Pacific Science (1975), Vol. 29, No. 1, p. 99–115
Printed in Great Britain

On the Use of Benthic Foraminifera as Sediment Tracers in a Hawaiian Bay[1]

WILLIAM T. COULBOURN[2] AND JOHANNA M. RESIG[3]

ABSTRACT: Populations of foraminifera were investigated in regard to the suitability of the various species as indicators of sand transport. Of 53 species recorded in the sediments of Kahana Bay, Oahu, 16 showed distribution patterns that give evidence of the direction of sand transport within the littoral cell.

IN THE COURSE of a study to map and calculate offshore sediment volume around Hawaii (Campbell et al. 1970), a detailed sampling of Kahana Bay, Oahu, was undertaken for the purpose of defining the sources of the sand as well as paths of transport within a littoral cell. A cursory examination of the microfaunas of the samples showed that foraminifera were dominant and that the foraminiferal populations varied specifically and numerically from sample to sample. Since data relevant to the physical oceanography and sedimentology of the bay were available, analyses of the foraminiferal populations of 53 selected samples were made to determine whether a systematic variation existed that could provide an additional means of determining the direction of sand transport. The behavior of foraminiferal tests as sediment particles has been investigated by Grabert (1971).

THE ENVIRONMENT

Kahana Bay, located on the northeast (windward) coast of Oahu, Hawaii (Figure 1), is a submarine extension of Kahana Valley. Abundant rainfall in the valley, more than 250 inches a year in the higher elevations (Mink, Lee, and Watson 1963), produces a discharge of 29.5 mgd by Kahana Stream (Cox and Gordon 1970). The stream usually discharges at the eastern side of the bay; however, after unusually heavy rainfall a channel opens through the center of the beach.

Along the east and west shores of the bay, the submarine topography is bounded by fringing reefs whose surfaces range from a little more than 10 feet below sea level to blocks of coral that are exposed during low tides (Figure 2). The outer edges of the reef drop vertically 30 feet or more to a sandy area in the center of the bay that forms a channel sloping gently seaward. The channel sands are rippled uniformly to depths of at least 40 feet. A small patch reef is located in the northwestern corner of the channel.

METHOD OF STUDY

Sediment samples and *in situ* water salinity and temperature measurements were taken in Kahana Bay, Stream, and Valley from September 1970 to August 1971. Of the 136 surface sediment samples collected, only 42 (those with the suffix F, Figure 3) were collected by hand and treated with a solution of rose bengal and ethyl alcohol to preserve the living protoplasm while staining it red. The remaining deep-water samples were obtained with a van Veen grab sampler and were not stained, because they were initially collected solely for sedimentological analysis. Thus, the reported distribution of live specimens is only an approximation because some of the samples were not stained to detect those individuals, and because seasonal variation was not sampled systematically.

As an independent means of determining paths of sediment transport, direct measurements of sand movement were made through a sand tracer experiment as described by

[1] Hawaii Institute of Geophysics contribution no. 637. Manuscript received 1 March 1974; revised and returned 21 June 1974.

[2] University of Hawaii: Hawaii Institute of Geophysics and Department of Geology and Geophysics, Honolulu, Hawaii 96822.

[3] University of Hawaii: Hawaii Institute of Geophysics and Department of Geology and Geophysics, Honolulu, Hawaii 96822.

