Of the 79 reefs, 25 have been dredged, most of them down to 30 ft., but a few only to 10 ft. The locations of the undredged reefs are shown on Figure 3, and the size statistics are given in Table 2. About 16 percent of the area of patch reefs in the bay, as well as some fringing reef, was dredged in 1929. None of the dredged patch reefs show signs of growing back to the surface.

The patch reefs approximate truncated circular cones. The width of the top is variable, up to 2,800 ft. The average of both fringing and patch reef slopes is about 27$^{o}$ (Table 1). The t ratio to test difference between fringing reef slopes and patch reef slopes is not significant at the 10 per cent level. Most undredged patch reefs in the bay come to within 2 or 3 ft. of mean sea level. There are no incipient patch reefs in the bay, although there are two or three reefs that have tops between 5 and 10 ft. deep.

Reefs larger than about 100 ft. across at the top have a sandy central area where live coral is absent and the bottom is sand, coral rubble, and encrusting coralline algae. Dead microatolls may be present (Wiens, 1962, p. 61). Around the edge of the top of the reefs there is often a zone of encrusting coralline algae (the algal ridge). This zone is generally 0.5 to 1-ft. shallower than the central part of the reef top. Seaward of the algal ridge, in 2 or 3 feet of water, is the top of the reef foreslope. On many reefs, particularily in the northwestern part of the lagoon, abundant coral occurs down the foreslope to a depth of about 25 ft. Below that depth the angle of slope decreases markedly and the bottom grades from sandy mud with large coral fragments to the normal lagoon mud.

Some patch reefs have large slump blocks (up to 15 ft. across) on their slopes. The algal rim cracks some distance in from the top of the reef foreslope and the large blocks spall off and slide down the slope. Although it is not uncommon to see detached blocks part way down the sides of the reefs, none were seen at the bottom of the slope, or out on the lagoon floor. Rather than breaking off and tumbling down the slopes, the blocks break off and slide downslope, until the bearing strength of the material in the toe of the slide is enough to support the weight of the block. The increase in strength apparently occurs before the blocks reach the lagoon floor. There are, however, fairly numerous, apparently displaced, 2- or 3-ft. diameter coral heads at the base of the reef foreslopes (J. Maragos, personal communication). These may be small blocks which have tumbled down the slope. Downward slumping of material--to extend the areas of suitable substrate, rather than slow continuous growth perpendicular to the face of the reef slope--appears to be the major mechanism for lateral expansion of the patch reefs.

There are two types of patch reefs in Kaneohe Bay, compound reefs, and simple reefs. The two types are distinguished by the nature of their outlines. The simple reefs have smooth regular, circular to ovate outlines. The compound reefs have multilobate outlines and appear to have formed by coalescence of a cluster of two or more simple reefs. The center to center distances to the included simple reefs are two large for the formation of the clusters to be explained as the spalling off of seed-reef slump blocks from some large parent. The clustered simple reefs apparently were of independent origin.

The simple reefs less than about 200 ft. in maximum dimension tend to be circular, while the larger ones are ovate (Fig. 4). The apparent circular nature of the smaller reefs is in part a reflection of the accuracy of

Table 1. Reef-slope statistics ($\overline{X}$ = average slope, s = standard deviation, n = sample size). The t ratio tests the null hypothesis of no difference between fringing-reef and patch-reef slopes. The t ratio is not significant at the 60 per cent level.

| | n | $\overline{X}$ (degrees) | s (degrees) | t ratio |
|---|---|---|---|---|
| Fringing-reef foreslope | 4 | 28.5 | 2.1 | 0.56 |
| Patch-reef foreslope | 10 | 25.8 | 9.0 | |
| Barrier-reef backslope | 3 | 24.3 | 4.9 | |
| Sand flat beyond the 90-ft. depth | 3 | 1.4 | 0 | |

Table 2. Size, nearest neighbor distance, and azimuth of major axes of patch reefs (reef locations are shown in Figure 3).

| Reef[a] | Area (sq. ft. X10$^{-4}$) | Major Axis (ft.) | Minor Axis[b] (ft.) | C.C.[c] (ft.) | S.S.[d] (ft.) | Azimuth of major axis |
|---|---|---|---|---|---|---|
| 1* | 28.60 | 833 | 417 | | 333 | |
| 2 | 5.01 | 200 | 200 | 1250 | 600 | |
| 3* | 83.88 | 1600 | 700 | 1300 | 200 | |
| 4* | 47.46 | 900 | 500 | 1400 | 400 | |
| 5* | 124.99 | 1800 | 900 | 1400 | 400 | |
| 6 | 5.68 | 250 | 250 | | 250 | |
| 7* | 58.15 | 1000 | 750 | 1550 | 200 | |
| 8* | 291.42 | 2800 | 1100 | 1800 | 200 | |
| 9 | 28.07 | 700 | 500 | 1000 | 450 | 24 |
| 10 | 27.74 | 700 | 500 | 1000 | 200 | 350 |
| 11 | 22.39 | 600 | 500 | 800 | 220 | |
| 12 | 10.36 | 370 | 370 | 800 | 150 | |
| 13* | 83.19 | 1200 | 800 | 800 | 200 | |
| 14 | 22.73 | 600 | 500 | 800 | 400 | 344 |
| 15 | 6.02 | 300 | 250 | 450 | 200 | 80 |
| 16 | 3.01 | 170 | 170 | 450 | 200 | |
| 17 | 6.35 | 250 | 250 | 450 | 100 | |
| 18 | 36.09 | 700 | 600 | 800 | 200 | 38 |
| 19 | 1.34 | 100 | 100 | 1500 | 140 | |
| 20 | 2.34 | 120 | 120 | 1250 | 1150 | |
| 21 | 0.67 | 70 | 70 | 750 | 650 | |
| 22 | 1.67 | 100 | 100 | 400 | 250 | |
| 23 | 3.01 | 200 | 150 | 400 | 250 | 51 |
| 24 | 7.69 | 300 | 300 | 700 | 400 | |
| 25 | 22.39 | 550 | 450 | 2200 | 1750 | 41 |
| 26 | 13.03 | 420 | 300 | 1000 | 650 | 39 |
| 27 | 11.70 | 420 | 300 | 900 | 400 | 25 |
| 28 | 13.37 | 420 | 350 | 550 | 200 | 78 |
| 29 | 22.74 | 850 | 400 | 550 | 200 | 79 |
| 30 | 16.04 | 550 | 350 | 700 | 140 | 76 |
| 31 | 18.38 | 500 | 500 | 520 | 100 | |
| 32 | dredged | | | 600 | 100 | |
| 33 | 13.37 | 400 | 400 | 500 | 150 | |
| 34 | 54.80 | 900 | 700 | 1200 | 150 | 120 |
| 35 | 24.73 | 600 | 500 | 680 | | |
| 36 | 43.11 | 850 | 600 | 700 | | 101 |
| 37 | 43.78 | 850 | 550 | 700 | | 73 |
| 38 | 13.70 | 350 | 350 | 500 | 150 | |
| 39 | dredged | | | 950 | 400 | |
| 40 | 2.34 | 170 | 170 | 450 | 100 | |
| 41 | 20.72 | 550 | 400 | 450 | 100 | 355 |
| 42 | 19.38 | 600 | 400 | 650 | 50 | |
| 43 | 26.07 | 750 | 400 | 650 | 50 | 77 |
| 44 | 41.78 | 1000 | 500 | 1000 | 500 | 300 |
| 45 | 4.34 | 220 | 220 | 550 | 120 | |
| 46 | 24.40 | 450 | 450 | 550 | 120 | 16 |
| 47 | 34.42 | 500 | 500 | 800 | 120 | 28 |
| 48 | 1.67 | 180 | 180 | | 75 | |
| 49 | 8.09 | 340 | 250 | 700 | 150 | 41 |
| 50 | 46.10 | dredged | | | | 46 |
| 51* | 71.90 | 1400 | 700 | | 450 | 21 |
| 52 | 26.40 | 125 | 125 | 650 | 280 | 50 |
| 53 | 1.67 | 700 | 430 | 650 | 280 | |
| 54* | 92.80 | 1650 | 800 | | 400 | |

Moku o Loe - 385.6 x 10$^4$ sq. ft.

* - composite reefs.

[a] - reefs shown on Fig. 3.

[b] - maximum length perpendicular to the absolute maximum dimension.

[c] - distance from patch reef center to nearest patch reef center.

[d] - distance from patch reef side to nearest reef.

the measurement method. Not until the reefs reach about 200 ft. in diameter is the magnitude of elongation sufficient to be detected with the measurement method used.

The frequency distribution of azimuths of major axes of ovate simple reefs is weakly bimodal (Fig. 6). The patch reefs tend to be elongate in a direction parallel to the prevailing wind. As the smaller reefs are more or less circular in outline, the initial substrate appears to have little or no geometric effect on the shape of the reefs by the time they reach the surface. As the reefs reach the higher energy region near the surface, only lateral expansion is possible. Growth appears to be stimulated on that part of the reef facing into the wind and currents, thus causing elongation. A few reefs have reached large sizes without becoming elongate. This presumably is a function of the local current regime.

Wiens (1962, p. 41) says that, in general, reef rims are wider on the leeward side than on the windward side of atolls, and that therefore, Keunen's (1950, p. 440) statement that reefs tend to grow into the wind is not substantiated. This problem is related to the magnitude of energy incident on the reefs. Figure 7 shows a diagram of possible relations between gross production of the reef complex (amount of $CaCO_3$ produced), net production (amount of $CaCO_3$ retained by the reef complex) (Chave et al., 1970) rate of erosion, and incident energy. The net production is how much the reef complex can grow, both laterally and vertically.

For purposes of illustration, the relation between erosion rate and incident energy is considered to be linear (Fig. 7). Gross production should maximize at some optimum energy level--thus the Gaussian curve. The nature of the intersection of the erosion and the gross production curves determines the relation of net production to incident energy. The situation envisaged for the Kaneohe Bay patch reefs is shown in Figure 7. The windward side of the reef has a higher incident energy, a larger gross production, a higher rate of erosion, and a larger net production than has the leeward side. Therefore, the reef grows into the wind. On atolls, with larger wave energy than is optimum for gross production on the windward reef, it is possible that net production is largest on the leeward side. Also, in spite of Wiens' statement, the width of the reef flat may not be a reasonable indicator of net production of the reef complex because much material may be broken off and dropped down the talus slope and out of sight. Wiens (1962, p. 127) suggests that increased deposition on the leeward reef flat may result in it being wider. Increased deposition on leeward slopes may be a factor in patch-reef elongation.

The frequency distributions of patch-reef major axis length, and of maximum dimension perpendicular to the major axis appear to be combinations of logarithmic distributions (Fig. 8). The bimodality of the distributions is quite marked, suggesting that there are at least two populations of patch reefs in the bay. There is a similogarithmic relation between frequency and area of simple patch-reef top (Fig. 9). In Figure 9 the area is divided into units of $5 \times 10^4$ square ft. There are two sections of linear trends in this data. Best-fit regression lines, using area as the independent variable, are shown on Figures 9a and 9b. On Figure 9b, successive points are joined by straight lines with the same slope as the initial series of data points of Figure 9a. The overall best-fit regression line is, however, somewhat different. The existence of a third population is more strongly suggested on Figure 9b than it is on Figure 9a.

These data are interpreted as indicating that there are three statistical populations of simple patch reefs in Kaneohe Bay. There are two ways to explain the logarithmic nature of the distribution, and two ways to explain the polymodal frequency distribution. In the first instance, all the reefs started to grow at the same time, but growth rate was variable, the size frequency distribution could be logarithmic. If growth rate of each reef was uniform, the distribution would also be logarithmic if, after onset of favorable conditions, the rate of formation of new reefs was logarithmic. Some combination of these two models therefore seems the most reasonable to explain the observed size distribution.

If all the patch reefs started at the same time, but the frequency distribution of growth rate was polymodal, the resultant distribution of patch-reef size would also be polymodal. The larger reefs tend to be clustered near the passages. This may be a reflection of growth rate differences. Another explanation for the polymodal distribution is that there may be three generations of patch reefs. There could have been sporadic occurrences of favorable substrate for patch reefs to start on. It is possible, even with subaerial exposure and death of the reef communities to have the form, if not the magnitude, of previous size frequency distributions present in the size distribution of younger reefs.

During subaerial exposure the patch-reef masses would tend to be eroded, but probably would continue as knolls. With submergence, there would be new, previously unoccupied substrate for a new generation of reefs to start on. As well, reef growth would begin again on the nubs of the relict reefs. This would produce two subpopulations, one whose size frequency distribution was a function of growth from zero size after subaerial exposure, and one whose size frequency distribution was inherited from a previous generation. In this way the size distributions of the previous generations of patch reefs is preserved through successive regenerations of the reef community.

There is little evidence to choose between the various suggestions as to why the site distributions are polymodal. It is known that there have been times when the reef underwent subaerial exposure, so the suggestion that the multimodal distribution is a reflection of generations past is appealing.

On Oahu, there is a -300 ft. and a -180 ft. terrace (Stearns, 1966). A barrier-reef complex in Kaneohe Bay was in existence prior to both these low stands of sea level. The evidence for this is the presence (seen on seismic reflection profiles) of terraces cut into the reef complex about the -300 and -180 ft. levels.

Stearns suggests that the -180 ft. terrace is younger than the -300 ft., but the ages are uncertain. In Kaneohe Bay the -180 ft. terrace is poorly developed and was seen only in the bay, and no evidence of it was found in the cliff above the -300 terrace. This suggests that the -180 ft. terrace is older than the -300 ft. terrace. Therefore, the last two generations of patch reefs could have been produced during the period of transgression that took place after formation of the two terraces. Shepard and Curray (1967) have proposed that sea level stood near -180 ft. at about 12,000 B.P.

Assume that:

(1) For the past 12,000 years the bay has been about 50 feet deep;

(2) the upper 50 feet of the patch reef volume has been a right circular cone with slopes of 25°, and with its apex at the water surface;

(3) the reef volume from -50 to -180 feet has been a cylinder;

(4) $CaCO_3$ production has been confined to the slopes of the cone; and

(5) that the specific gravity of the reef has remained at 1.

With these assumptions, a net $CaCO_3$ production of $(3,300\ g/m^2)/yr$ would have been required to produce the patch reef volume. This is a reasonable rate of net production (Chave et al., 1970).

Presumably conditions began to stabilize in the bay when the rate of eustatic sea-level rise began to decrease about 8,000 B.P. (Shepard and Curray, 1967). It seems unlikely that new reefs would have formed after that time because the lagoon bottom no doubt had rapidly become muddy. It seems most likely therefore that the youngest patch reefs in the bay began to grow in the period between 12,000 and 8,000 B.P.

The frequency distribution of the minimum distance from center to center of simple patch reef is unimodal, with 200-ft. classes (Fig. 10). A chi-square test was used to compare the frequency distribution with a normal curve. The chi square was not significant at the 0.1 percent level. The frequency distribution of both the center to center distances (Fig. 10), and the nearest neighbor distances (Fig. 11) appear to approximate log-normal distributions, but no tests were made.

The distribution of center to center distances is not random (Fig. 10). Rather, there is a preferred, relatively small interdistance. Figure 5 shows that nearest neighbors of elongate simple patch reefs are always at least one minor axis-length away, but often about only one major axis-length distant. Also, the larger the major axis, the farther away is the center of the nearest neighbor.

There appears to be a distinct minimum inter-reef distance less than which patch reefs do not start growing or survive. The nearest neighbor distribution (Fig. 10) suggests that the simple reefs grow until they are some minimum distance apart, i.e., about 100 ft. With a reef foreslope of 25°, and a water depth of 30 ft. around the reef, the toe of the foreslope would extend out about 60 ft. beyond the top of the reef. Thus two patch reefs 120 ft. apart at the surface would touch at the base of the foreslope. When this occurs further growth towards each other may slow. However the compound patch reefs in the bay obviously have grown together, so growth does not stop entirely. A slowing could however produce a modal nearest-neighbor distance of about 100 ft.

It appears that close spacing of patch reefs promotes elongation of the reefs, and formation of deep narrow channels between them. About 70 per cent of the elongate simple reefs are less than 300 ft. from other reefs (Fig. 5). In general, the farther a reef is from another reef, the more circular it is. The reason for this relationship is not known. As discussed before (p. 5), the deep, narrow channels seem to be maintained by increased current velocities in the channels. Why this does not promote reef growth and cause the channel to close is not understood.

Patch reefs are not randomly distributed in Kaneohe Bay, but rather are concentrated in two areas; landward of Kaneohe Passage, and landward of the deeper water area associated with Mokolii Passage (Fig. 1). There are only a few reefs between the two concentrations. Prior to dredging in 1939, there were 21 patch reefs in the lagoon west of Moku o Loe Island. Most of them were in the northern half of the area. Patch-reef distribution in the bay seems to be related to the position of passes through the barrier reef, rather than to basement configuration. Wiens (1962, p. 127) states that patch reefs are commonly very abundant near the lagoon side of passes in atoll rims, and--although the reasons for the distribution are debatable --he suggests increased food availability as a likely cause. The distribution of patch reefs in Kaneohe Bay is analogous to the atoll-pass situation, and is presumably caused by the same factors. These factors are somehow related to the relatively large influx of oceanic water and relatively strong currents associated with the passes.

BARRIER REEF COMPLEX. For purposes of discussion, the barrier-reef complex can be divided into a number of parts; lagoon edge, seaward edge, passes, shallow reef (less than 5 ft. deep), and deep reef (from the 5-ft. isobath to the 60-ft. isobath at the top of the seaward drop-off to 90 ft.) (Fig. 2).

Lagoon edge. Sand occurs on about 50 per cent of the 5.5 miles of the lagoon of the barrier reef complex from Kaneohe passage to Mokolii passage. Along this length there are a number of prominences that appear to be patch reefs which have been partially covered by sand moving off the barrier reef. The slopes of the prominences have the same characteristics as the fringing and patch reef foreslopes. Moberly and Campbell (1969) found that the sand along the lagoon side of the barrier reef is greater than 60 ft. deep in some places, ample for patch-reef burial.

The sand on the barrier-reef backslopes stands at angles up to 29$^{\circ}$ (as determined from fathometer traces) (Table 1). The steep slopes are maintained down to about 35 ft., here the slope decreases to merge with the flat lagoon floor. In only one place was a moat seen at the toe of the backslope. This was seaward of navigational buoy N'12', and presumably was the result of subsidence due to loading of the very compressible lagoon mud by sand that had slumped down onto it. In general, the sand slopes are smooth and planar, although the upper parts tend to be oversteepened. Minor evidence of slump features is seen on the fathometer traces. The steepness of the slopes seems to be variable throughout the year.

Seaward Edge. The seaward edge of the barrier reef is delimited by a cliff which starts about the 60-ft. depth and drops off rapidly to about 90 ft. The face has caves and overhangs. The upper edge of the cliff has indentations, which, from their bathymetric configuration, appear to be erosional channels cut into the reef. At the base of the cliff there is a sand-covered bottom, starting about 90 ft. and sloping seaward at $1^{\circ}26'$. This sand area appears to be the surface of a fan-complex built by sand spilling out of the valleys in the reef front onto a broad shelf that occurs at about -300 ft. This shelf is seen on seismic reflection profiles, and off Mokolii passage it is covered by a sand wedge that thins from about 150 ft. near the cliff to almost nothing about 5,000 ft. seaward.