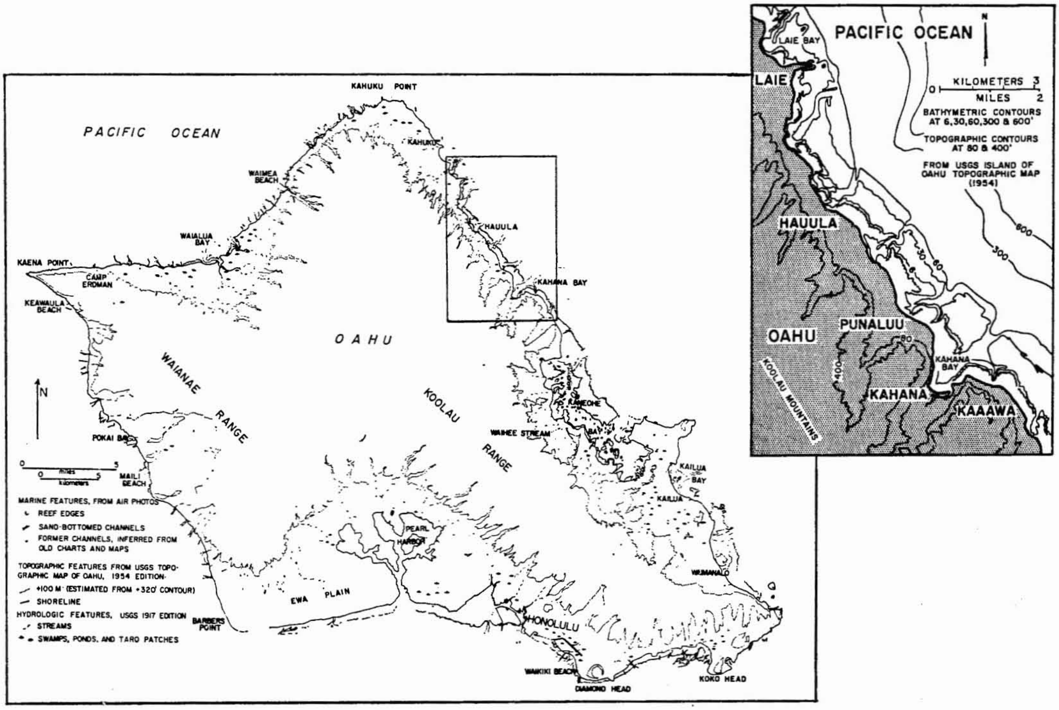

FIGURE 1. Location map for Kahana Bay (after Moberly 1968).

Obdyke (1966). (See Coulbourn 1971 for full description of method of study.)

Grain-size analyses were performed on the samples by the standard methods. Statistical size-parameters were determined graphically according to the formulas presented by Folk (1968). Approximations of the weight percent of calcareous, organic, and terrigenous fractions in each sample were made by dissolving the calcareous fraction of 2- to 5-gram samples in hydrochloric acid, reweighing, oxidizing the organic fraction with hydrogen peroxide, and finally weighing the terrigenous residue.

Foraminifera were concentrated from selected samples through flotation in perchloroethylene. About 300 individuals were then tallied from a split of the concentrate. Tests that were so abraded as to render species identification impossible were ignored.

OCEANOGRAPHY

The results of the *in situ* measurements of salinity and temperature, reported in detail elsewhere (Coulbourn 1971), are summarized here. The course taken by stream water entering the bay is marked by reduced salinity and temperature, and high turbidity relative to water flowing off the flanking reef flats. At the stream mouth, the temperature and salinity gradients are large but vary in position depending on the ebb and flow of the tide. Near shore, clear and warmer water flowing off the eastern reef flat adjacent to Huilua fishpond displaces the flow of the stream toward the western side of the bay. Farther offshore, high coral blocks along the eastern reef margin prevent any significant flow of marine water into the channel. Just to the southeast of the patch reef, a line of floating debris trending northeast–southwest marks the convergence of water flowing off the northern and western reefs and the mixture of stream and marine waters flowing seaward in the channel. Sand-tracer experiments performed at grids 1 and 2 (Figure 3) demonstrated a southeasterly sediment drift.

The seaward flow of water within the bay results primarily from contributions off fringing reefs flanking both sides of the bay and from

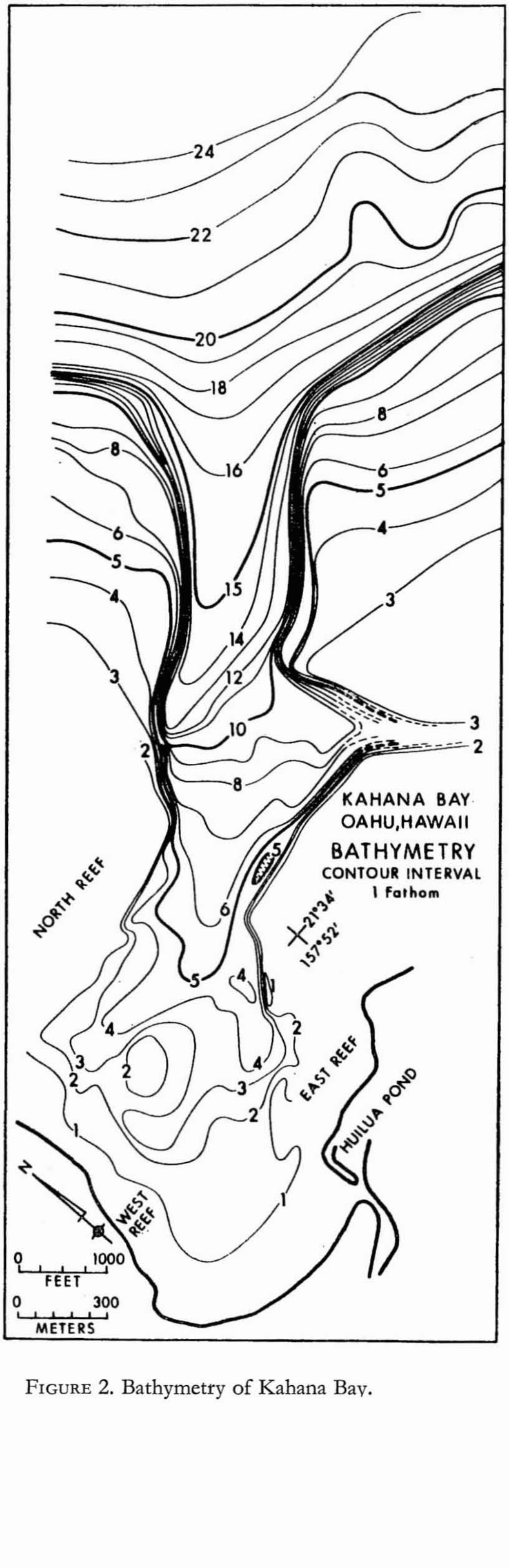

FIGURE 2. Bathymetry of Kahana Bay.

the stream discharge. Freshwater springs located along the base of the reef contribute volume to the flow, but have little effect on the environment, since they are rapidly mixed with the seaward flow. The overall flow pattern closely resembles that proposed by Inman, Gayman, and Cox (1963) for a littoral cell at Kapaa, Kauai.

SEDIMENTS

Values of mean grain size and percent by weight of the terrigenous fraction of each sample are given at the top of Table 1. Comparison of plots of these values for the 136 samples reveals that areas of low mean ϕ values (larger grain sizes) are also characterized by high percentages of calcareous constituents. It is of particular interest that these areas are highly reflective in aerial photographs, irrespective of bathymetry. Conversely, samples with high mean ϕ values and with high percentages of terrigenous material (determined by microscopic examination to be mostly grains of weathered basalt rock) are associated with dark areas in aerial photographs, again irrespective of bathymetry. Thus, where sample distribution was sparse, allowing several possible interpretations, the contours were biased to trend along the borders between light and dark areas.

The interrelation of the properties of sediment grain size and composition provides an insight into sediment transport in the bay. The middle of the bay is characterized by finer grain size and high percentages of terrigenous material, suggesting that sediment introduced from Kahana Stream settles out from suspension in the area seaward of the surf zone. It would appear that calcareous, coarse-grained sand is being introduced into the channel from localized points along the edges of the fringing reefs. Substantiation of direction of transport came from the southeasterly movement of dyed sand monitored at two test stations, and from the distribution of the terrigenous component in the sand. Although the sand tracer experiment provided conclusive results, it was costly and extremely time-consuming. Another approach, utilizing biological components as tracers, is proposed as a desirable alternative.