Passes. At the northwest and southeast ends of the barrier-reef complex passes of relatively deep water (Fig. 2) separate the barrier reef from the fringing reef. (The names of the passes are taken from G. Jackson's 1882 chart). Kaneohe pass, the southeast pass, is shallow, with a sill about 8 ft. deep at the lagoon edge. From the sill the bottom slopes seaward at about $0^{\circ}$ 10'. About 3,500 ft. seaward of the sill the water deepens as the head of a shallow broad valley is encountered. The valley is 500 to 1,000 ft. wide, with water depths of 10 to 15 ft. deep at its head to about 90 ft. where it reaches the seaward cliff line. Its slope is about $0^{\circ}$ 30'. Near the head of the valley is a boat passage that has been dredged through the fringing reef, from the southeast part of the lagoon to Kaneohe pass. The dredged channel is 10 to 15 ft. deep and is floored by sand.

Most of the bottom of Kaneohe pass is covered by sand, but there also are numerous patches of hard bottom made up of encrusting coralline algae and a few corals. The fathometer traces show that some of these areas are asymetric in profile, with the steeper side toward the lagoon. The patches measure up to 200 ft. across and stand two or three feet above the general profile. Just lagoonward of the patches the bottom is one or two feet deeper than the general profile. The seaward side of the patches apparently are being covered by sand.

Reasons for the peculiar configuration are not known, but the geometry suggests that there is a seaward-moving bottom current. The hard patches may block the current and cause the sand to be eroded upstream from the patch, and to be deposited downstream from it, much like snow blowing around a building.

Mokolii pass on the northwest side of the barrier reef has a distinct channel. Much of the present depth of the channel is due to dredging. At the lagoon end of the channel, near buoy N' 6', there is a sill 30 to 35 ft. deep. The floor of the channel is nearly horizontal out to about buoy N' 4', where the slope increases to $0^\circ$ 30'. This slope continues for a distance of about 1,500 ft. to a depth of about 60 ft. The slope then decreases for about 2,500 ft., and the valley floor merges with the fan complex. Prior to the 1939 dredging the channel had much the same general configuration, but it was shallower, and there was a 18-ft.-deep sill at the lagoon end.

Shallow Barrier Reef Complex. On the barrier reef there is an extensive and complex set of environments and bottom types in water less than 5 ft. deep (Fig. 2). An algal ridge, 200 to 300 ft. wide, occurs as an arc, convex seaward, from where the 5-ft. isobath reaches the lagoon edge on the northwest and southeast edges of the barrier reef (Fig. 12). The arc reaches about half-way to Kapapa Island from the lagoon edge. In Figure 12 the lagoon side of the ridge is outlined by light-colored material. A generalized profile is shown on Figure 13.

The algal ridge is in about 1 ft. of water. It is asymmetric, with a steep lagoon side, and a gentle seaward slope. In places there is a vertical drop of 4 or 5 ft. on the lagoon side. The nature of the ridge is variable. From the northwest, where it is really just an area of hard bottom, the ridge attains higher and higher relief as it progresses toward the east. Lagoonward of Kapapa is the maximum relief of about 5 ft. Up to this point, the ridge is mainly composed of encrusting coralline algae, with only minor coral. Coral becomes increasingly abundant toward the southeast end of the algal ridge feature. On the southeast quarter, the ridge is a Porites thicket, at least on the lagoon side.

The general trend of the ridge parallels the impinging wave-fronts. During normal conditions the main surf-break is near the 10-ft. isobath. The waves then refract in arcuate patterns and break again, rather gently, on the ridge, 3,000 to 4,000 ft. inside the main surf-break. Transport of water over the ridge is perpendicular to the main trend of the ridge but parallel to local features such as sand channels and algal buttresses (Fig. 12).

The linear features are very pronounced, particularly on the 'trailing edge' of the algal ridge. In the region 500 to 1,000 ft. landward of the algal ridge, narrow ridges trend more or less perpendicular to the ridge, and trail away from the landward edge. These features are spur-and-groove features of a sort. Apparently they form by growth and coalescence of microatolls and coral heads into solid ridges coated in part by encrusting coralline algae. Localization of growth on the ends and sides of the incipient ridges may have occurred as a result of a lack of suitable substrate elsewhere due to sand movement. Like the spurs described by Shinn (1963), growth occurs on the lee side of established heads, but in this case, the lee side is to the front of the spur. Once the pattern was started, it would be perpetuated by the effects of the topography on the currents.

The microatolls are comprised of circular-to ovate-shaped heads of coral. Many of the microatolls appear to be a single colony of Porites cf. compressa. Others have a dead Porites substrate but the surface is covered with live Montipora. The lateral extent of the microatolls is up to 20 ft., while the height is limited by the depth of the water (Table 3). All rise to within a few inches of lower low water. The microatolls are most abundant near the lagoon side of the algal ridge.

The algal ridge is unlike algal ridges on most reefs in that it is farther from the surf zone, and has a gentle slope in front of it. The ridge may be a relict feature such as a beach or a dune ridge that has since been covered by a thin skin of algae and coral. There are other relict features nearby. Kapapa and Kekepa islands are eroded fossil sand dunes, and dune material has been found in about 30 ft. of water seaward of Kapapa Island. The progressive change in the nature of the ridge from the west to the east, suggests that there is a difference in age along the ridge. The oldest part is in the northwest, is composed entirely of coralline algae, and is nearly covered by sand. The younger eastern part is still partly coral thicket.

Deep Barrier Reef Complex. The area of the barrier reef complex that is deeper than 5 ft. has a bathymetric configuration that appears to be a relict stream-drainage pattern (Fig. 14). Superposed on this pattern are features of more recent origin. There is a pronounced shoal running northwest from Kapapa Island. This shoal is a sand bar formed as a result of longshore drift from the southeast due to the main surf-break at about the 10-ft. isobath.

Another feature is the well defined spur-and-groove structure. In the vicinity of the surf-break these features are often deep narrow cracks, and appear to be the result of mechanical erosion. They are common wherever the energy conditions are high, and are similar in appearance to yardang structure, which is formed by subaerial sand blasting (Thornbury, 1954).

In the area northwest of Kapapa there is a swell-and-swale-like topography. The mounds are 20 to 30 ft. across, more than 100 ft. long, and stand up to 4 ft. above the adjoining swales. The relief decreases inshore and offshore of an area about 1,000 ft. seaward of the surfbreak. The swales have sand and rubble in them, while the swells are covered by live coral about a foot high and by encrusting coralline algae. The change in relief seems to be related to deposition on the swales, although the offshore swells are narrower and show greater evidence of erosion by the large sea urchins that are common in the area. The origin of the features is not known but the fractures seem to be mainly the result of biological erosion, with minor mechanical erosion. Growth of coral and coralline algae on the swells tends to perpetuate the topography, but it appears that erosion is gaining at present.

## Sediments

BARRIER REEF SEDIMENTS. The sediments of the barrier reef are calcareous sands and gravels. Sorting is variable; in general, the coarser the material, the poorer the sorting. The sand in the passes is fine to very fine and well sorted. An average calcite-aragonite ratio in 17 samples of sand from the barrier reef is 1.4, with an average of 13 mole per cent Mg in the calcite.

SUSPENDED MATERIAL. The minerals found in suspension in the bay during a 24 hour sampling period were calcite, aragonite, and quartz. The clay mineralogy was not determined. Peak resolution was poor, but it appears that the calcite-aragonite ratio of the suspended sediment is not less than 1. Figure 15 is a frequency distribution of the 2 Θ values for calcite peaks that rise more than 2 intensity units above the general curve (Cu Kα radiation, 35 Kv, 20 ma, detector 2 - 1,600 v, rate meter -100, time constant - 4, divergence slit -1°, receiving slit - 0.006", antiscatterslit -1°, Norelco type 42273/1). The frequency distribution is distinctly bimodal. The curve tells nothing about the relative amounts of magnesian calcites in suspension, only that calcites with about 19 and about 5 mole per cent Mg frequently occur.

The intensity of background radiation was measured by estimating a best-fit straight line for the background between 26° and 31° 2 Θ. The intensity was then read off the diffractometer trace at 28.5° 2 Θ. The average background intensity and the variance of the intensity for the six stations occupied during the 24-hour study are shown on Figure 16. The relatively high background is attributed to excitation of iron in the samples by the Cu Kα radiation. Much iron oxide and hydroxide is associated with the clays brought to the bay by streams. Thus the pattern of the intensity is interpreted as indicating the distribution of suspended terrigenous load in the water. The average value is highest in the vicinity of Kaneohe stream. This is expected if the stream is the major source of the land-derived material. The variance of the intensity is also highest in the vicinity of Kaneohe stream. This is explainable in terms of the relation between the tide and the stream inflow. In general, the data show that, on a falling tide, the area of highest intensity tends to expand into the bay. On a rising tide the high background area tends to shrink back towards Kaneohe stream. With this kind of action the variance is maximized in the vicinity of the stream, as indicated on Figure 16. The relatively rapid decrease in the background intensity across the southeast part of the lagoon suggests that much of the terrigenous clay-sized material brought into the bay by streams gets deposited in the bay rather than passing over the reef and on out to sea.

LAGOON FLOOR SEDIMENTS. A mixture of sand-sized skeletal grains and indurated fecal pellets, as well as silt and clay-sized calcium carbonate and terrigenous grains make up the sandy mud that covers the lagoon floor. Just behind the barrier reef, and in particular behind those regions where the backslope is sand, the sand fraction of the lagoon sediment is predominently fine to very fine skeletal grains. Elsewhere in the lagoon, the sand fraction is mainly indurated fecal pellets that are up to 0.5 mm in longest dimension.

The lagoon mud is gray (2.5Y5/0 on the Munzell soil color chart) except for the upper tenth of an inch, which is dark reddish brown (2.5YR3/4). The reddish color is about the same as the color of the soil in the Kaneohe drainage basin. The exact thickness of the upper reddish layer is not

Table 3. Relation of microatoll physiography to water depth.

| Depth[a] (ft) | Physiography |
|---|---|
| 1 | No live coral on the rim: top dead, center eroded nearly to level of the surrounding bottom. |
| 2 | Part of the rim is live coral: top dead, center partly eroded. |
| 3 | All of the rim is live coral: top dead, flat, not eroded. |
| 4 | All of the rim is live coral: some live coral on top, top tends to be domal rather than flat, not eroded. |

[a] depth of water on surrounding bottom.

known because of the fluid nature of the sediment-water interface. The sediment is little compacted, and even slight disturbances of the bottom cause immense clouds of suspended mud. The lagoon floor has local irregularities of a few inches in length caused by burrowing organisms. Waterlogged leaves and pieces of wood are not uncommon on the bottom.

Foraminifera tests are common in the sediment but do not make up more than about 1,000 individuals per gram (Resig, 1969). Forty of the largest 10 per cent of the tests in one of the samples were weighed using a Cahn electrobalance. The average weight was 5 μg per specimen. Thus the total of all tests make up a maximum of 0.5 weight per cent sediment, and are only a minor part of the total $CaCO_3$ in the sediment.

The average $CaCO_3$ content, by weight, in 11 lagoon-floor samples is 72 per cent, with a standard deviation of 10 per cent (Table 4). Fan and Burnett (1969) report that the $CaCO_3$ in lagoon sediments near Moku o Loe Island range from 50 to 85 per cent with an average of 65 per cent. J. Southworth (unpublished data) analyzed a core from the same area as that of Fan and Burnett, and found that the $CaCO_3$ content in the upper 30 cm of the core varied between 50 and 85 per cent but that the content in the lower 65 cm was nearly constant at 65 per cent. Both sets of analyses were done with an infrared analyzer. The values are within one standard deviation unit of the average $CaCO_3$ content determined in this study.

The weight per cent of the lagoon-floor sediment that is soluble in 2.3 N hydrochloric acid is considerably larger than the weight per cent $CaCO_3$. The difference is probably due to the presence of acid-soluble iron oxides and hydroxides associated with the terrigenous fraction. In general, weight per cent difference increases with increases in the amount of terrigenous material in the sediment. There may be some error due to passage of colloidal material through the filter paper, but it appears that the lagoon sediments contain about 11 per cent acid-soluble material that is not $CaCO_3$.

Porosity of the lagoon muds ranges from 65 to 88 per cent, with an average porosity of 77 per cent (J. Southworth, unpublished data).

The average mole per cent $MgCO_3$ in the calcite of the lagoon muds is 11 per cent with a range of ± 1 per cent. The per cent $CaCO_3$ that is aragonite is more variable, however; the average being 41 per cent with a standard error of the mean of 2.9 per cent (data in Table 4). Analysis of variance (Table 5) shows that there is no significant difference ($p = .1$) between the sample variance and the subsample variance or between the subsample variance and the replicate analysis variance. The distribution of per cent aragonite values in the lagoon however suggests a gradient. Pairs of samples were compared using F and t ratios (Table 6). The four values (replicate determinations on a slide, and two subsamples from each sample) were used to obtain the mean and variance for each sample. Table 6 shows that the three samples in the southeast part of the lagoon are different from one another and different from all the other samples. Samples 4 through 9 are not different from one another, but are different from all the other samples. Samples 10 and 11 are similar to one another but different from all others.

This pattern indicates a lower production rate of calcitic sediment in the southeast bay than elsewhere in the lagoon. Presumably this reflects a difference in biota. The barrier reef contains much coralline red algae. Erosion of this material could increase the per cent calcite in the lagoon sediments behind the barrier reef.

There are two major sources of sediment for the lagoon floor: the point sources (the streams), and a line source (the barrier reef). The patch reefs and the fringing reef also contribute material, but it is estimated that their contribution is small compared to that of the other two sources. In general, the farther from the barrier reef, the larger is the terrigenous component. Texturally the lagoon sediments are sandy muds to muddy sands. Interpretations of energy conditions on the bottom using the sand to matrix ratio is incorrect for two reasons: (1) much of the sand is comprised of fecal pellets, and is therefore authigenic in origin; and (2) the distribution of skeletal grains is not so much a function of bottom energy as it is of settling velocity. In all cases sediment is introduced to the lagoon at or near the top of the water column, and is deposited on the deep lagoon floor by settling down through the water column. There is no appreciable bottom transport of sand-sized material on the lagoon floor.

## Survey Precision and Accuracy

A major part of this study is the determination of the depth changes of the bay with time. Depth changes were determined by comparing bathymetric maps that were prepared from data collected in 1882, 1927-1933, and 1969. Paramount in all of the analyses is the confidence that can be placed on the final numbers. The determination of depth changes is primarily a statistical analysis. Three pieces of information are needed; the accuracy of the maps being compared, the precision of the surveys, and reliability of the average differences. F and t tests, with a variety of null hypotheses, were used to compare means and variances (methods after Snedecor and Cochran, 1967).

Within the values obtained for precision are the errors due to faulty tide correction, to fluctuations due to sea state, and, most of all, to error in profile location. On the barrier reef the local bottom relief is as much as 2 or 3 ft. Variations as little as 200 ft., due to error in sextant fixes and location plotting, could easily cause depth differences of a few feet at survey-track crossings. Because the accuracy of location decreases seaward, and because bottom relief in the lagoon is much different from that of the barrier reef, the bay was divided into three parts for purposes of survey precision analysis: outer region--seaward of the line between Kekepa and Mokolii; inner region--on the barrier reef inshore of the Kekepa-Mokolii line; and the lagoon.

The precision of both the 1969 and the 1927-1933 surveys was determined by using absolute differences in depth where tracks of a survey cross one another. Means and variances of the deviations were calculated (Table 7). F and t ratios were calculated to test the null hypothesis that there is no difference in the average crossing deviations from one region to

Table 4. Composition of Lagoon Sediments.

| Station | $CaCO_3$[a] (%) | HCl Soluble (%) | Aragonite[b] (%) | $MgCO_3$[c] (%) | % less than 62 μ |
|---|---|---|---|---|---|
| 1 | 55 | 69 | 60 | 11 | 73 |
| 2 | 67 | 80 | 58 | 11 | |
| 3 | 59 | 75 | 50 | 10 | |
| 4 | 68 | 89 | 37 | 11 | |
| 5 | 78 | 81 | 37 | 11 | |
| 6 | 79 | 91 | 37 | 10 | |
| 7 | 84 | 93 | 37 | 11 | |
| 8 | 88 | 95 | 38 | 10 | 46 |
| 9 | 82 | 80 | 38 | 11 | |
| 10 | 66 | 82 | 32 | 11 | 81 |
| 11 | 71 | 82 | 33 | 12 | |

[a] gasometric analysis (% by weight).

[b] x-ray diffraction analysis (% of total calcium carbonate).

[c] mole per cent $MgCO_3$ in the calcite (X-ray analysis).

Table 5. Analysis of variance of the per cent of $CaCO_3$ in the lagoon muds that is aragonite (11 samples, 2 subsamples from each sample, 2 X-ray determinations on each subsample). The F ratios test the null hypotheses that the between sample variance is larger than the between subsample variance, and that the subsample variance is larger than the between determination variance. Neither F ratio is significant at the 10 per cent level.

| Source of Variance | Degrees of Freedom | Sums of Squares | F ratio |
|---|---|---|---|
| Sample | 10 | 958 | 1.03 |
| Subsample | 11 | 1,025 | 0.97 |
| X-ray Slide | 22 | 2,086 | |
| Total | 43 | 4,069 | |

Table 6. F and t ratios to test similarity of per cent aragonite for all combinations of sediment samples from the lagoon (see Table 4 for data). F tests the null hypothesis that one variance is not larger than the other and is rejected at the 2.5 per cent level. The t ratio tests the null hypothesis that the means are the same and is rejected at the 5 per cent level. Blanks in the matrix indicate pairs that have significant ratios. (Where F is significant, t is evaluated using (n-1) degrees of freedom (Snedecor and Cochran, 1967, p. 115).

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | * | * | * | | | * | * | * | * | * |
| 2 | | | * | * | * | * | * | * | * | * | * |
| 3 | | | | * | * | * | * | * | * | * | * |
| 4 | | | | | * | * | * | * | * | * | * |
| 5 | | | | * | | | | | | | |
| 6 | | | | * | * | | * | * | * | * | * |
| 7 | | | | * | * | * | | * | * | * | * |
| 8 | | | | * | * | * | * | | * | * | * |
| 9 | | | | * | * | * | * | * | | * | * |
| 10 | | | | | | | | | | | * |
| 11 | | | | | | | | | | * | |

Samples from the Southeast part of the lagoon

F ratio

t ratio

another in a survey. The same null hypothesis was used to test differences between regions of different surveys (see Table 10).

For both the 1969 and the 1927 surveys, the F ratio for the pairing of the precision data from the outer region with that from the inner region, and that from the lagoon, is significant at the 5 per cent level. As discussed before, this significant difference is probably a function of the inexact location of the survey tracks in the outer region. In both surveys the precision in the inner region is not significantly different from that in the lagoon (see Table 10).

A comparison of the precision in the various regions of the two surveys indicates that the precision in the outer and inner regions in the 1927 survey is not significantly different from the precision in the inner region and the lagoon in the 1969 survey. All other combinations are significantly different at the 5 per cent level. Although, statistically, the 1927 survey is significantly more precise than the 1969 survey, there is little difference in the average crossing differences (Table 7). The 1969 survey average deviation is only 0.5 ft. larger.

The precision of the surveys is such that in the outer region there is a 35 per cent probability that absolute depth differences between surveys of 3.6 ft. are due to survey error. In the inner region, and in the lagoon, depth differences of 2.5 ft. have a 5 per cent probability of being due to survey error. For the lagoon and the inner region, recorded depth differences of 2.5 ft. are considered to be real changes in depth and not artifices.

Eleven hand-line soundings were done in the lagoon to test the accuracy of the 1969 fathometer survey, and also to see if the differences in depth between the 1969 fathometer survey and the 1927 hand-line survey are due to differences in the survey methods (Table 8). A t ratio was calculated to test the null hypothesis that deviations between the 1969 fathometer and hand-line surveys are not significantly different from zero. The t ratio is not significant at the 10 per cent level. A t ratio was also calculated to test whether the 1969 hand-line fathometer survey-depth deviations are different from the 1969-1927 deviations. This t ratio is significant at the 0.1 per cent level. These tests indicate that the two survey methods do not give significantly different depths, and that the depth deviations between the 1969 and the 1927 surveys are not due to problems of relative accuracy. The fact that the depth deviations between the two surveys are significantly different from one part of the bay to another (see Fig. 18 and Table 10) indicates that the differences are not the result of some systematic error.

Lack of coverage in the 1882 survey precludes analysis of precision and relative accuracy. It is assumed because sounding lines were used in the 1882 survey, that the survey's relative accuracy is the same as the 1927 survey. It is also assumed that the precision is no worse than that of the 1969 survey. These assumptions seem to be reasonable, particularly nearshore, in the lagoon.

### <u>Comparison of the 1969-1927 Surveys</u>

Eighteen bathymetric profiles were chosen to determine the depth differences between the 1969 and the 1927-1933 surveys (Figure 18). The depth-deviation statistics are given in Table 9.

Depth-deviation data from the various sample locations are compared with the precision data to determine if the observed depth differences are significantly different from the deviations expected from the survey precision (Table 10). A null hypothesis of no difference was used for all tests. An F ratio was calculated for each pair of samples. The pairs with F ratios that were not significant at the 5 per cent level were assumed to have the same variances. The variances were pooled and t ratios were calculated to test differences between the means.

There are a number of samples from the barrier reef which have average depth differences that are significantly larger than the precision estimates (Table 10). However, only samples from locations 1 and 6 have average deviations significantly different from zero (Table 9). The mean deviation and standard error of the mean are so large at location 1 that there appears to have been a gross error in line location. The area commonly has large swell and it is difficult to see points on shore for reliable sextant fixes. Also, the bottom is quite irregular. These factors could be responsible for the apparent infilling. At location 6 the same conditions occur. Qualitative judgment indicates that there has been no recognizable change in depth at locations 1 and 6 during the period 1927-1969. The t and F tests indicate that the rest of the locations on the barrier reef have had no significant depth changes either.

During the same period however, significant depth decrease occurred in the lagoon. The mean infilling is 5.4 ft. All of the lagoon samples have means that are significantly different from zero (Table 9), and also are significantly different from the values expected from the survey precision estimates (Table 10). Analysis of variance indicates that there is more variation between the sample locations than within the samples (Table 11). There apparently are strong gradients of infilling within the lagoon. However, the pattern of these gradients is not apparent from the data (see Fig. 18). The pattern may be a very complicated one due to the variable nature of the source of the sediment and the distribution patterns.

In general a sample average is somewhat different from the true average of the target population. To arrive at an estimate of probable error in the calculated mean infilling, the average sampled-depth deviation can be expressed in terms of the total population average, and a number of error terms:

$$\bar{X}_T = \mu + e_1 + e_2 + e_3$$

Where $\bar{X}_T$ is the sample average infilling; $\mu$ is the average of the target population; $e_1$ is a term associated with the between sample variance; $e_2$ is a term associated with the within sample variance, and $e_3$ is a term associated with variance from the survey precision. If the terms are independent, the variance of the sample mean is the sum of the variance of the terms on the right side of the equation, the variance of the true mean being zero. The formulas for the calculations are shown in Table 12.

This analysis of error indicates that the average infilling is 5.4 ± 1.6 ft. with 95 per cent confidence (Table 13).

Table 7. Survey precision statistics.

| | Survey 1927-33 | | | | Survey 1969 | | | | Precision[5] |
|---|---|---|---|---|---|---|---|---|---|
| | n[3] | $\bar{X}$[4] (ft) | s (ft) | $s/\sqrt{n}$ (ft) | n | $\bar{X}$[4] (ft) | s (ft) | $s/\sqrt{n}$ (ft) | 1.96s (ft) |
| Outside[1] | 35 | 1.49 | 1.17 | 0.25 | 29 | 3.90 | 3.40 | 0.73 | 4.40 |
| Inside[2] | 60 | 1.03 | 0.80 | 0.13 | 62 | 1.29 | 0.99 | 0.16 | 1.52 |
| Lagoon | 79 | 0.70 | 0.68 | 0.08 | 87 | 1.21 | 0.95 | 0.10 | 1.38 |

[1] area seaward of line between Kekepa and Mokolii islands.

[2] area landward of the Kekepa-Mokolii Island line.

[3] number of crossing in the sample.

[4] mean absolute-depth difference at the crossings.

[5] $s = (s^2_{1969} + s^2_{1927})^{+1/2}$; ±1.96s gives the 95% confidence interval, assuming the mean deviation is zero.

Table 8. Comparison of fathometer data with sounding-line data. The t ratio tests the null hypothesis of no difference between (A-B) and (A-C).

| | | | | | | | | | | | | $\bar{X}$ | s | t |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A[1] | 46 | 46 | 44 | 44 | 43 | 41 | 38 | 41 | 42 | 43 | 45 | | | |
| B[2] | 44 | 46 | 43 | 43 | 41 | 41 | 38 | 42 | 42 | 44 | 46 | | | |
| A-B | 2 | 0 | 1 | 1 | 2 | 0 | 0 | -1 | 0 | -1 | -1 | 0.3 | 1.1 | |
| C[3] | 53 | 52 | 51 | 49 | 47 | 43 | 42 | 45 | 46 | 48 | 50 | | | |
| A-C | -7 | -6 | -7 | -5 | -4 | -4 | -4 | -4 | -4 | -5 | -5 | 5.0 | 1.2 | 7.8 |

[1] A is the depth recorded by the 1969 fathometer survey

[2] B is the depth recorded by 1969 sounding-line survey

[3] C is the depth recorded by 1927 sounding-line survey

Table 9. 1969-1927 and 1927-1882 depth deviation statistics. The t ratio tests the null hypothesis that the average deviation is not different from zero.

| Sample Line | Number of Samples | Average difference (ft) | Standard deviation | Standard error of the mean | t ratio | Significance level (probability) | | |
|---|---|---|---|---|---|---|---|---|
| 1 | 11 | -2.70 | 3.29 | 0.99 | 2.73 | .05 | Reef | 1969-1927 |
| 2 | 11 | -0.45 | 1.51 | 0.45 | 1.00 | .4 | | |
| 3 | 11 | -2.1 | 4.16 | 1.26 | 1.65 | .2 | | |
| 4 | 11 | 0.55 | 1.22 | .37 | 1.51 | .2 | | |
| 5 | 11 | -0.55 | 3.45 | 1.04 | 0.53 | .7 | | |
| 6 | 11 | -1.50 | 1.86 | .56 | 2.67 | .05 | | |
| 7 | 11 | -0.50 | 2.54 | .77 | 0.65 | .6 | | |
| 8 | 11 | -1.10 | 1.97 | .59 | 1.83 | .1 | | |
| 9 | 8 | 0 | 1.51 | .54 | 0 | 1.0 | | |
| 10 | 11 | -0.80 | 2.36 | .71 | 1.13 | .3 | | |
| 11 | 11 | -4.2 | 0.98 | .30 | 14.2 | .001 | Lagoon | |
| 12 | 11 | -6.5 | 0.82 | .25 | 26.3 | .001 | | |
| 13 | 11 | -5.8 | 0.60 | .18 | 31.8 | .001 | | |
| 14 | 11 | -5.0 | 1.20 | .36 | 14.0 | .001 | | |
| 15 | 11 | -6.7 | 1.68 | .51 | 13.2 | .001 | | |
| 16 | 10 | -4.2 | 1.23 | .39 | 10.8 | .001 | | |
| 17 | 11 | -6.5 | 0.82 | .25 | 26.3 | .001 | | |
| 18 | 11 | -5.0 | 0.78 | .24 | 21.3 | .001 | | |
| 1A | 10 | 2.8 | 1.03 | .11 | 8.56 | .001 | Lagoon | 1927-1882 |
| 2A | 10 | 1.4 | 1.26 | .16 | 3.50 | .01 | | |
| 3A | 13 | 3.0 | 0.88 | .06 | 12.3 | .001 | | |
| 4A | 10 | -1.0 | 1.15 | .13 | 2.74 | .05 | | |
| 5A | 12 | -3.5 | 1.88 | .30 | 6.39 | .001 | | |
| 6A | 11 | 2.3 | 1.68 | .26 | 4.55 | .01 | | |
| 7A | 12 | .20 | 0.74 | .12 | 0.58 | .6 | | |
| 8A | 17 | -6.4 | 4.13 | 1.00 | 6.40 | .001 | Reef | |
| 9A | 17 | -2.0 | 1.66 | .16 | 4.65 | .001 | | |
| 10A | 17 | 2.6 | 3.24 | .62 | 3.31 | .01 | | |

Table 10. F and t ratios for all combinations of 1969-1927 average-depth-deviation and survey-precision estimates. F tests the null hypothesis that one variance is larger than another, and t tests the null hypothesis that the average depth deviaitons are not different. F is rejected at the 2.5% level, and t at the 5% level. Rejected ratios are underlined. Location of the depth deviation transects are shown in Figure 18.

| | 1927 | | | 1969 | | | Lines sampled for depth differences | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | O | I | L | O | I | L | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | |
| O | | 2.24 | 2.98 | 8.70 | 1.40 | 1.51 | 7.88 | 1.66 | 1.07 | 10+ | 8.70 | 2.53 | 4.72 | 2.84 | 1.67 | 4.06 | 1.43 | 2.05 | 3.81 | 1.02 | 2.06 | 1.10 | 2.05 | 2.28 | |
| I | | | 1.39 | 10+ | 1.53 | 1.42 | 10+ | 2.52 | 1.62 | 10+ | 10+ | 5.18 | 10+ | 6.08 | 2.53 | 6.15 | 2.17 | 3.10 | 5.77 | 1.55 | 3.12 | 2.36 | 3.10 | 3.45 | |
| L | | 1.57 | | 10+ | 2.13 | 1.99 | 10+ | 4.93 | 3.20 | 10+ | 10+ | 8.67 | 10+ | 9.73 | 4.97 | 10+ | 2.09 | 1.46 | 1.28 | 3.04 | 6.14 | 3.78 | 1.46 | 1.31 | |
| O | | | | | 10+ | 10+ | 1.10 | 5.26 | 8.14 | 1.45 | 1.00 | 3.44 | 1.84 | 3.07 | 5.22 | 2.14 | 10+ | 10+ | 10+ | 8.53 | 4.24 | 7.90 | 10+ | 10+ | Precision estimates |
| I | 0.49 | 0.90 | | | | 1.08 | 10+ | 2.31 | 1.50 | 10+ | 10+ | 3.54 | 6.60 | 3.96 | 2.34 | 5.68 | 1.02 | 1.40 | 2.72 | 1.43 | 2.96 | 1.54 | 1.48 | 1.63 | |
| L | 0.33 | 0.78 | | | 0.31 | | 10+ | 1.56 | 1.00 | 1.19 | 8.15 | 3.81 | 7.11 | 4.27 | 1.57 | 3.81 | 1.52 | 2.18 | 4.06 | 1.04 | 1.93 | 1.65 | 2.18 | 2.44 | |
| 1 | | | | 0 | | | | 4.75 | 7.35 | 1.60 | 1.10 | 3.11 | 1.67 | 2.78 | 4.72 | 1.94 | 10+ | 10+ | 10+ | 7.71 | 3.83 | 7.15 | 10+ | 10+ | |
| 2 | 0.70 | | | | | 0.60 | | | 7.62 | 1.54 | 5.24 | 1.53 | 2.85 | 1.71 | 1.01 | 2.45 | 2.36 | 3.39 | 6.31 | 1.62 | 1.24 | 1.50 | 3.39 | 3.78 | |
| 3 | 0.74 | 1.13 | | | 0.92 | 0.88 | | | | 10+ | 8.10 | 2.37 | 4.40 | 2.65 | 1.56 | 3.78 | 1.53 | 2.23 | 4.09 | 1.05 | 1.92 | 1.03 | 2.19 | 2.45 | |
| 4 | | | | 2.55 | | 0.50 | 0.54 | 3.27 | | | 1.45 | 4.99 | 2.67 | 4.45 | 7.56 | 3.11 | 10+ | 10+ | 10+ | 10+ | 6.13 | 10+ | 10+ | 10+ | |
| 5 | | | | 0.45 | | | 1.50 | | | 2.61 | | 3.43 | 1.84 | 3.06 | 5.20 | 2.14 | 10+ | 10+ | 10+ | 8.50 | 4.22 | 7.98 | 10+ | 10+ | Reef |
| 6 | | | | | | | 0.96 | 1.05 | 2.14 | | 0.75 | | 1.86 | 1.12 | 1.52 | 1.60 | 3.61 | 5.18 | 9.64 | 2.48 | 1.23 | 2.30 | 5.18 | 5.78 | |
| 7 | | | | 1.23 | | | 1.89 | 0.36 | | 1.82 | 0.04 | 0.87 | | 1.66 | 2.83 | 1.16 | 6.74 | 9.66 | 10+ | 4.62 | 2.29 | 4.28 | 9.66 | 10+ | |
| 8 | | | | | | | 0.49 | 0.62 | 1.66 | | 0.45 | 0.39 | 0.50 | | 1.70 | 1.43 | 4.05 | 5.81 | 10+ | 2.78 | 1.38 | 2.58 | 5.81 | 6.48 | Barrier |
| 9 | 0.24 | | | | | 0.09 | 2.18 | 0.64 | 0.85 | | | 1.43 | 0.44 | 1.50 | | 2.43 | 2.38 | 3.47 | 6.35 | 1.64 | 1.23 | 1.51 | 3.47 | 3.82 | |
| 10 | | | | 1.38 | | | 1.45 | 0.41 | | 2.76 | 0.20 | 0.62 | 0.25 | 0.41 | 0.89 | | 5.80 | 8.31 | 10+ | 3.98 | 1.97 | 3.68 | 8.31 | 9.28 | |
| 11 | 4.93 | | | | 6.32 | 6.31 | | 6.94 | 10+ | | | 2.90 | | | 6.87 | | | 1.43 | 2.67 | 1.46 | 2.94 | 1.57 | 1.43 | 1.60 | |
| 12 | 10.0 | | 10+ | | 10+ | 10+ | | 10+ | 10+ | | | | | | 10+ | | 5.96 | | 1.86 | 2.09 | 4.21 | 2.25 | 1.00 | 1.12 | |
| 13 | | | 10+ | | | | | | | | | | | | | | 4.61 | 1.07 | | 3.89 | 7.83 | 1.07 | 1.86 | 1.67 | |
| 14 | 3.74 | 8.10 | | | 7.13 | 10+ | | 7.98 | 10+ | | | 3.83 | | 5.63 | 7.78 | | 1.73 | 1.93 | | | 2.01 | 1.86 | 2.09 | 2.33 | |
| 15 | 5.75 | | | | | 8.10 | | 9.19 | 8.20 | | | 7.49 | 6.51 | 7.20 | 9.10 | 6.72 | 4.27 | | | 2.47 | | 2.25 | 2.52 | 4.70 | Lagoon |
| 16 | 5.89 | | | | 6.77 | 6.92 | | 5.40 | 6.60 | | | 2.78 | | 3.15 | 4.38 | | 0 | 2.84 | 1.97 | 1 | 2.60 | | 4.42 | 4.93 | |
| 17 | 5.69 | | 10+ | | 10+ | 10+ | | 10+ | 10+ | | | | | | | | 5.97 | 0 | 2.28 | 3.46 | 0.23 | | | 1.12 | |
| 18 | 3.99 | | 10+ | | 9.28 | 9.30 | | | 10+ | | | | | | | | 2.35 | 0.44 | 2.69 | 0 | | | 4.40 | | |

t ratios

F ratios

Table 11. Analysis of variance of lagoon depth changes for the periods 1969-1927 and 1927-1882.

| Source of Variation | Sum of Squares | Degrees of freedom | Mean Square |
|---|---|---|---|
| (1969-1927) | | | |
| Between Sample lines | 78 | 7 | 11.10 |
| Within Sample lines | 90 | 79 | 1.14 |
| Total | 168 | 86 | 1.95 |
| | | | |
| (1927-1882) | | | |
| Between Sample lines | 389 | 6 | 64.80 |
| Within Sample lines | 129 | 71 | 1.82 |
| Total | 518 | 77 | 6.72 |

Bosch (1967) collected sediment deposited over a 19-week period on the reef slopes at three locations in the bay. Two collections (0.6 and 0.5 cm of sediment) were made on the sides of patch reefs near the back of the barrier reef in the vicinity of buoy N 18 (see Fig. 1). The other collection (18.5 cm of sediment) was made on the forereef slope of the fringing reef in front of Kahaluu stream. These values add up to 2.2 and 1.9 ft/42 years for the patch reef collections, and 70 ft/42 years for the fringing reef collection. No particulars of the sampling devices were given, but most methods used for collecting settled material contain many sources of error. The inshore water in front of Kahaluu stream is generally very muddy.

Presumably the collecting device collected more than is normally deposited on the bottom. The other two values are more reasonable in view of the bathymetric data but their reliability is unknown.

Since 1927, 140 x $10^6$ cubic ft. of material has been dredged in Kaneohe Bay (data from U.S. Army Corp of Engineers dredging permits). Of this volume, 1.42 x $10^6$ cubic ft. was permitted to be dumped onto the lagoon floor. The rest was to be used as land fill, or disposed of at sea. The major dredging operation in the bay was done in 1939 when 133 x $10^6$ cubic ft. was dredged by the U.S. Navy. A ship channel was dredged through Mokolii passage to the southeast end of the bay. Also at this time, extensive dredging was done to construct a seaplane landing area in the southeast end of the bay. All of the dredged material from both jobs was to have been used either as land fill, or as fill beyond the 100-fathom isobath.

Spreading all the dredged material evenly on the lagoon floor would be sufficient to fill the lagoon by only 0.8 ft. Since most of the dredged material was removed from the bay, the actual infilling from dredge material is assumed to be 0.2 ft. (25% of the maximum). (These calculations assume initial and final porosities to be the same.) Most of the dredging has been done in the vicinity of the southeast end of the bay. The area of the lagoon southeast of Moku o Loe is about 90 x $10^6$ square ft. Repeating the calculations for the southeastern area, all the dredged material would cause an infilling of 1.5 ft., and 25 per cent would infill 0.4 ft. Dredging therefore can be discounted as a significant contributor to the average lagoon-floor fill discussed in this report. However, deposition of material on the lagoon floor as a result of dredging does have serious effects on local bathymetry, and on the nature of the change in bathymetric configuration through time (see p. 22).