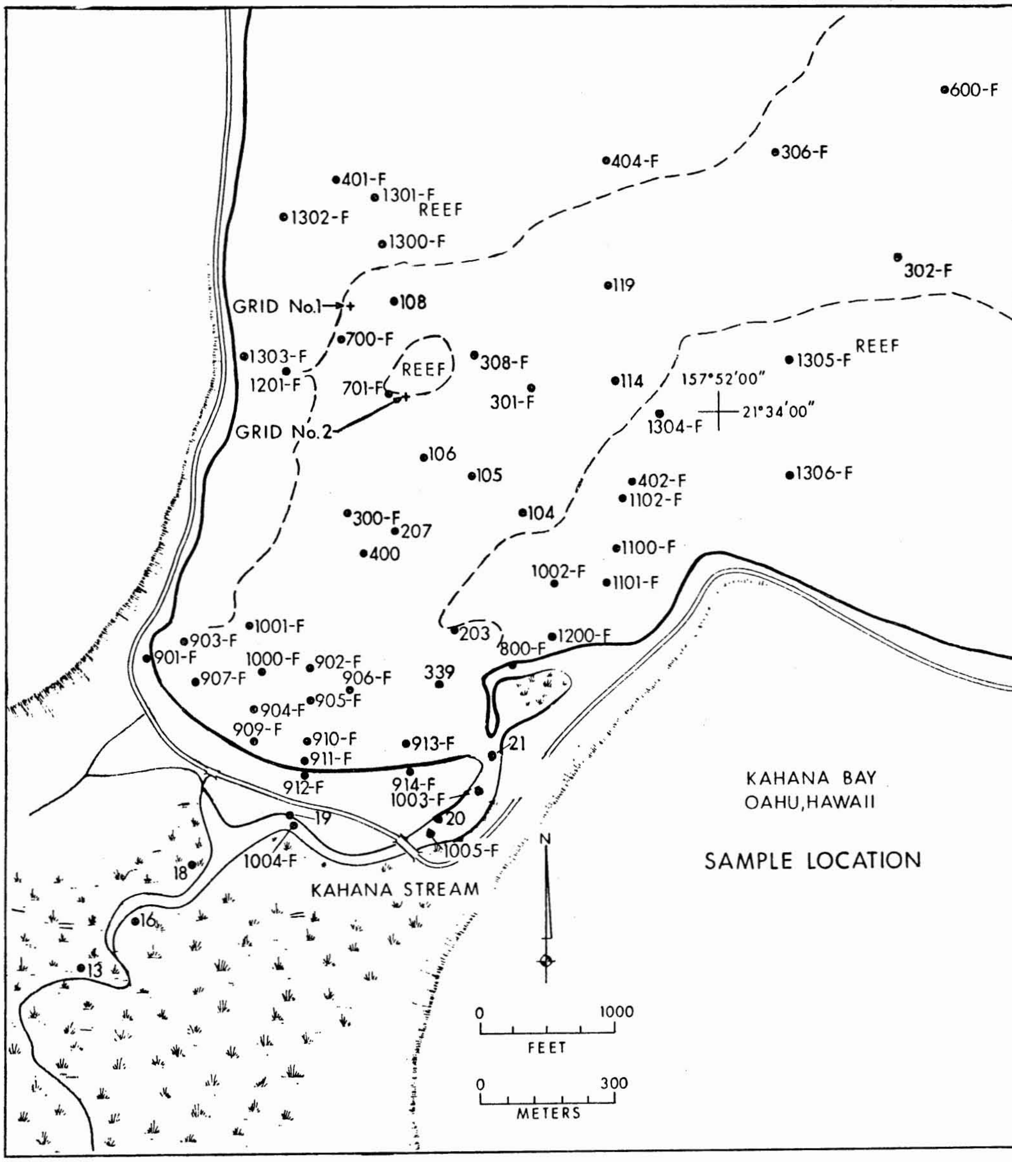

FIGURE 3. Location of sample stations in Kahana Bay, Stream, and Valley, and of grids 1 and 2.

A compilation of all foraminiferal species recorded in the samples and grouped according to the constraints of mean grain size of the substrate, weight percent terrigenous material, and location is shown in Table 1. The samples of group I belong to an estuarine environment that strongly influences the microfaunal population and sedimentological makeup of group IIa, i.e., high percentages of terrigenous material and significant representation of brackish water species. An anomalous sample, 1303 (group IIb) is placed with group IIa on the basis of its microfaunal population alone. Groups III and IV represent mixed environments subject to varying input from terrigenous and reef sources. Group III differs from group II in that wave action winnows out much of the terrigenous material represented in the 3.5ϕ

and finer fractions, as well as significant numbers of the smaller foraminifers. The samples of group IV are representative of areas where significant quantities of coarser, calcareous, reef-derived material dilute the very fine, highly terrigenous, channel sands. Samples of group Vb have coarser grain sizes incorporating small quantities of terrigenous material, and are located on the reef flat. Note that sample 600 (group Va) must be separated because of location, even though its microfaunal population indicates a very close liaison with the reef flat. The samples of group VI are from fossil beach ridges influenced by the admixture of varying quantities of organic swamp muds. They are important only in that the estuarine populations of group I are contaminated by reworked specimens from these old strands.

Within this framework of six environmental groupings, we separated species of foraminifera into four categories based on percentage occurrences. Sixteen of the species which appear to give evidence of sediment transport direction are discussed below.

MICROFAUNAL DISTRIBUTION PATTERNS

Small values for the foraminiferal number (number of specimens per gram of sediment, Figure 4) distinguish the reef flat environment from the quieter wave- and current-regime of the channel, where high foraminiferal numbers occur in fine-grained sediment. Actual concentrations of specimens of the various species are distributed in patterns that tend to duplicate that of foraminiferal number. Therefore, a format of relative percentage of each foraminiferal species was adopted in order to emphasize the contribution of each species to the various assemblages and to moderate the effects of the inverse relationship between foraminiferal number and grain size. In the following descriptions, significant species of foraminifera whose distributions are relevant to the determination of sediment transport direction are grouped according to similarity in distributional patterns. The distribution of one member of each group is illustrated (Figures 5–8); the presence of living specimens is indicated on the figures by diamonds. The reader is referred to Coulbourn (1971) for a more complete presentation of these data.

Brackish Water Species

Ammonia tepida (Cushman) (Figure 5) and *Protelphidium tisburyense* (Butcher) were found alive only in the stream bed, but their tests were distributed along a southwest to northeast line in fine-grained, highly terrigenous sediment. Both species were absent from the northwest side of the sand channel. Their distribution follows the pattern of stream-derived sediment in the bay, independently indicating the direction of sediment movement.

Small Species

Distribution of *Bolivina rhomboidalis* (Millett), *Cibicides lobatulus* (Walker & Jacob), *Elphidium hyalocostatum* Todd, *Glabratella patelliformis* (Brady), *Rosalina vilardeboana* d'Orbigny (Figure 6), and *Pateoris australis* (Parr) shows a close relationship to large foraminiferal numbers, fine-grained sands, and high percentages of terrigenous material. In this respect these six species are distributed similar to the two aforementioned brackish water species, but no live specimens were found in the stream bed. In fact, of all the tests of members of this group examined, only two live specimens of *Rosalina* and four of *Cibicides* were found in the channel; single live specimens of *Cibicides* and *Elphidium* were found on the reef. Without further knowledge of the habitation sites of these species, we can only postulate that living specimens arrive on the moving, inhospitable channel (and reef) sands through dislodgement from algae or displacement from protected sedimentary substrate.

Distribution of the tests of these species may best be explained as a function of sorting during sediment transport toward and down the channel. Large foraminiferal numbers are directly related to high percentages of the six species (see "Very Fine Channel Sands," Table 1), so that the percentage patterns are generally indicative of real concentrations.

In particular, information relating to the energy of the transporting forces may be derived from the percentage occurrence of the