Dredging permits back to 1921 were examined. According to the permits, only one was issued prior to 1967 that allowed dumping of dredged material into the bay. This permit was for 1,200 cubic ft. in 1938. Since 1967, however, there have been 11 permits issued, allowing 1.5 x $10^5$ cubic ft. of material to be dumped into the lagoon, generally in 30 to 40 ft. of water, a few hundred feet off the front of the fringing reef. If this practice continues, it could, at least in local areas, cause significant depth changes.

## Comparison of 1927-1882 Surveys

The 1927-1882 surveys were compared in the same manner as the 1969-1927 surveys. Location of the sampling sites are shown on Figure 19 and the depth deviation statistics are given in Table 9). Because of the scarcity of 1882 data, the precision estimates were not done, and the 1969-1927 estimates were used. F and t ratios were calculated and tested in the same manner, and at the same levels as in the 1969-1927 comparison (Table 14).

Of the 10 location points only one (7A) has a mean deviation not significantly different from zero (see Table 9). For the others, the null hypothesis that the mean deviation is not different than zero is rejected at the 5 per cent level. The null hypothesis that the mean is not different from the 1927 lagoon precision estimate is rejected at the 5 per cent level for all locations. This is also true for all but three (2A, 4A, 7A) samples when compared to the 1969 lagoon precision estimate (Table 14). Therefore four locations (1A, 3A, 5A, and 6A) have mean deviations that are significant when tested against the individual sources of variance.

However, when all sources of variability are considered together, and the reliability of the grand mean is calculated, it is found that the average infilling of the lagoon during the period 1882 to 1927 was -0.74 ± 1.0 ft. with 65 per cent confidence. This means that there is a 0.23 probability that the true mean is zero or larger. There was no significant change in depth of the lagoon between 1882 and 1927.

## Basement Configuration

The seismic reflection data have been only superficially analyzed. It appears that seaward of the dropoff in depth from 60 to 90 ft. in front of the barrier reef, there is a terrace at about the -300 ft. elevation. The terrace is covered by a wedge of sand that is about 200 ft. thick at the base of the dropoff, thinning almost to zero about 5,000 ft. seaward. The sand wedge appears to have been formed by coalescence of fans originating in valleys like those at Kaneohe and Mokolii passages. These passages appear, from the reflection profiles, to lie over deep infilled valleys. The valley floors are at about -300 ft. at the seaward end. The valleys were cut down through the reef complex, or the reef grew up around them, or, more likely, a little of both occurred. The valleys have been filled with sand to their present depth.

The basalt basement in the bay has an irregular configuration but is generally between -100 and -300 ft. There appears to have been a river valley heading in the present Heeia stream valley, a drainage divide running out toward Kapapa Island, and another stream system draining into the valley under Mokolii passage. The system had tributaries in the valleys of Kahaluu and Waiahole streams. A cursory examination of the seismic reflection data suggests that the configuration of the basaltic basement under Kaneohe Bay is not much different from that presently seen in the subaerial drainage basin of the bay. A 300-ft. rise in sea level would produce a bottom configuration similar to that of the basement under the reef complex.

Table 12. Equations concerning reliability of calculated average lagoon infilling.

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$a_{i,j}$ = $j^{th}$ value of $i^{th}$ sample 1969 survey

$s_{ai}$ = expected standard deviation resulting from precision estimates

$b_{i,j}$ = corresponds to $a_{i,j}$ but 1927 survey

$s_{bi}$ = expected standard deviation resulting from precision estimates

$\bar{X}_i$ = mean of $i^{th}$ sample

$s_i$ = standard deviation of $i^{th}$ sample

$\bar{X}_T$ = average of the sample means

$s_T$ = standard deviation associated with $\bar{X}_T$

$n$ = number of samples

$m$ = sample size

$\bar{X}_T = \sum_{i=1}^{n} (\bar{X}_i/n) = \left| \sum_{i=1}^{n} \sum_{j=1}^{n} (a_{i,j} - b_{i,j})/m \right| /n$

$\partial\bar{X}_T/\partial\bar{X}_i = 1/n;\ \partial\bar{X}_T/\partial a_{i,j} = \partial\bar{X}_T/\partial b_{i,j} = 1/mn$

$s_{e_1} = (s_T^2/n)^{1/2}$: standard error associated with between sample variance

$s_{e_2} = (\sum_{i=1}^{n} (\partial\bar{X}_T/\partial\bar{X}_i)s_i^2)^{1/2}$: standard error associated with within sample variance

$s_{e_3} = (\sum_{i=1}^{n} \sum_{j=1}^{m} (\partial\bar{X}_T/\partial a_{i,j}\ s_{ai}^2 + \sum_{i=1}^{n} \sum_{j=1}^{m} (\partial\bar{X}_T/\partial b_{i,j})s_{bi}^2\ )^{1/2}$ : standard error associated with survey precision.

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## Sedimentation

Two major changes in the bathymetry of the bay occurred during the period 1927-1969. One, as a result of the dredging of the ship channel, was a decrease in the area of patch reefs in the bay by about 15 per cent, and a deepening of the sill depth of the lagoon from about 20 ft. to about 35 ft. (Fig. 20). In addition, the dredging also straightened the deep outflow-channel. The consequence of this change in terms of water circulation is not known. It is possible that more water now flows in through Kaneohe passage and out through Mokolii passage than was formerly the case. This increase in inflow could have two effects: one, an increase in the amount of material being transported off the reef flats in the vicinity of Mokolii Island and out onto the -300 ft. terrace; and two, an increase in the amount of material moving into the lagoon through Kaneohe passage. The increase in the amount of material moving through Kaneohe passage could cause the passage to fill, and increase the amount of $CaCO_3$ deposited in the lagoon.

Infilling of the passage is probably not a major problem because incident wave energy on the bottom of the passage would prevent any great deposition of sand. However, as will be discussed later, there is a serious problem concerning apparent increase in depositional rates of fine-grained sand and silt in the lagoon during the past 42 years. An increase in the influx of $CaCO_3$ through Kaneohe passage could help explain this.

The second change in bathymetry is a shoaling of the lagoon by about 5.4 ft. that has taken place in the 42-year period from 1927 to 1969. The sediment filling the lagoon is about 72 per cent $CaCO_3$, most of which must be reef-derived. The other 28 per cent is land-derived material brought into the bay by streams. These values reduce to 3.9 ft. of calcium carbonate sediment and 1.5 ft. of terrigenous sediment deposited in 42 years.

There was no apparent infilling of the lagoon during the period 1882 to 1927 (45 years). A clayey sediment layer with 80 percent initial porosity is expected to compact by about 40 percent of its original thickness on burial to 6 ft. (Weller, 1959). However, as the infilling comparisons were made over comparable time intervals, 1969 to 1927 and 1927 to 1882, both intervals should show the same range of compaction if depositional rates had been the same in the two periods. It is obvious therefore that the rate of deposition both of $CaCO_3$ and of terrigenous material has increased since 1927.

The increase in terrigenous material can be explained by increased runoff and increased suspended-load brought to the bay by streams. The urban area in the Kaneohe basin doubled between 1946 and 1962 (Vargha, 1962). This large increase no doubt resulted in increased runoff. The increase has in part been alleviated by the tapping of streams in the northern part of the basin for water supply use. However, Kaneohe stream, one of the major streams in the basin, has not been tapped.

Using values of average $CaCO_3$ content and of average sediment porosity, the calculated minimum deposition rate of terrigenous material on the lagoon floor is $1.31 \times 10^5$ T/yr. On February 1, 1969, a large flood occurred and Kaneohe stream was monitored by Fan and Burnett (1969) who estimated that $0.385 \times 10^5$ T/day of silt- and clay-sized material were carried into the bay during the flood period. Using the average figures, only three such days are required per year to deposit the sediment required by the infilling estimates (Tables 15, 16, and 17).

A flood as large as the February 1969 flood may occur only once every decade. (The 1956 Keaahala flood may have been comparable). However, smaller floods are more frequent. For Kamooalii stream the records between July 1966 and June 1967 show 13 days which the discharge was more than six times the average. There was one day in which the discharge was 8.5 times the average discharge; this discharge was 65 per cent of the total discharge during the February 1969 flood. (Lee and Ewat, 1970). These values suggest that a 13-fold increase of discharge would give results like those of the February 1969 flood. Because the relations between rainfall, runoff, discharge, and suspended load are complex and not linear, suggestions based on linear relations are likely to be in error. But these suggestions should at least indicate the magnitude of the relations. The number of days of 3- and 6-times-average-discharge suggest that the expected discharge of sediment into the bay by streams is about that required by the infill estimates.

The increase in the $CaCO_3$ input is not so easy to explain. Possibly there has been an increase in suspended $CaCO_3$ brought down the coast by longshore drift and into the lagoon through Kaneohe passage by tidal currents. It is also possible that with an increased flow in through the passage (as discussed above), material from the barrier reef that previously went out to sea is now transported into the lagoon. A third possibility is that there may have been a general increase in the suspended load coming off the reefs as a result of an increase in the rate of erosion of the reefs. There appears to have been a change in the reef community in recent years. This change may have resulted in a change of erosion rate as the composition of the community changed.

The mechanical energy incident on the reef has the capacity to do a certain amount of work. Some of the energy is expended on the live organisms on the bottom. The effectiveness of this process in producing sediment is variable, depending on the durability of the calcareous organisms. Some energy is expended by shifting sediment and grinding it up. Some energy is used to erode the bottom. The relative effectiveness of the energy in the three categories is a function of the nature and amount of the material available for the energy expenditure. Because the total amount of energy is more or less constant, any energy not used by one category gets used elsewhere, and changes in some aspect of the system can drastically affect other parts of the system.

### Projected Depositional Rates

The frequency distribution of lagoon floor depths in 1969 and in 1927 are shown on Figure 21. (Hypsographic data are given in Table 18.) The distributions are bimodal, and the 1969 distribution shows a distinct shift of the modes toward shallower depths relative to the positions of the 1927 modes. The hypsographic curves for the lagoon floor in 1969 and 1927 are shown in Figure 22. They indicate a discontinuity in the amount of fill at about -30 ft. More material was deposited on the 1927 surface above and below -30 ft. than was deposited at -30 ft. The large amount of fill in depths shallower than 30 ft. is probably a combination of delta-building by streams, and dumping of dredged material just offshore of the fringing

Table 13. Reliability of average lagoon infilling estimates.

| | 1969-1927 | df[d] | 1927-1882 | df |
|---|---|---|---|---|
| Average infilling (ft) | 5.4 | | -0.74 | |
| $s_{e_1}^{a}$ (ft) | 0.37 | 7 | 0.90 | 6 |
| $s_{e_2}$ (ft) | 0.13 | 75 | 0.13 | 70 |
| $s_{e_3}$ (ft) | 0.12 | 150 | 0.51 | 140 |
| $s_T^{b}$ (ft) | 0.81 | 231 | 1.00 | 215 |
| $t^{c}$ ratio | 1.96 | | 1.96 | |
| reliability of the mean with 95% confidence (ft) | ±1.5 | | ±2.0 | |

[a] See Table 10 for explanation of $s_{e_1}^{a}$, $s_{e_2}$, and $s_{e_3}$.

[b] ($s_T^2 = s_{e_1}^2 + s_{e_2}^2 + s_{e_3}^2$), $s_T$ is the standard error of the estimate of the mean.

[c] t ratio, 95% confidence (ft).

[d] degrees of freedom.

Table 14. F and t ratios for all combinations of 1927-1882 average-depth-deviations and survey-precision estimates. F tests the null hypothesis that one variance is larger than another, and t tests the null hypothesis that the average depth deviations are not different. F is rejected at the 2.5% level, and t at the 5% level. Rejected ratios are underlined. Location of the depth-deviation transects are shown in Figure 19.

| | 1927 | | | 1969 | | | Lines Sampled for depth changes (1927-1882) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | O | I | L | O | I | L | 1A | 2A | 3A | 4A | 5A | 6A | 7A | 8A | 9A | 10A |
| O | | | | | | | .013 | 1.17 | 1.78 | 1.03 | 2.06 | 2.59 | 1.04 | 10+ | 2.01 | 7.66 |
| I | | | | | | | 1.67 | 2.50 | 1.20 | 2.08 | 4.41 | 5.55 | 2.23 | 10+ | 4.30 | 10+ |
| L | | | | | | | 2.33 | 3.48 | 1.67 | 2.89 | 6.13 | 7.72 | 3.11 | 10+ | 5.98 | 10+ |
| O | | | | | | | 10+ | 7.46 | 10+ | 8.97 | 4.23 | 3.36 | 8.34 | 1.42 | 4.34 | 1.14 |
| I | | | | | | | 1.09 | 1.63 | 1.27 | 1.36 | 2.88 | 3.62 | 1.45 | 10+ | 2.81 | 10+ |
| L | | | | | | | 1.17 | 1.76 | 1.18 | 1.46 | 3.10 | 3.90 | 1.57 | 10+ | 3.02 | 10+ |
| 1A | 3.17 | 5.14 | | | 10+ | 4.12 | | 1.50 | 1.39 | 1.24 | 2.64 | 3.32 | 1.34 | 10+ | 2.57 | 9.81 |
| 2A | 0.21 | | | | 0.70 | 0.49 | 2.31 | | 2.08 | 1.20 | 1.76 | 2.22 | 1.12 | 10+ | 1.72 | 6.56 |
| 3A | 4.28 | 7.14 | 9.20 | | 5.86 | 6.40 | 0.49 | 0.85 | | 1.73 | 3.66 | 4.61 | 1.86 | 10+ | 3.57 | 10+ |
| 4A | 0.68 | 0.51 | | | 0.25 | 0.53 | 3.27 | 0.74 | 1.82 | | 2.12 | 2.67 | 1.08 | 10+ | 2.07 | 7.89 |
| 5A | 1.40 | | | | | | 0.80 | 1.08 | | 1.77 | | 1.26 | 1.97 | 6.03 | 1.03 | 3.72 |
| 6A | | | | | | | | 2.79 | | 3.48 | 1.60 | | 2.48 | 4.79 | 1.29 | 2.96 |
| 7A | 1.14 | | | | 0.79 | 1.11 | 3.75 | 1.13 | 4.76 | 0.40 | 2.13 | 3.45 | | 10+ | 1.92 | 7.34 |
| 8A | | | | | | | | | | | | | | | 6.18 | 1.62 |
| 9A | 1.04 | | | | | | 1.54 | 0.70 | | 1.48 | 0.46 | 2.21 | 1.89 | | | 3.82 |
| 10A | | | | 0.36 | | | | | | | | | | 3.38 | | |

t Ratios

F Ratios

Lagoon

Reef

Table 15. Tabulation of data pertinent to infilling of the lagoon.

| | |
|---|---|
| Lagoon area | 209.43 x $10^6$ square feet |
| Area of patch reefs | 21.72 x $10^6$ square feet |
| Area of lagoon floor | 187.71 x $10^6$ square feet |
| Average infilling 1927-69 | 5.4 feet |
| Minimum infilling $\overline{X}$-2s | 3.8 feet |
| Average porosity | 77 per cent |
| Porosity range | 65-88 per cent |
| Average $CaCO_3$ content | 72 per cent |
| Range of $CaCO_3$ content | 55-88 per cent |

Table 16. Weight of terrigenous material deposited on the lagoon floor |(Tons/year) x $10^{-5}$| for various values of $CaCO_3$ content and sediment porosity. The underlined value is for average porosity and average $CaCO_3$ content. The specific gravity of the sedimentary grain is considered to be 2.7.

| | % of $CaCO_3$ | | |
|---|---|---|---|
| % porosity | 55 | 72 | 88 |
| 55 | 4.11 | 2.56 | 1.10 |
| 77 | 2.10 | 1.31 | 0.56 |
| 88 | 1.10 | 0.68 | 0.29 |

Table 17. The number of days of flood like the February 1, 1969 flood which would be required to meet the infilling between 1927-69. The number of days are given for various values of $CaCO_3$ content and sediment porosity. The underlined value is for the average porosity and average $CaCO_3$ content.

| | % of $CaCO_3$ | | |
|---|---|---|---|
| % porosity | 55 | 72 | 88 |
| 55 | 11 | 7 | 3 |
| 77 | 6 | 3 | 2 |
| 88 | 3 | 2 | 1 |

Table 18. Hypsographic data from lagoon surveys in 1927 and 1969 (areas obtained by planimeter).

| | Area (sq. ft. x $10^{-6}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1927 | | | | 1969 | | | |
| depth (ft) | Total Area[a] | Patch Reef[b] | Lagoon Floor | % deeper than | Total Area[a] | Patch Reef[b] | Lagoon Floor | % deeper than |
| > 5 | 217.80 | 14.96 | 202.84 | 100 | 239.82 | 10.46 | 229.36 | 100 |
| >20 | 191.09 | 13.68 | 177.41 | 93 | 193.21 | 10.38 | 182.83 | 80 |
| >30 | 171.64 | 12.71 | 158.93 | 73 | 170.65 | 6.86 | 163.79 | 71 |
| >35 | 156.92 | 10.34 | 146.58 | 67 | 129.51 | 6.64 | 122.87 | 54 |
| >40 | 128.36 | 6.75 | 121.61 | 56 | 88.83 | 1.67 | 87.16 | 38 |
| >45 | 85.18 | 0.27 | 84.91 | 39 | 11.15 | 0 | 11.15 | 5 |
| >50 | 19.97 | 0.07 | 19.90 | 9 | 1.03 | 0 | 1.03 | 0.5 |
| >55 | 2.74 | 0 | 2.74 | 1 | | | | |
| >60 | 0.41 | 0 | 0.41 | 0.2 | | | | |
| average depth[c] | | | 38.3 | | | | 32.9 | |

[a] area of lagoon inside respective isobaths.

[b] area of patch reefs included in the total area.

[c] used per cent area for weighting.

reefs. The part of the curves below -30 ft. represents lagoon infilling away from the immediate shoreline effects.

Figure 22b shows that the magnitude of lagoon infilling is not the same for all depths. Below -30 ft. the plot of infill versus depth is nearly linear. Curve 1 on Figure 22b is a best-fit regression line (Infilling = 0.24 x (1927 depth) - 5.2). Curve 2 represent infilling if the mechanism of deposition was just settling of material out of a uniformly mixed water column. If the percent $CaCO_3$ in the sediment is subtracted from curve 1, the resultant curve has a slope nearly the same as that of curve 2. The similarity in slope suggests that the terrigenous component of the lagoon muds is deposited by settling out of a uniformly mixed suspension, and that the depositional rate of terrigenous material on the deeper parts of the lagoon floor is primarily a function of the water depth.

The deposition of $CaCO_3$ has the same relation to water depth as does the deposition of the terrigenous fraction. However, the pattern of $CaCO_3$ deposition is much more complex since the fringing reef, the patch reefs, and the barrier reef all produce sediment. Sedimentation in the lagoon results from two or three major point sources of terrigenous material (the streams); and two line sources, of $CaCO_3$ (the fringing and barrier reefs) as well as numerous $CaCO_3$ point sources (the patch reefs). Of all the sources of $CaCO_3$ sediment, the barrier reef appears to be quantitatively the most important; at least gradients related to it are more apparent.

If the bay continues to fill at the same mean rate as it did between 1927 and 1969, the change in the hypsographic curve with time is shown on Figure 22c. The amount of fill per 50-yr. period, at depths of 5, 10, 20, 30, 40, and 50 ft., was determined using Figure 22a. These rates were then used to project the 1969 hypsographic curve through time. The depths were decreased by an amount appropriate for the depth on the previous curve.