TABLE 1

DISTRIBUTION OF FORAMINIFERA BY PERCENTAGE OF ABUNDANCE

	I ESTUARINE SANDS					IIa VERY FINE CHANNEL SANDS										IIb	III BEACH AND FINE "NEARSHORE" SANDS										
SAMPLE NUMBER	20	21	1003	1004	1005	104	105	207	400	701	902	905	906	1000	1001	1303	339	901	903	904	907	909	910	911	912	913	914
Mean Grain Size (ϕ)	2.0	2.6	−0.7	2.1	1.7	3.8	2.9	3.8	3.4	,	3.3	3.1	3.0	3.5	3.5	3.7	2.5	2.8	3.0	3.0	1.9	2.9	2.5	2.8	2.6	2.7	2.3
Percentage of Terrigenous Material	41	16	45	45	42	17	9	29	24	23	15	14	11	25	21	3	14	16	11	10	10	10	13	11	9	17	13
Brackish Water Species																											
Ammonia tepida (Cushman)	36	6	6	.	**9**	4	1	*X*	1	*X*	3	4	3	4	2	.	2	.	2	1	3	2	3	2	*X*	2	2
Protelphidium tisburyense (Butcher)	27	1	**31**	.	**32**	2	*X*	1	1	*X*	1	.	*X*	1	3	2	*X*	.	2	.	*X*	*X*	*X*	.	.	.	.
Small Diagnostic Species																											
Bolivina rhomboidalis (Millett)	.	1	.	.	*X*	2	1	1	2	*X*	*X*	*X*	.	1	1	3	*X*	*X*	.	*X*	*X*	*X*	.	.	.	*X*	*X*
Cibicides lobatulus (Walker & Jacob)	3	5	7	.	3	9	10	11	**14**	**15**	10	8	15	7	9	5	6	5	12	**12**	5	8	7	5	6	**4**	5
Elphidium hyalocostatum Todd	4	7	3	.	2	5	5	6	8	6	8	8	7	5	6	9	3	1	5	3	2	2	4	4	2	3	1
Glabratella patelliformis (Brady)	1	3	2	.	1	12	4	4	8	4	*X*	*X*	*X*	*X*	3	8	1	*X*	*X*	1	*X*	*X*	2	*X*	1	*X*	2
Rosalina vilardeboana d'Orbigny	1	3	.	.	.	22	17	27	**21**	16	**3**	2	3	8	18	42	.	.	.	*X*	*X*	.	.	.	*X*	*X*	*X*
Pateoris australis (Parr)	.	1	.	.	.	3	5	4	2	4	.	*X*	2	3	5	*X*	1	.	.	.	*X*	1	*X*	3	3	1	*X*
Large Diagnostic Species																											
Amphistegina madagascariensis d'Orbigny	.	.	.	.	.	.	*X*	*X*	*X*	*X*	.	*X*	1	.	*X*	.	2	.	.	*X*	1	.	.	1	*X*	*X*	*X*
Cymbaloporetta bradyi (Cushman)	3	1	5	.	8	2	1	1	2	*X*	2	2	2	2	5	.	8	*X*	2	1	4	1	5	*X*	3	3	2
Fijiella simplex (Cushman)	1	4	4	.	3	*X*	2	1	*X*	2	1	2	1	*X*	*X*	.	7	*X*	*X*	1	4	3	5	*X*	7	5	6
Marginopora vertebralis (Blainville)	.	1	.	.	1	*X*	.	.	.	*X*	*X*	.	.	.	.	.	6	*X*	.	1	**2**	1	3	3	3	3	4
Peneroplis pertusus (Forskål)	.	1	*X*	.	1	.	*X*	.	.	*X*	.	.	.	*X*	.	*X*	*X*	.	3	.	*X*	*X*	*X*	.	*X*	.	*X*
Quinqueloculina curta Cushman	6	6	12	.	6	2	5	3	3	7	4	5	4	3	2	1	12	17	6	8	12	10	15	7	9	14	18