It seems reasonable to expect that the projected configuration will hold until the maximum depth in the bay equals that of the sill depth (30 to 35 ft). This is projected as occurring in the year 2100; at that time, sedimentation of fine material in the lagoon will probably change. There will be no closed basin below the sill depth for fine material to settle into. Presumably more material will be transported over the sill, and the bay may then fill more slowly. However, at that time 50 per cent of the present lagoon area will be 10 ft. deep or less; seventy per cent will be 20 ft. deep or less. There will be a great deal more suspended material in the water than there is at present. All the environments in the bay will likely be completely different from what they are now.

This model of filling rate is based on the assumption that accelerated deposition began in 1927. If the accelerated deposition began during the increased urbanization around 1947, then the projected rates of infilling may be conservative by a factor of 2.

## ACKNOWLEDGMENTS

J. Gordon, D. Lum, J. Maragos, and M. Valencia aided in collection and reduction of the bathymetric data. J. Gordon was instrumental in obtaining the old charts and provided valuable service by researching previous work in the bay. A. Malahoff supervised the seismic reflection survey. Data reduction was done at the Hawaii Institute of Geophysics. The Hawaii Institute of Marine Biology provided boats and space for the project. L. Zukeran provided valuable assistance by taking the R/V SALPA into very unlikely areas, thus considerably increasing the scope of the seismic survey.

K. E. Chave is principal investigator on the Coral Reef project (Sea Grant GH-28), and initiated the study. S. V. Smith aided in all phases of the preparation of this report.

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**Figures 1 through 22**

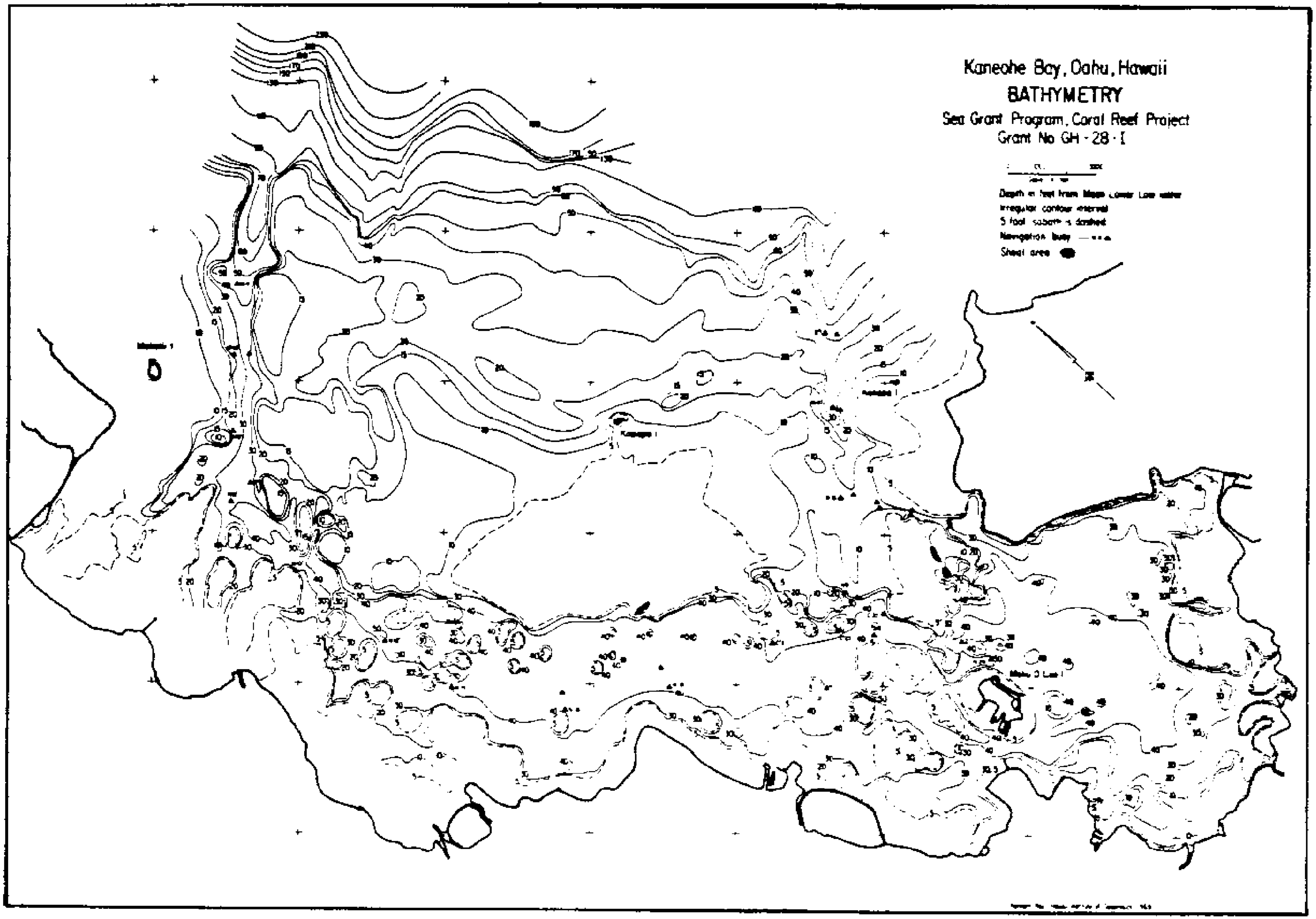

Fig. 1. Bathymetric map of Kaneohe Bay.

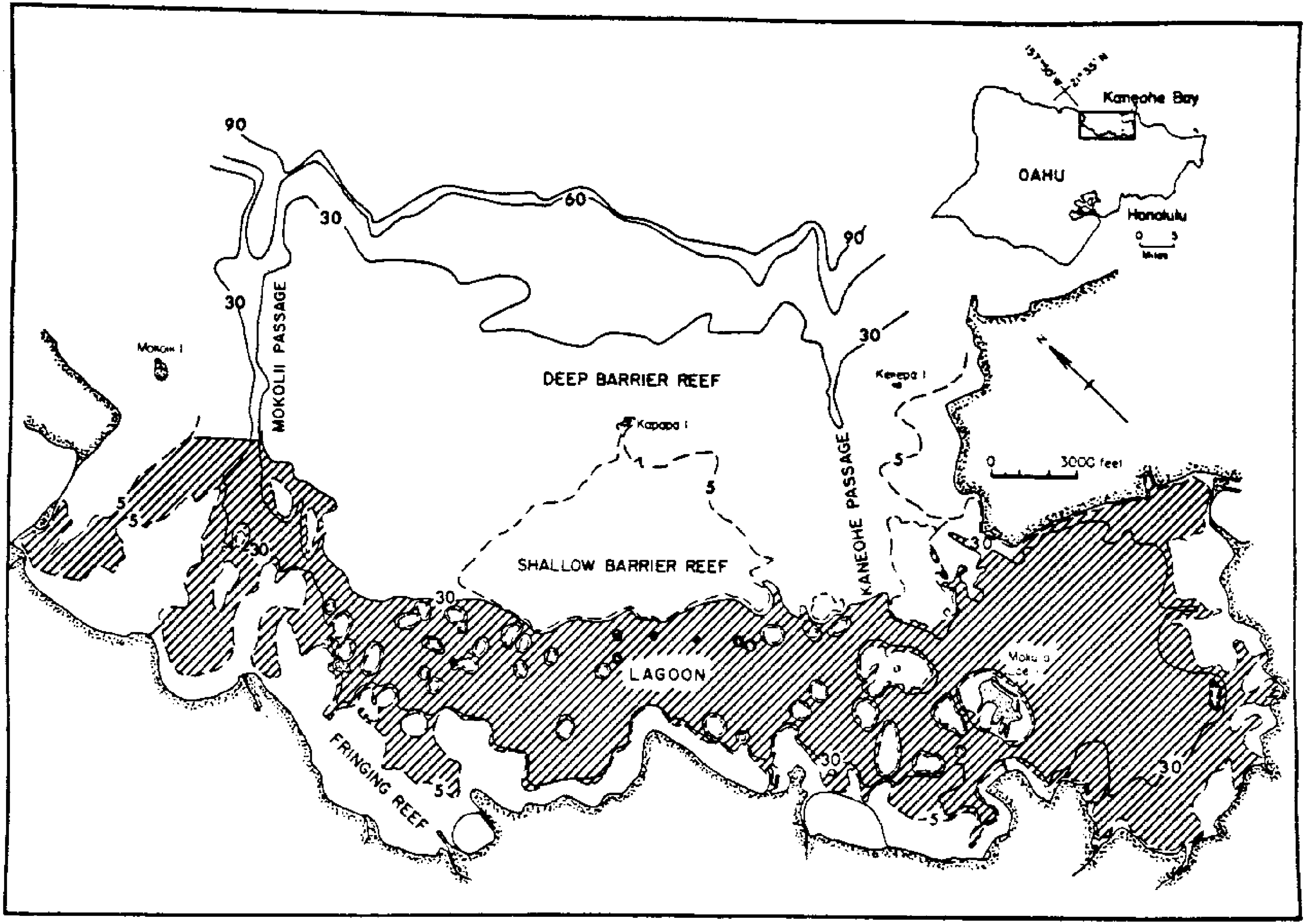

Fig. 2. Physiographic provinces in Kaneohe Bay.

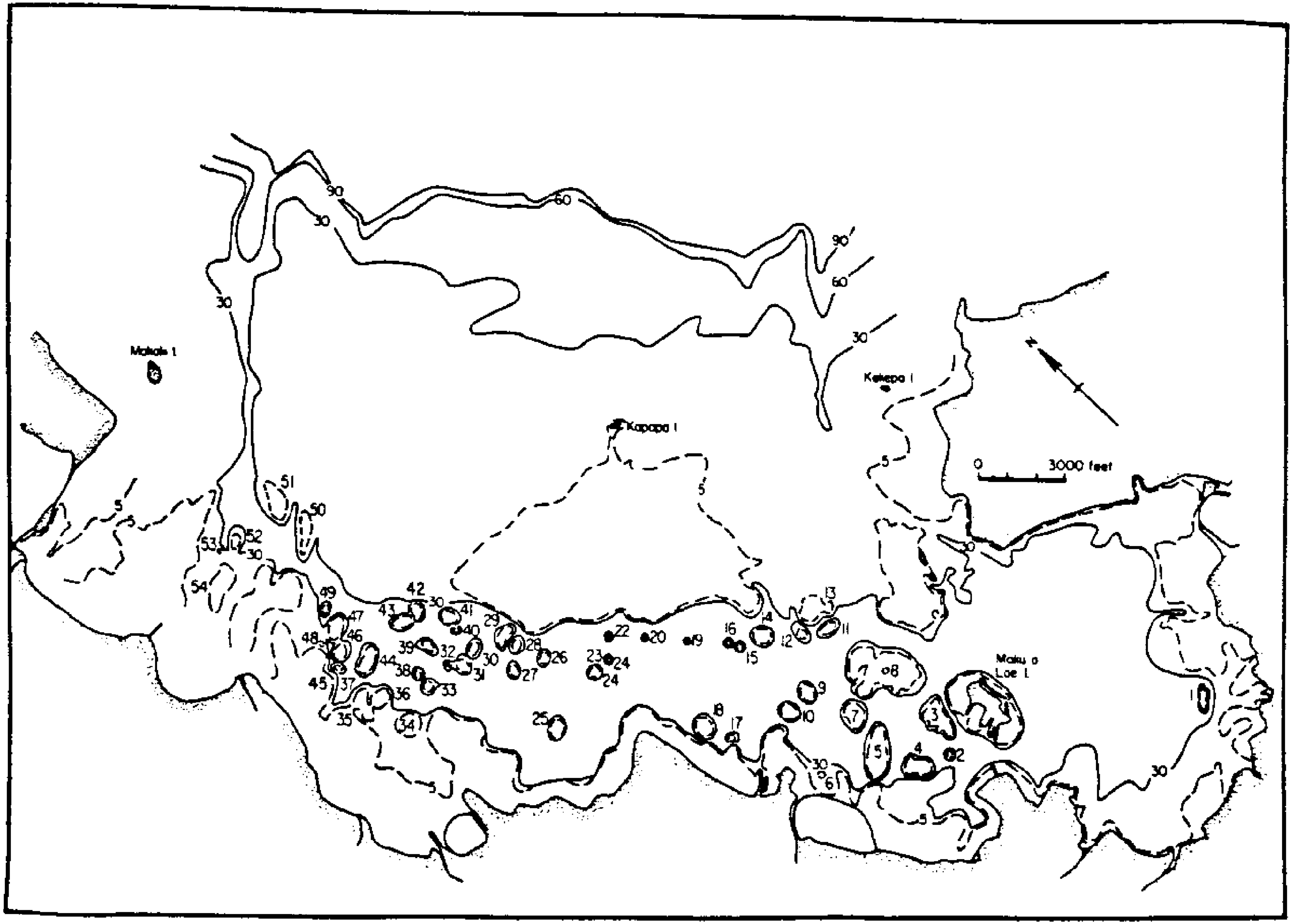

Fig. 3. The location of patch reefs in Kaneohe Bay. Reef numbers correspond to those given in Table 2, which presents the dimension data for the reefs.

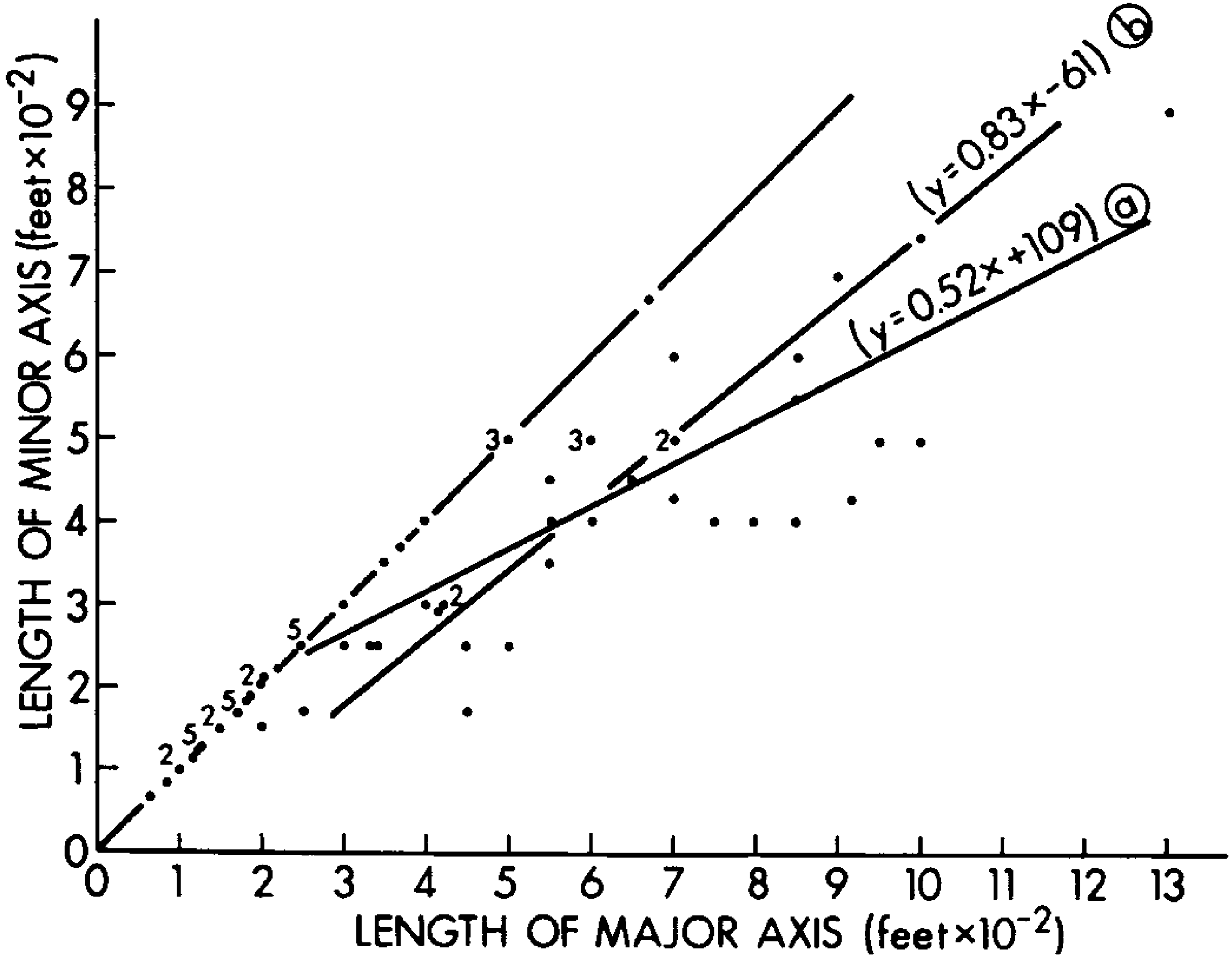

Fig. 4. The relation between length of minor and major axes of simple patch reefs. The two equations represent the least-squares regression lines: (a) using all the data; (b) using only lengths of major axis greater than 200 ft.

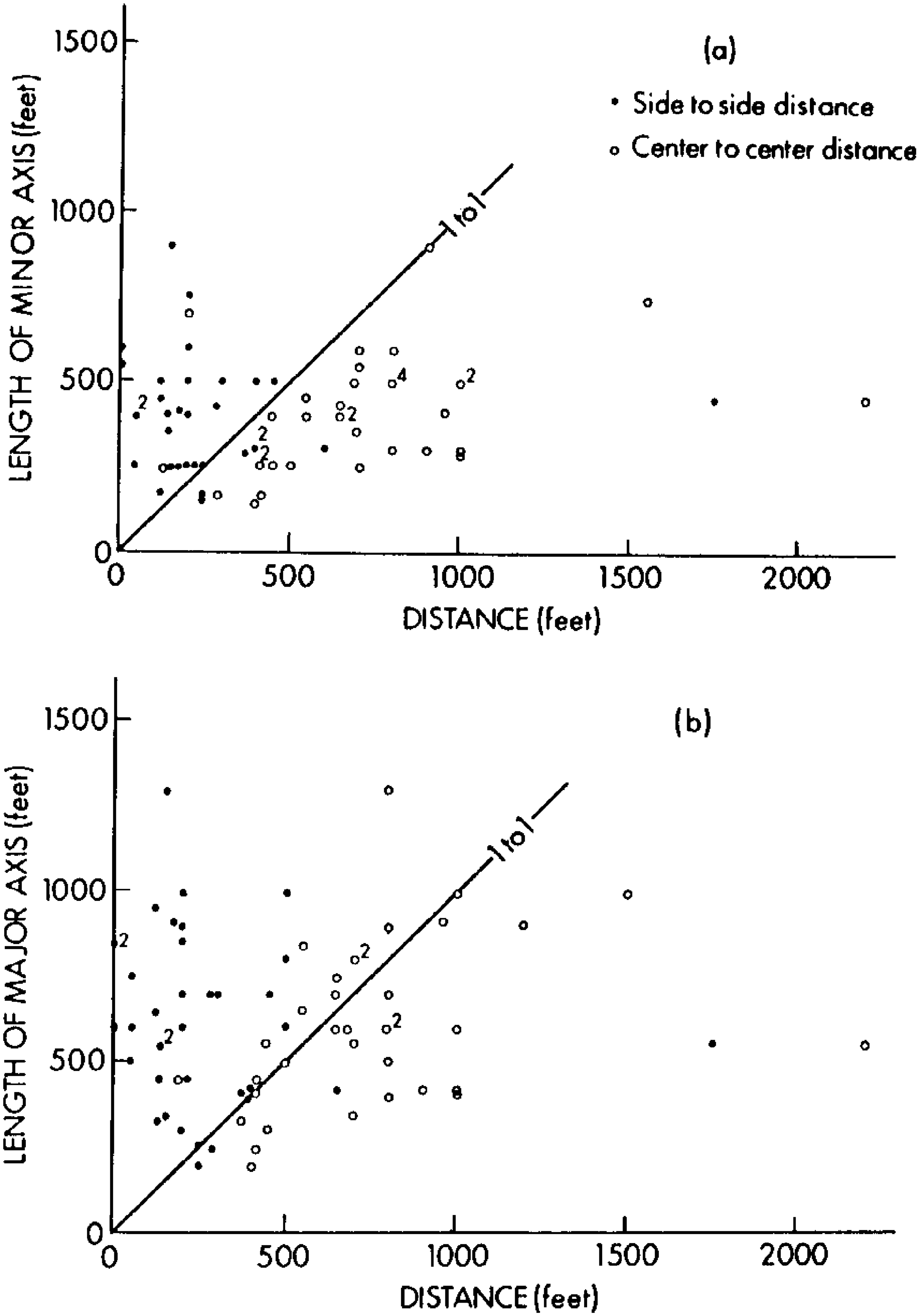

Fig. 5. The relation between (a) length of minor axis and (b) length of major axis of the elongate simple patch reefs and nearness of other reefs and distance between reef centers.