Quinqueloculina parkeri (Brady)	.	1	*X*	.	*X*	.	1	1	*X*	*X*	*X*	*X*	*X*	.	.	.	2	2	1	*X*	3	2	*X*	*X*	.	.	1
Spirolina arietina (Batsch)	.	1	*X*	.	3	1	3	3	**2**	2	*X*	3	2	*X*	*X*	*X*	5	6	3	4	5	6	2	7	10	*X*	4
Other Species																											
Anomalina glabrata Cushman	3	.	*X*	.	*X*	2	1	1	2	*X*	.	.	.	1	*X*	2	.	.	.	.	*X*	*X*	*X*	*X*	.	.	.
Bolivina limbata Brady	2	4	*X*	.	1	15	7	7	5	6	2	3	5	7	**4**	15	3	.	3	2	3	5	2	2	2	1	2
Bolivinella folia (Parker & Jones)	.	.	.	.	.	.	.	.	.	.	.	.	.	*X*	*X*	.	.	.	.	.	.	.	.	.	.	.	.
Clavulina pacifica Cushman	.	*X*	7	.	*X*	.	*X*	.	.	*X*	.	.	.	.	.	.	1	.	.	.	.	.	*X*	.	.	*X*	*X*
Elphidium advenum (Cushman)	1	2	2	.	*X*	*X*	1	1	*X*	*X*	*X*	2	.	2	2	.	*X*	.	5	5	*X*	2	2	1	1	1	*X*
Elphidium simplex Cushman	1	.	.	.	.	*X*	2	1	*X*	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Fissurina marginata (Montagu)	.	*X*	.	.	.	.	*X*	.	.	*X*	*X*	.	.	*X*	.	.	*X*		.	*X*	.	.	.	.	.	*X*	.
Globigerinoides trilobus (Reuss)	.	1	.	.	.	1	*X*	1	4	*X*	**1**	*X*	*X*	*X*	*X*	.	1	.	*X*	*X*	.	.	.	.	.	*X*	.
Hauerina ornatissima (Karrer)	.	1	.	.	.	*X*	1	1	*X*	*X*	*X*	.	.	.	.	.	1	*X*	.	*X*	*X*	.	*X*	1	1	*X*	*X*
Hauerina pacifica Cushman	1	13	6	.	4	6	16	10	14	13	36	34	28	22	12	4	2	56	29	38	22	36	14	34	28	19	23
Heterostegina suborbicularis d'Orbigny	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	*X*	.	.	.	.	.	.
Planorbulina mediterranensis d'Orbigny	.	*X*	.	.	.	*X*	*X*	.	*X*	*X*	*X*	.	.	*X*	*X*	.	1	.	.	*X*	.	.	*X*	.	*X*	*X*	.
Quinqueloculina distorqueata Cushman	.	3	.	.	*X*	1	2	1	1	2	3	3	*X*	2	2	.	2	4	5	3	5	3	3	10	5	4	3
Quinqueloculina granulocostata Germeraad	*X*	2	*X*	.	2	1	.	.	*X*	*X*	2	2	2	2	2	.	2	*X*	2	*X*	2	*X*	3	3	1	2	1
Quinqueloculina kerimbatica (Heron-Allen & Earland)	.	1	.	.	1	.	.	.	.	*X*	*X*	1	.	.	*X*	.	*X*	.	.	*X*	2	*X*	1	1	4	2	2
Quinqueloculina laevigata d'Orbigny	2	8	11	.	4	3	5	4	5	3	5	5	6	16	8	4	1	*X*	5	2	5	2	3	2	2	6	*X*
Quinqueloculina poeyana d'Orbigny	.	2	*X*	.	*X*	1	*X*	1	1	1	2	2	4	3	4	1	*X*	*X*	4	1	*X*	*X*	3	2	.	1	*X*
Siphogenerina costata Schlumberger	.	1	.	.	*X*	*X*	*X*	.	.	*X*	*X*	.	.	.	*X*	.	1	.	.	*X*	*X*	1	*X*	.	1	*X*	*X*
Siphonina tubulosa Cushman	.	.	.	.	.	.	.	.	.	.	.	*X*	*X*	.	.	.	.	.	.	.	.	.	.	.	.	.	.