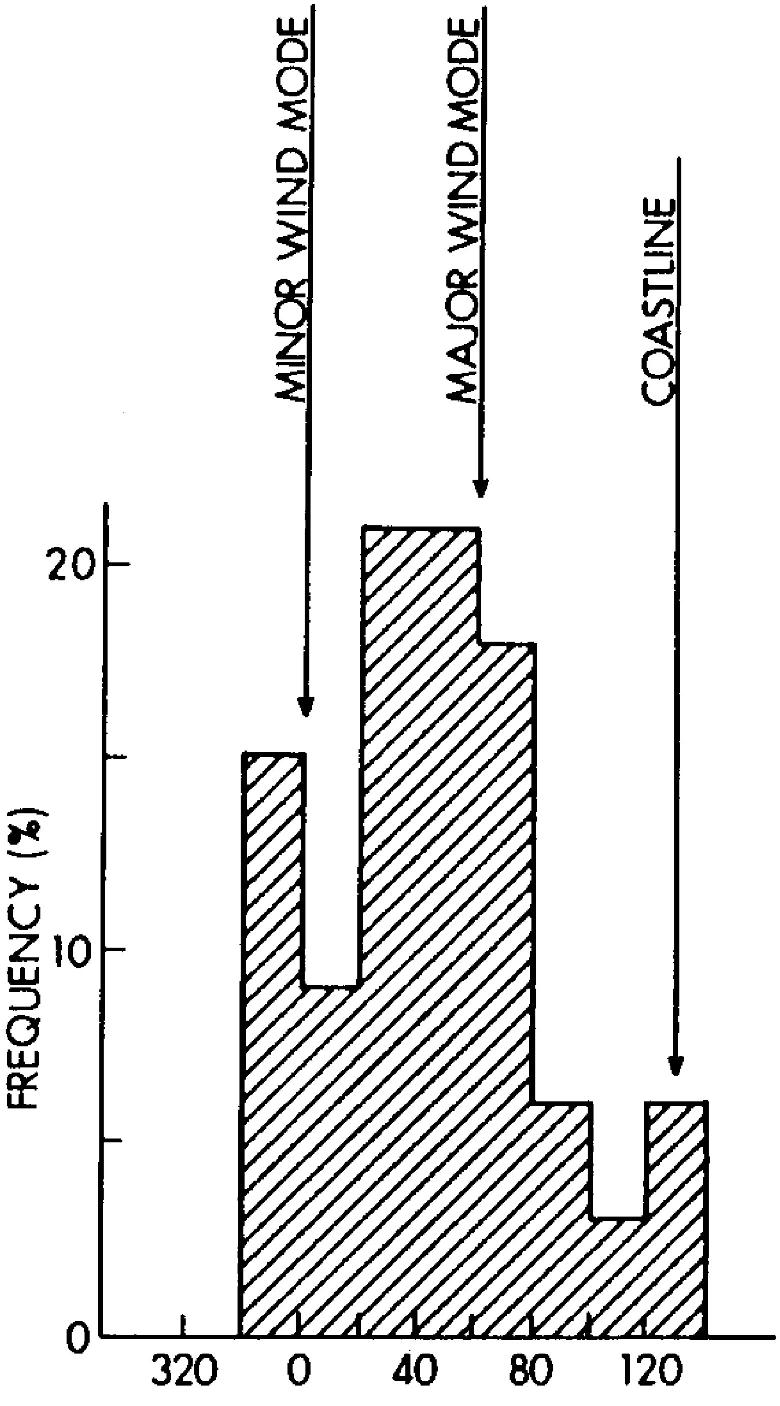

Fig. 6. The frequency distribution of the azimuth of the direction of elongation of simple patch reefs.

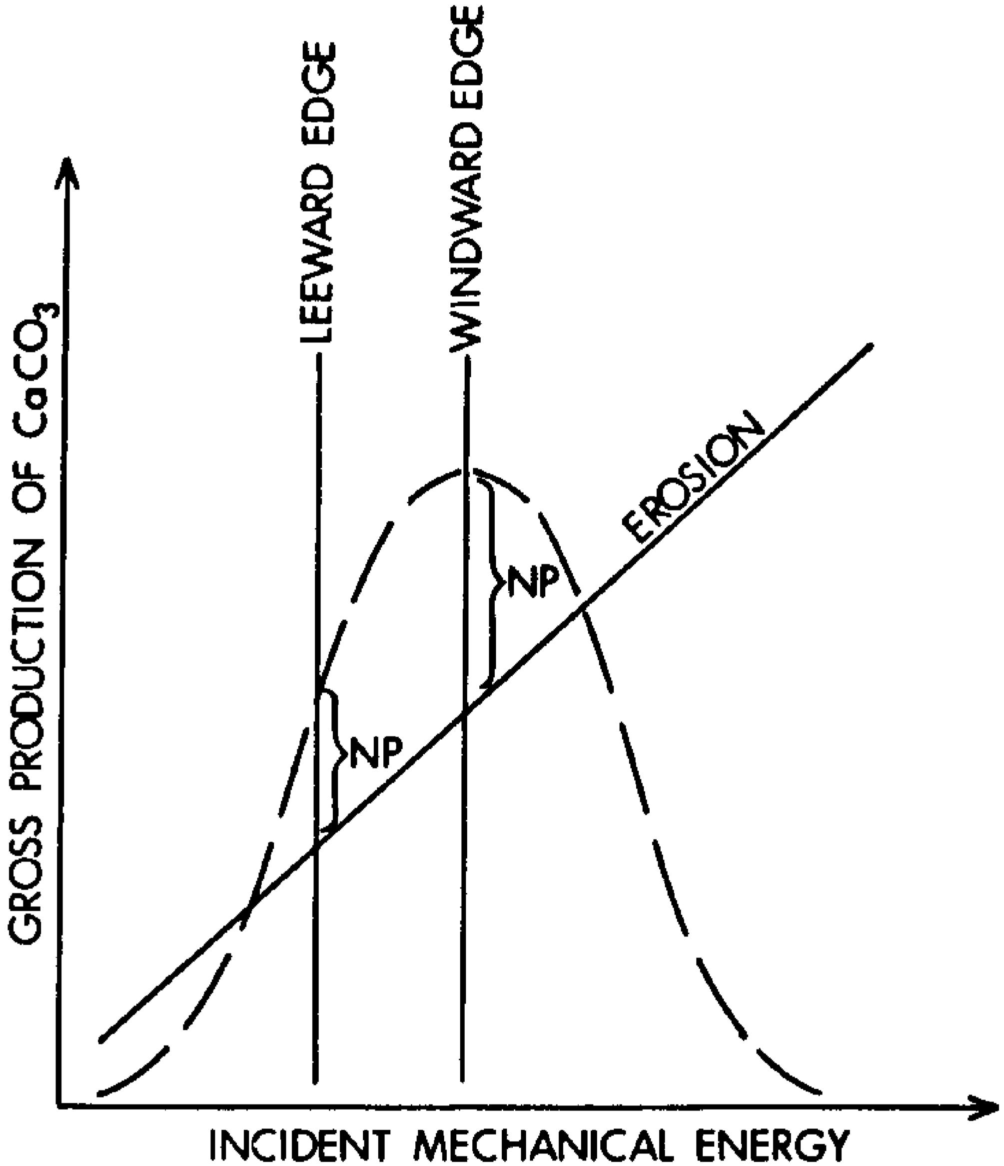

Fig. 7. A diagram relating mechanical energy incident on a reef and gross production of $CaCO_3$ by the reef. NF is net production; the dashed line indicates gross production.

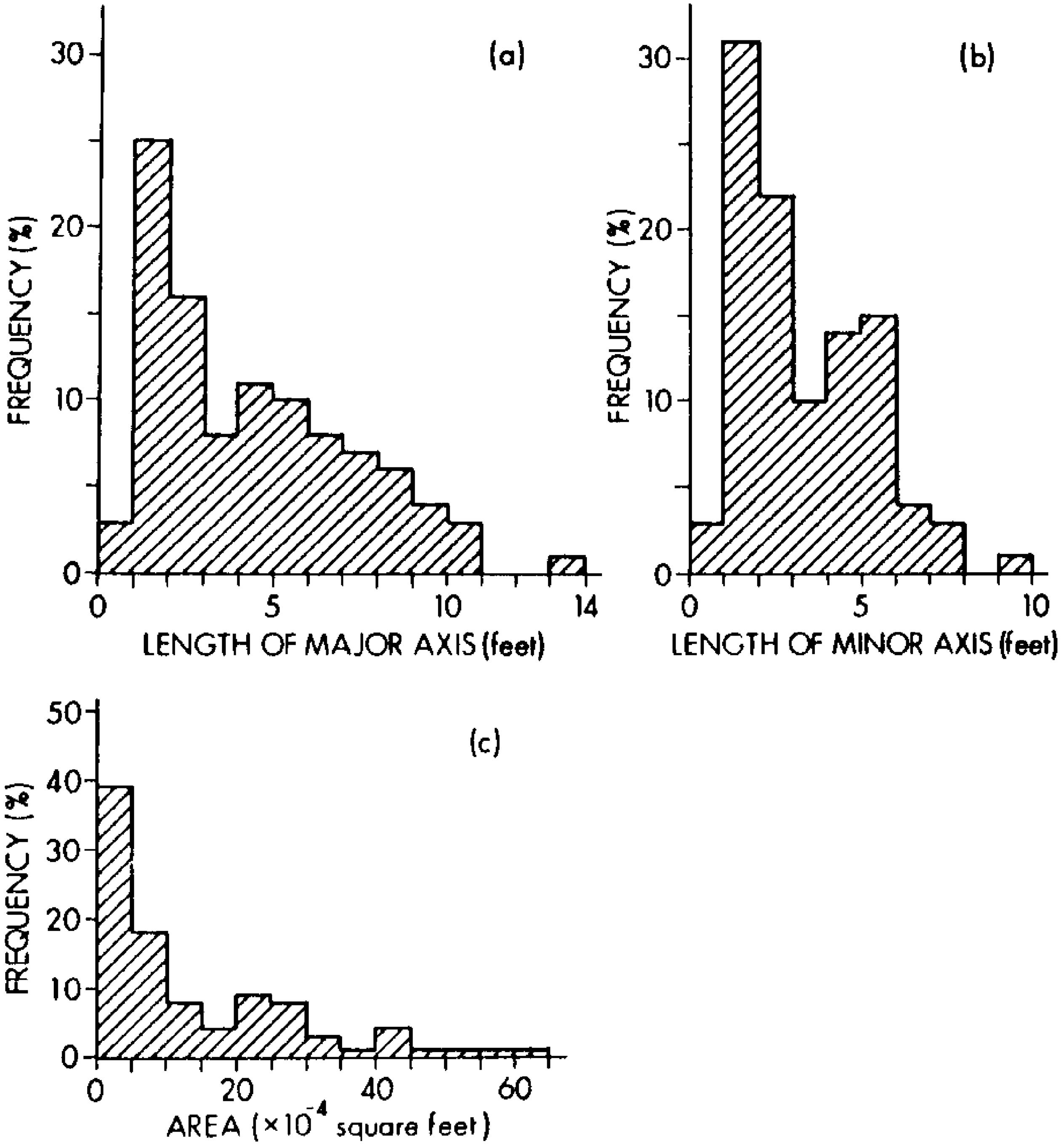

Fig. 8. Frequency distributions of the dimensions of simple patch reefs; (a) is length of major axis; (b) is length of minor axis; and (c) is area of the simple reefs.

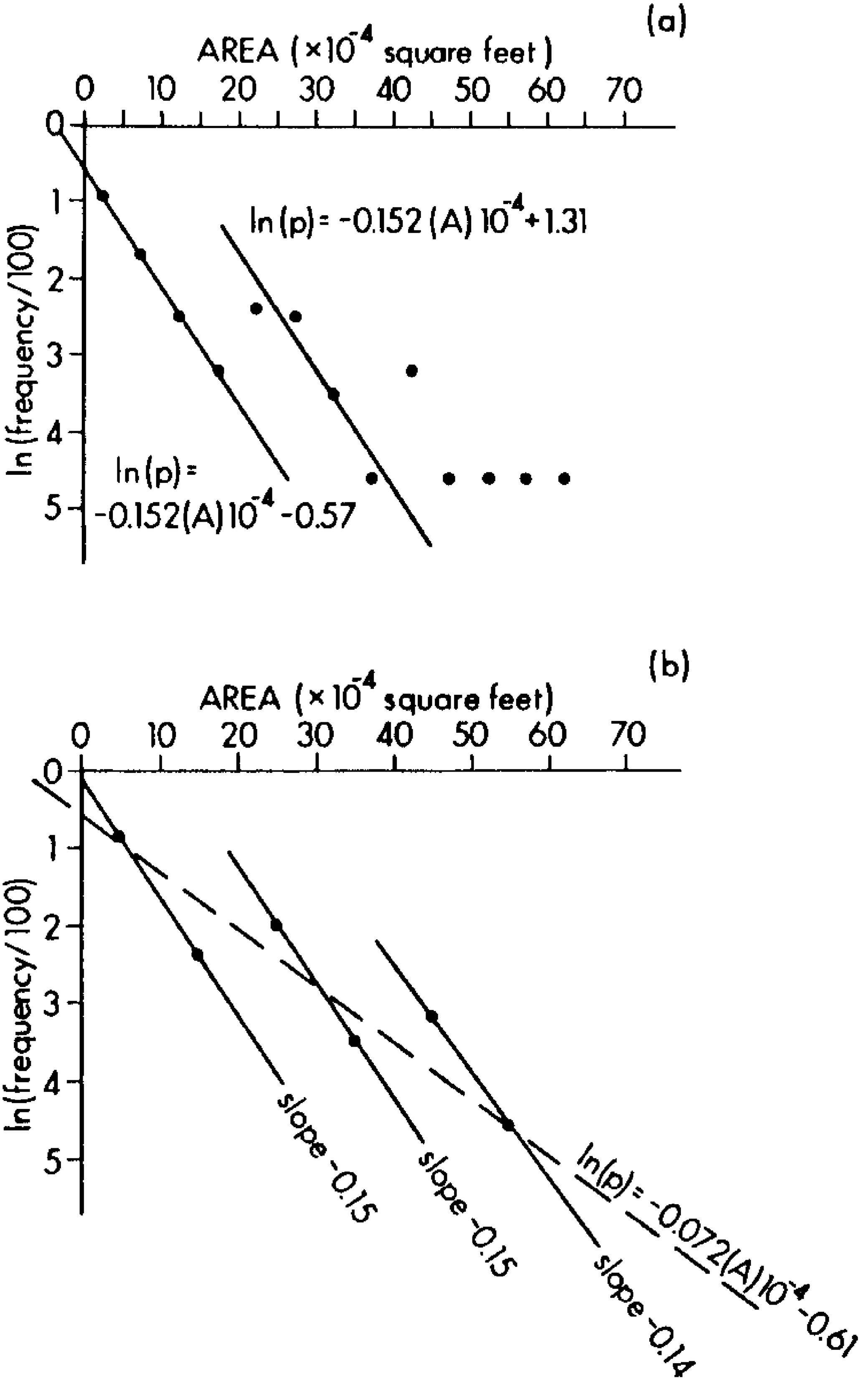

Fig. 9. The relation between ln (frequency/100) and the area of simple patch reefs; (a) has size classes of 5 x $10^4$ sq. ft.; (b), size classes of 10 x $10^4$ sq. ft. The equations represent least-squares regression of ln (frequency/100) on the area.

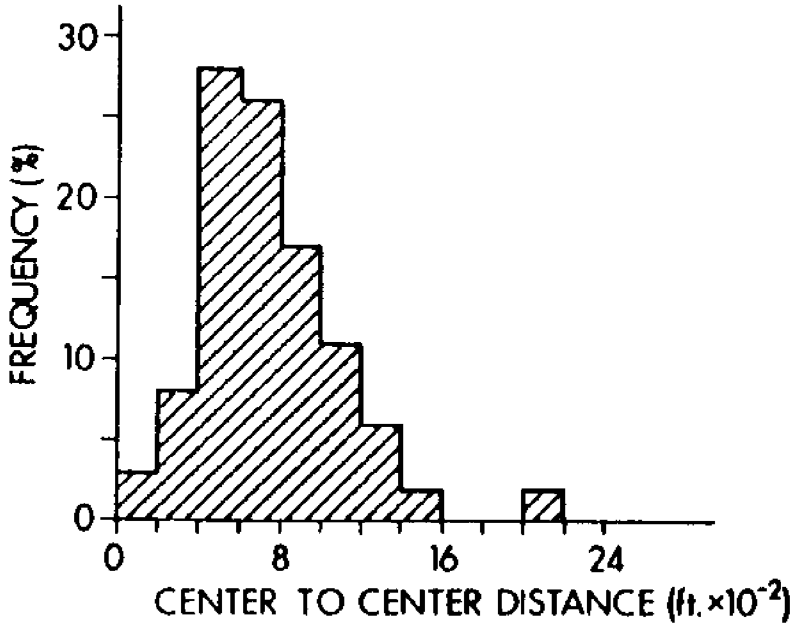

Fig. 10. Frequency distribution of minimum center-to-center distance for simple patch reefs in the bay. (This is the minimum distance from the center of a simple reef to the center of another patch reef.)

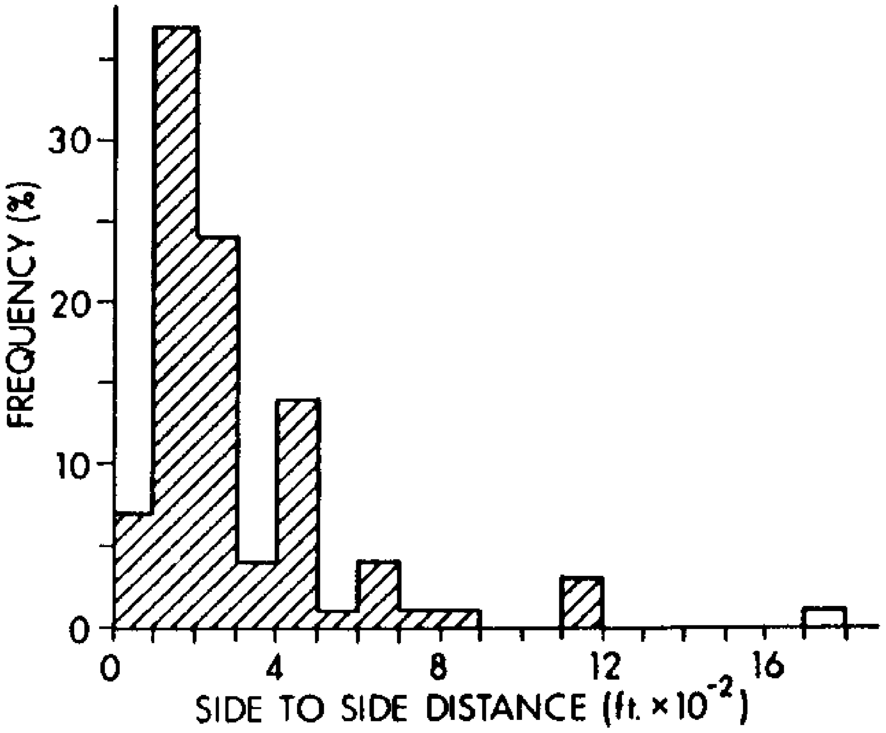

Fig. 11. Frequency distribution of the distance to nearest neighbor reef for simple patch reefs in the bay.

Fig. 12. Photograph of the shallow barrier-reef complex, showing the algal ridge.

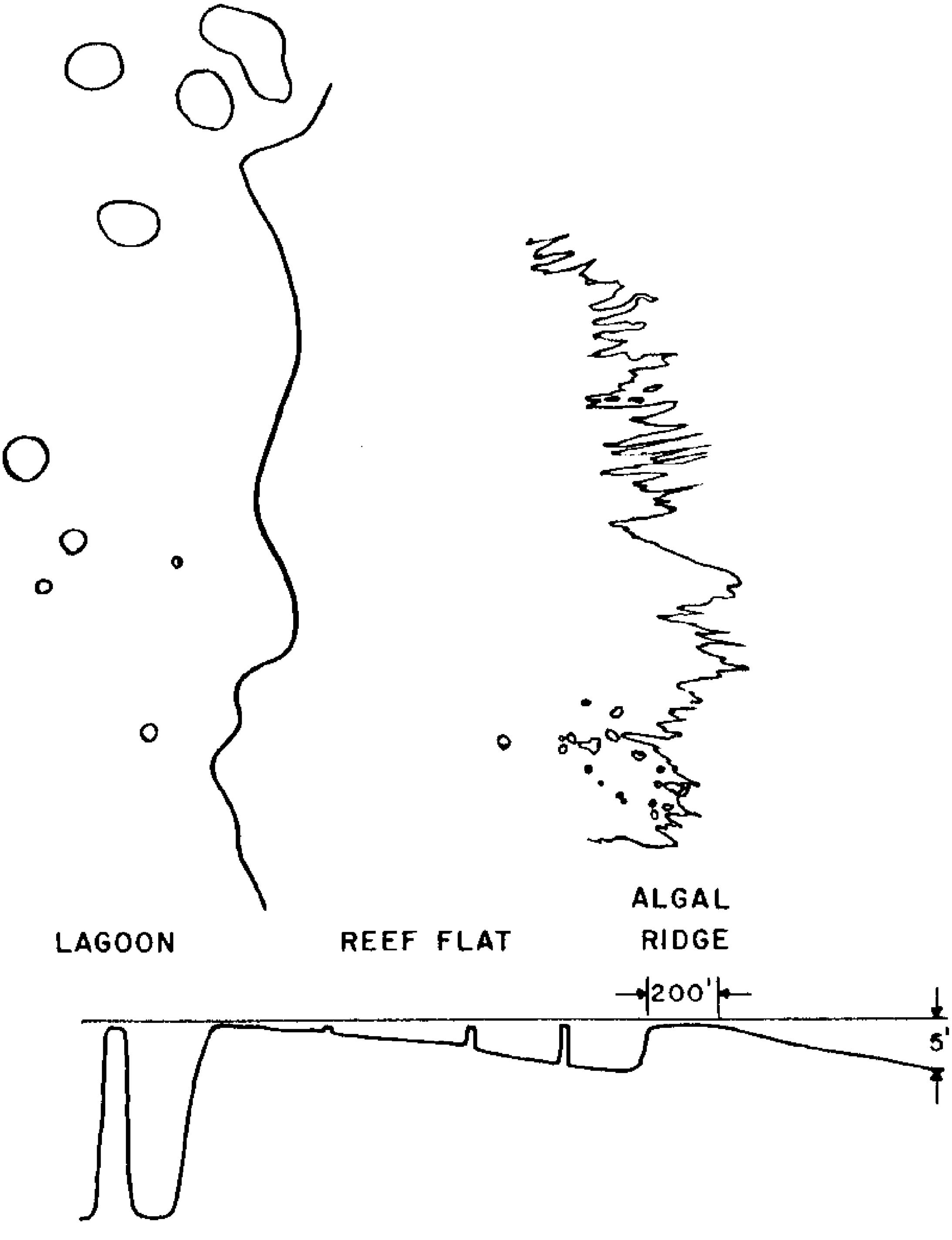

Fig. 13. A sketch of the algal ridge and related features.

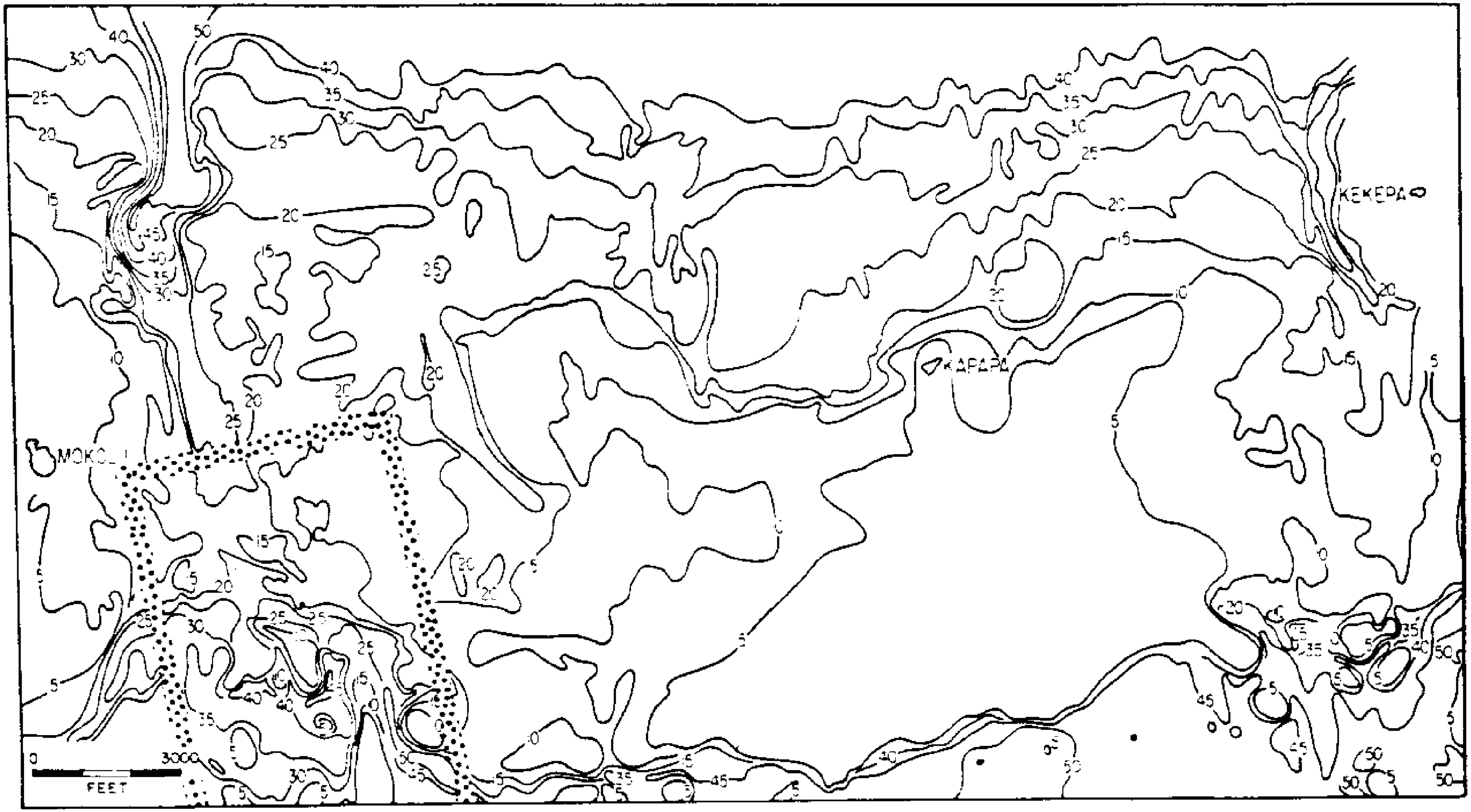

Fig. 14. Bathymetric configuration of the barrier reef showing relict stream-drainage topography (1933 data). The dotted outline encloses area depicted in Figure 20.

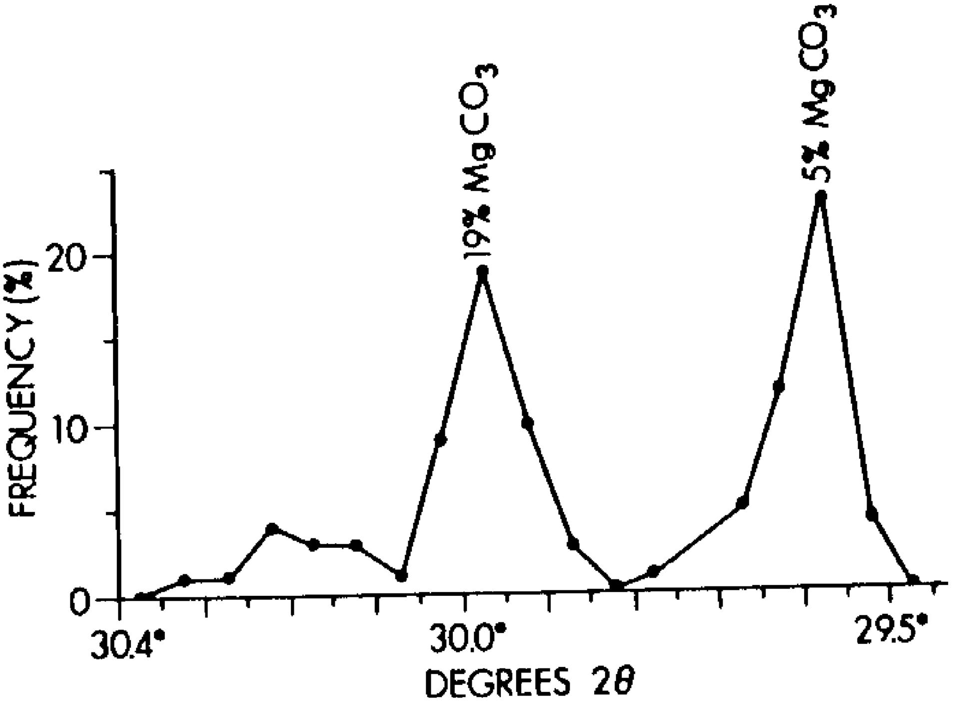

Fig. 15. The frequency distribution of calcite peaks on X-ray diffractograms of suspended sediment samples collected during a 24-hour study in the southeastern part of the bay. The sample locations are shown on Figure 16.

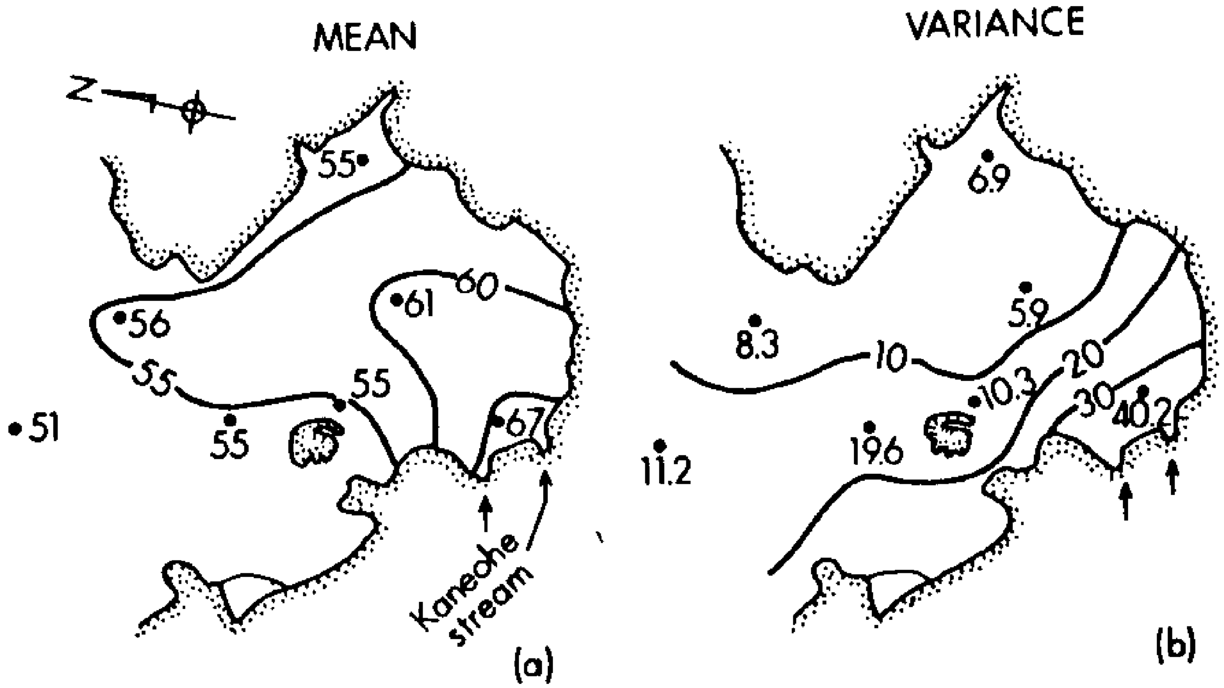

Fig. 16. The distribution of the average and variance of X-ray background intensity on analyses of suspended sediment samples collected at seven locations during a 24-hour study in the southeastern part of the bay.

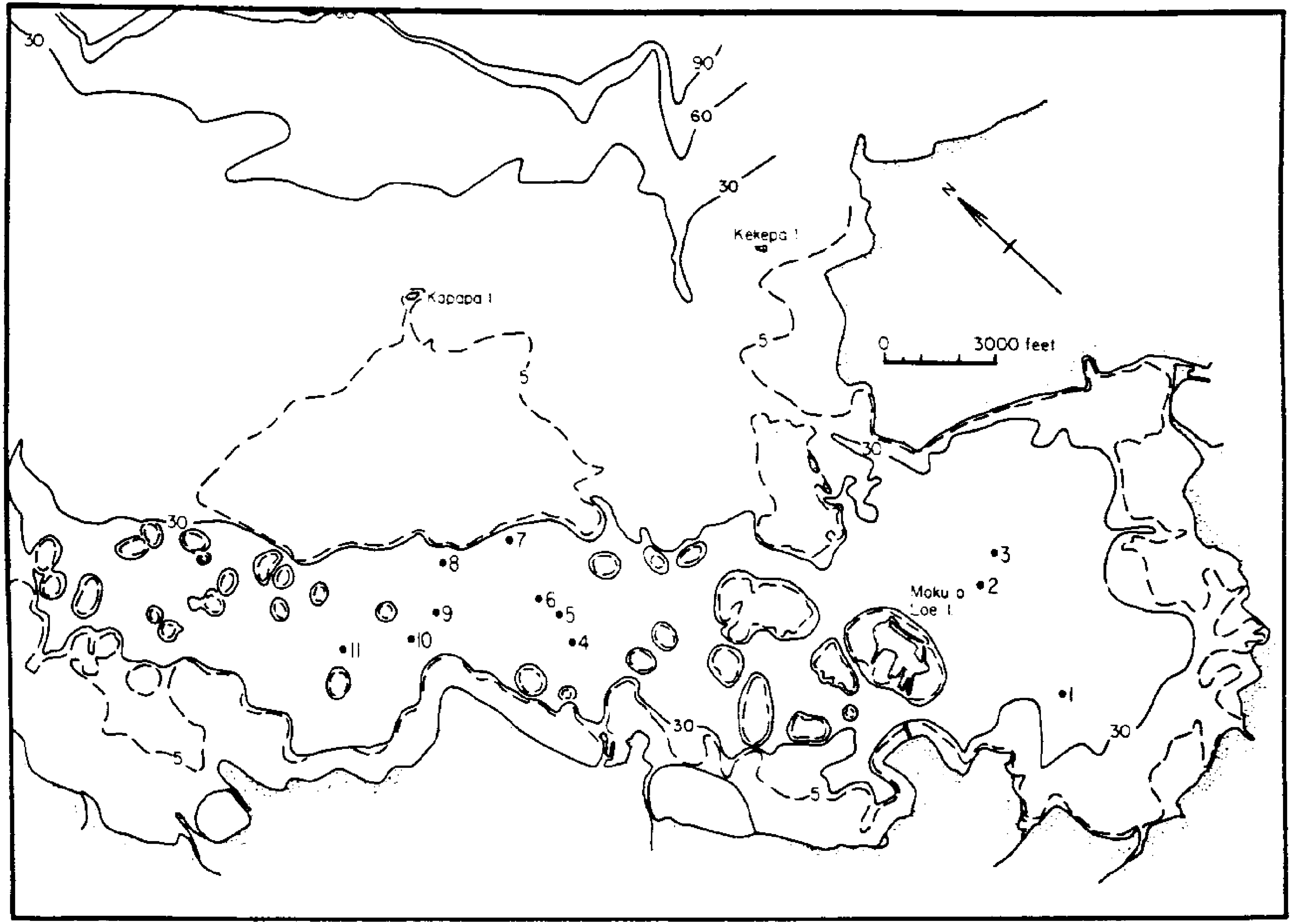

Fig. 17. Locations of the 11 samples of lagoon-floor sediments (See Table 4 for pertinent data).

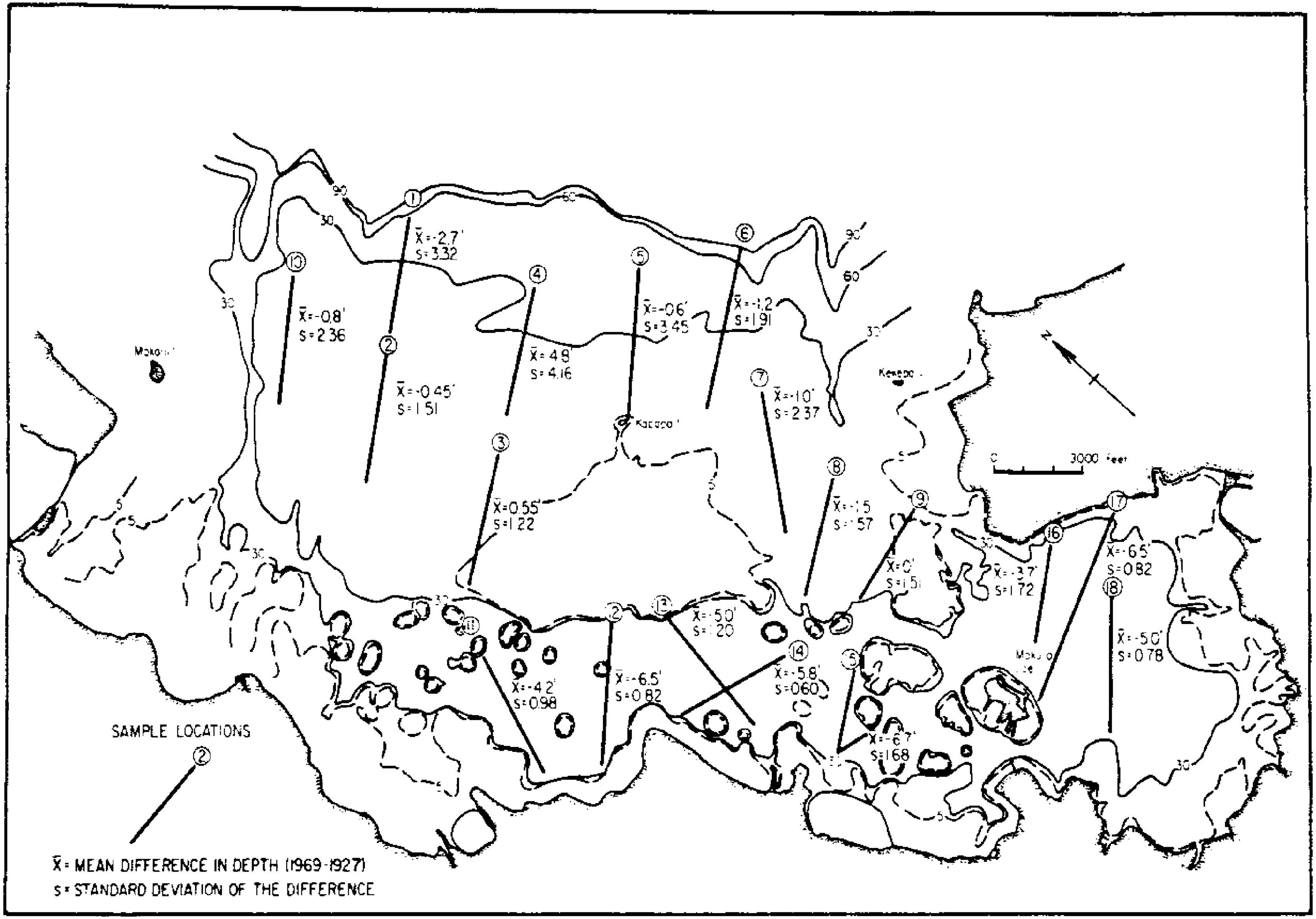

Fig. 18. Locations of the sample transects for comparison of the 1969 depths with those of 1927. A negative value indicates that the depth in 1969 was less than it was in 1927.

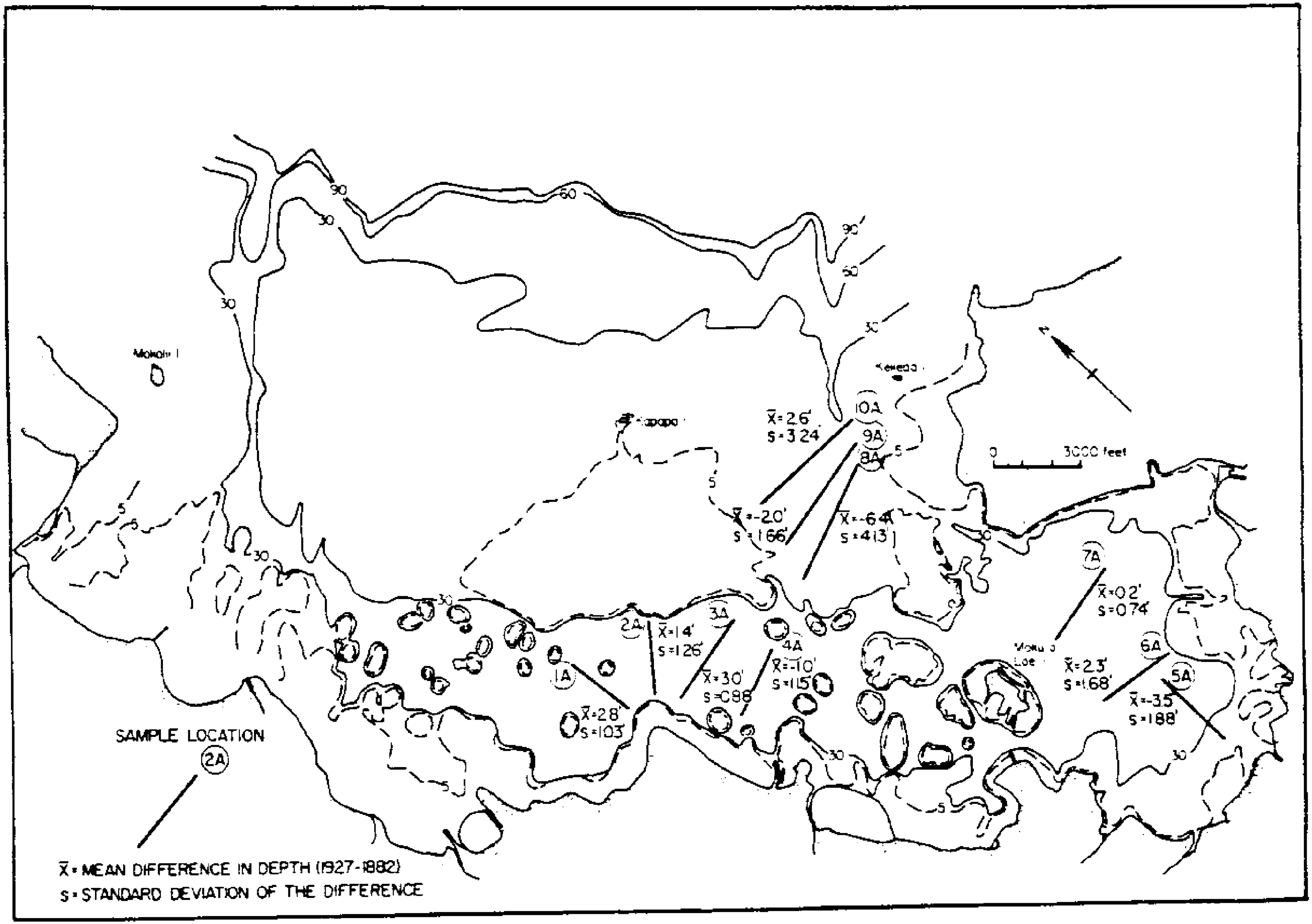

Fig. 19. Locations of the sample transects for comparison of the 1927 depths with those of 1882. A negative value indicates that the depth in 1927 was less than it was in 1882.

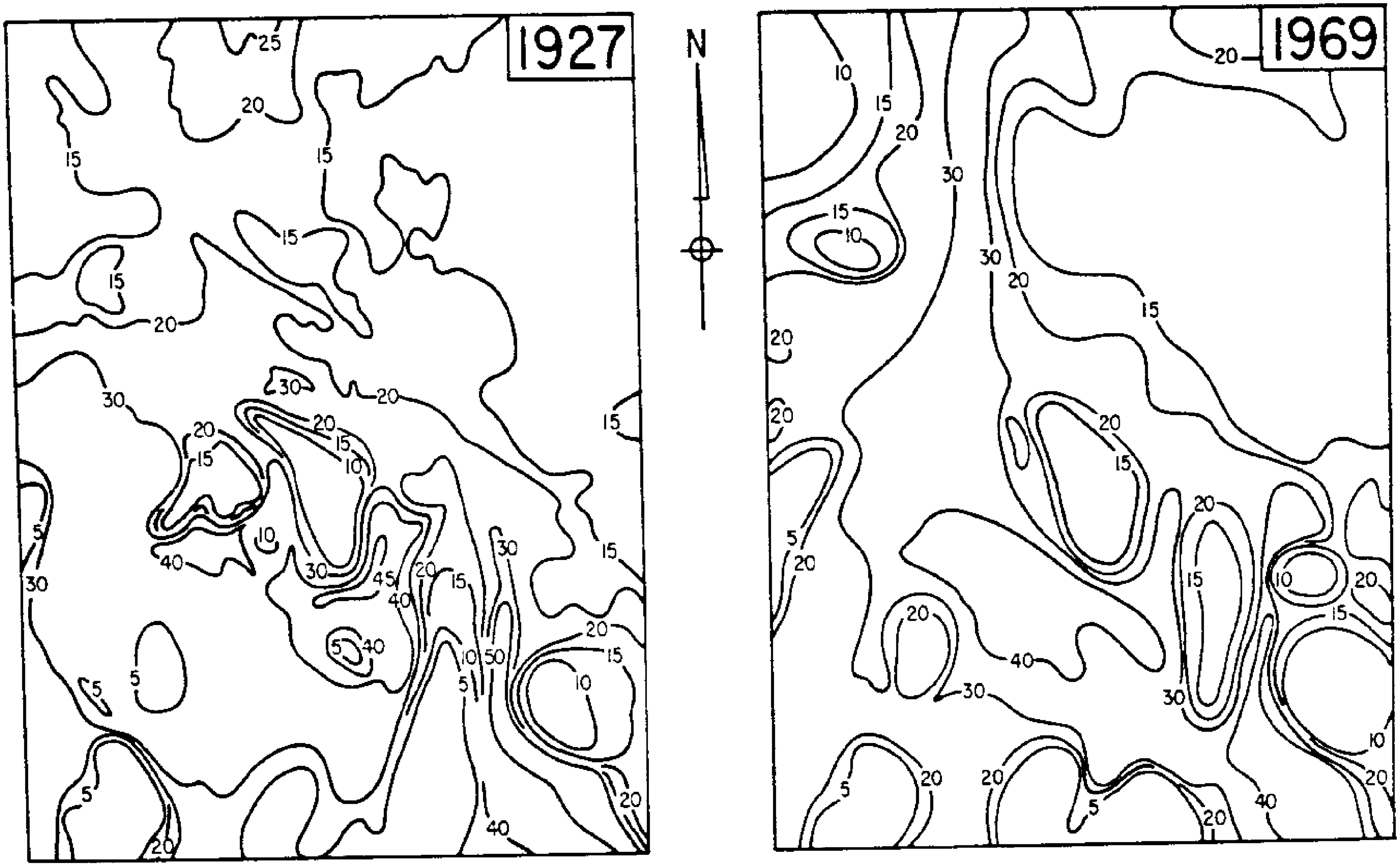

Fig. 20. Maps showing the change in the lagoon sill due to dredging in 1939. The location of the figures is shown by the shaded outline on Figure 14. Depths are in feet.

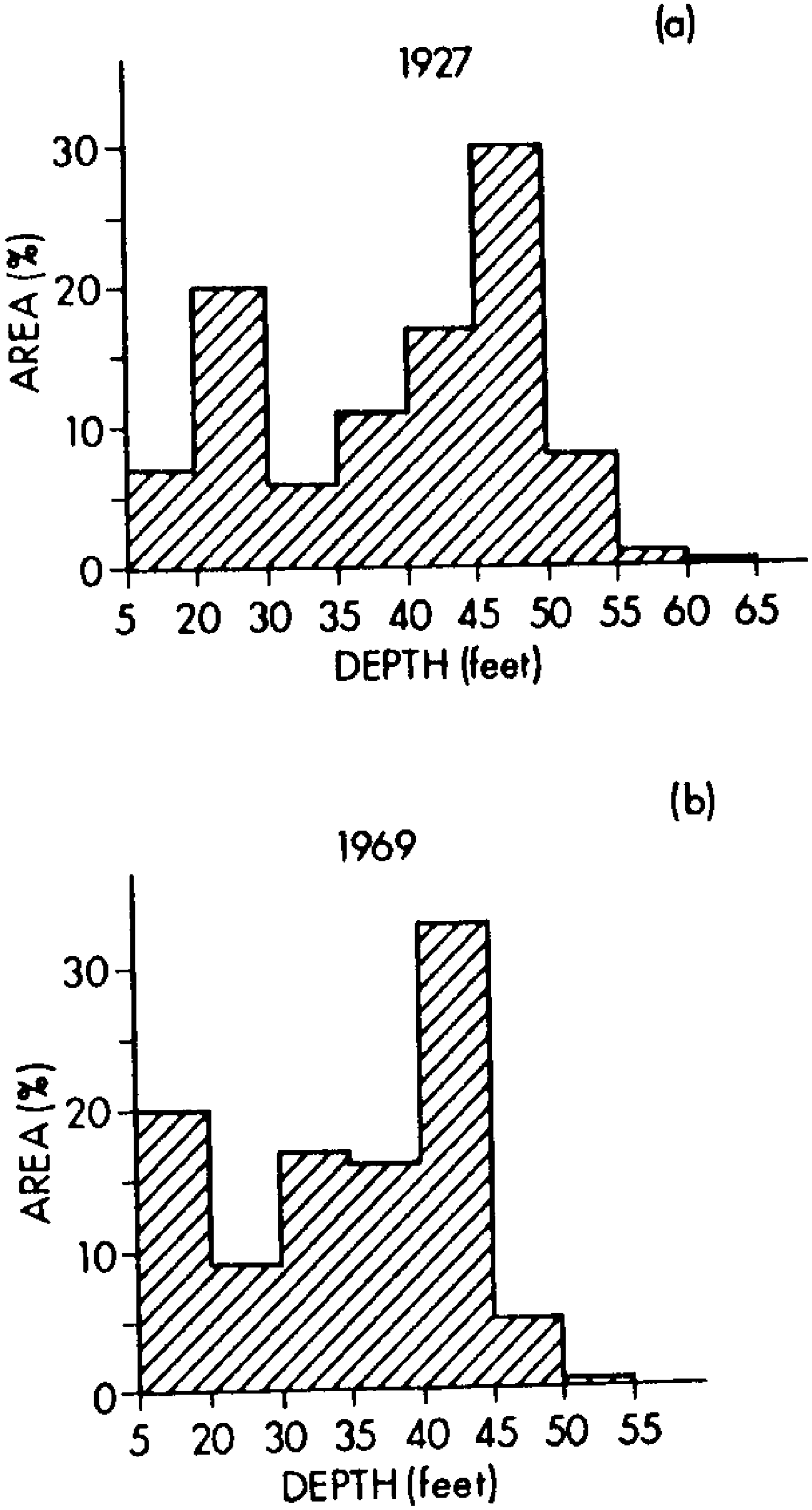

Fig. 21. Hypsographic data for the lagoon floor in (a) 1927 and in (b) 1969.

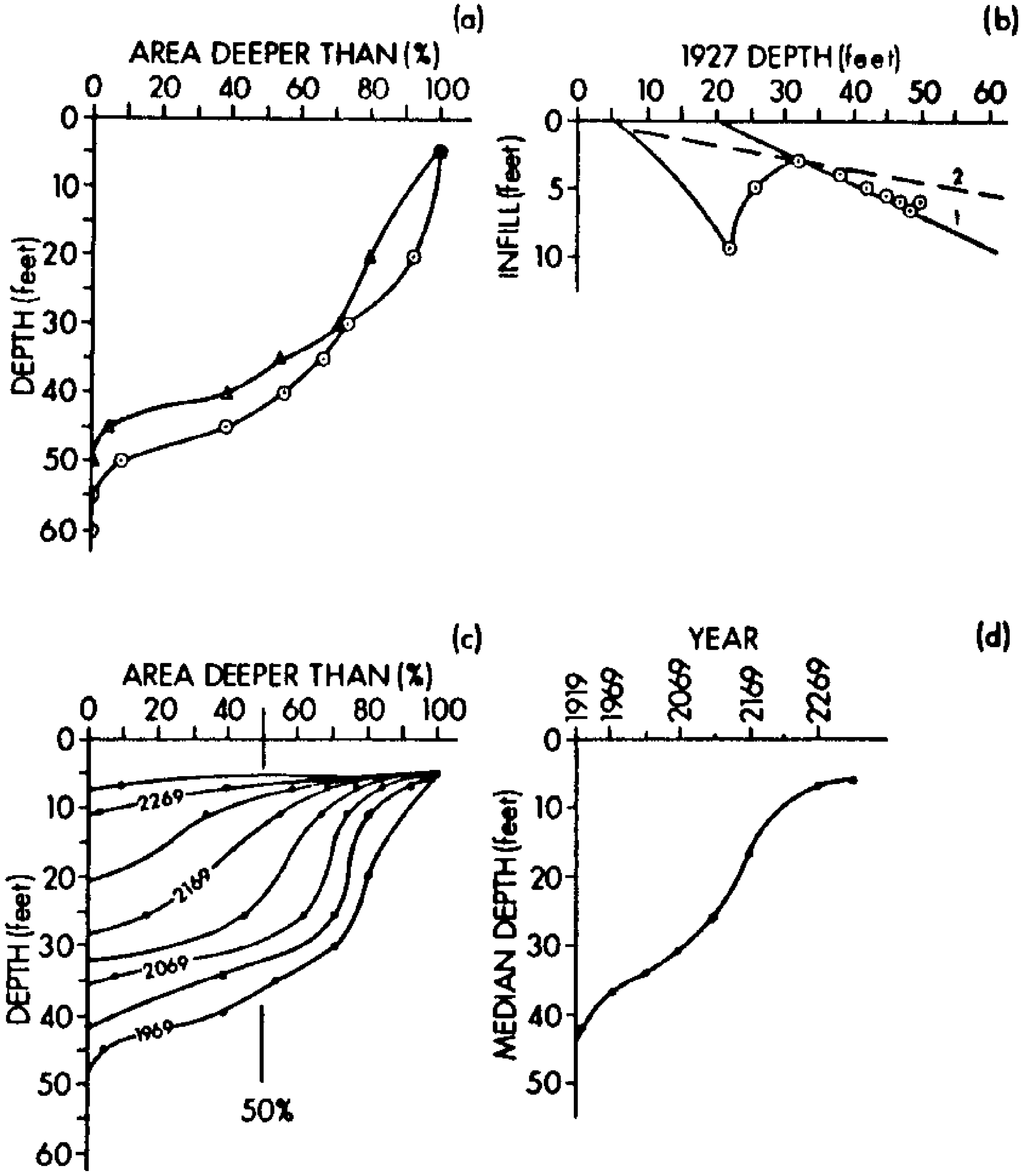

Fig. 22. Infilling of Kaneohe Bay lagoon: (a) cumulative depth distributions for 1927 and 1969; (b) infilling for the period 1969-1927, relative to the 1927 depths; (c) cumulative depth distributions projected to A.D. 2319, using 1927-1969 filling rates (see text for explanation of method); (d) projected change in median depth of the lagoon.

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