TABLE 1 (*cont.*)

	I ESTUARINE SANDS					IIa VERY FINE CHANNEL SANDS										IIb	III BEACH AND FINE "NEARSHORE" SANDS										
SAMPLE NUMBER	20	21	1003	1004	1005	104	105	207	400	701	902	905	906	1000	1001	1303	339	901	903	904	907	909	910	911	912	913	914
Siphoninoides echinata (Brady)	1	2	*X*	.	*X*	.	.	.	.	*X*	.	*X*	.	*X*	.	*X*	2	*X*	*X*	2	2	*X*	1	3	1	1	3
Spirillina inaequalis Brady	.	.	*X*	.	.	*X*	1	.	**X**	*X*	*X*	.	.	*X*	*X*	2	*X*	.	.	.	.	.	.	.	.	.	.
Spiroloculina communis Cushman & Todd	.	.	.	.	.	*X*	*X*	*X*	*X*	*X*	*X*	.	.	*X*	*X*	.	*X*	.	.	.	.	.	.	.	.	*X*	*X*
Spiroloculina corrugata Cushman & Todd	2	2	*X*	.	1	*X*	2	.	.	*X*	1	*X*	*X*	.	*X*	.	2	*X*	.	*X*	1	*X*	2	*X*	*X*	*X*	*X*
Spiroloculina elegantissima Said	.	.	.	.	.	.	.	.	.	.	.	*X*	.	.	.	.	.	.	.	.	*X*	.	.	.	.	*X*	.
Textularia agglutinans d'Orbigny	.	1	.	.	.	1	.	.	*X*	*X*	.	.	.	.	.	.	1	.	.	.	*X*	.	*X*	.	*X*	1	*X*
Trifarina bradyi Cushman	4	12	*X*	.	8	1	2	1	**1**	5	6	6	4	3	2	*X*	9	2	6	**5**	5	7	**11**	3	5	17	10
Triloculina irregularis (d'Orbigny)	.	.	.	.	*X*	.	*X*	.	.	*X*	*X*	.	.	.	*X*	.	*X*	*X*	.	*X*	*X*	.	*X*	.	*X*	*X*	.
Triloculina linneiana d'Orbigny	.	.	*X*	.	*X*	.	.	*X*	*X*	*X*	.	.	.	*X*	*X*	*X*	1	.	.	.	*X*	*X*	*X*	.	*X*	*X*	.
Triloculina oblonga (Montagu)	1	3	*X*	.	*X*	2	1	3	*X*	1	5	3	5	2	2	.	2	1	3	*X*	3	1	1	*X*	.	*X*	1
Triloculina trigonula (Lamarck)	.	*X*	*X*	.	.	*X*	*X*	1	.	*X*	.	.	.	*X*	*X*	.	*X*	.	.	.	*X*	.	*X*	.	.	*X*	.
Others (7 spp.)	.	*X*	*X*	.	4	2	3	1	2	1	**2**	1	3	3	4	*X*	2	.	*X*	*X*	2	**4**	3	3	2	3	3
Number of specimens/g sediment	8	95	7	0	22	972	516	116	455	285	325	173	173	297	799	540	275	5	136	111	150	55	309	39	56	307	368

NOTE: values in bold faced type indicate living specimens present. $X = < 1\%$.

TABLE 1 (*cont.*)

DISTRIBUTION OF FORAMINIFERA BY PERCENTAGE OF ABUNDANCE

	IV FINE CHANNEL SANDS LOW TERRIGENOUS CONTENT											Va DEEP CHANNEL			Vb REEF FLAT SANDS														VI FOSSIL BEACH SANDS			
SAMPLE NUMBER	106	108	114	119	203	300	301	302	306	308	700	600	401	402	404	800	1002	1100	1101	1102	1200	1201	1300	1301	1302	1304	1305	1306	13	16	18	19
Mean Grain Size (ϕ)	2.5	2.5	2.0	2.5	2.5	2.0	2.7	2.0	1.8	2.3	2.1	0.5	0.2	2.4	0.9	0.3	0.7	0.6	1.2	0.3	0.9	2.3	0.4	−0.3	0.2	0.3	−0.7	−0.7	2.2	0.6	1.0	2.6
Percentage of Terrigenous Material	4	4	4	4	8	.	6	3	3	2	8	–	3	2	–	5	6	14	4	8	1	6	1	1	1	2	1	1	64	2	–	29
Brackish Water Species																																
Ammonia tepida (Cushman)	*X*	.	*X*	.	4	.	.	.	1	*X*	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	2
Protelphidium tisburyense (Butcher)	.	.	.	.	*X*	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4
Small Diagnostic Species																																
Bolivina rhomboidalis (Millett)	.	*X*	*X*	1	1	.	*X*	*X*	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2
Cibicides lobatulus (Walker & Jacob)	5	12	4	8	6	1	11	5	4	2	1	.	3	8	*X*	.	.	**1**	*X*	3	2	1	.	2	1	4	2	1	.	.	14	11
Elphidium hyalocostatum Todd	2	12	1	6	5	*X*	3	3	.	1	2	.	1	3	.	.	.	.	1	2	2	1	.	.	1	**3**	.	.	.	.	.	5
Glabratella patelliformis (Brady)	3	4	3	5	2	1	2	3	.	2	*X*	.	.	2	*X*	.	.	.	*X*	*X*	.	1	.	*X*	2	2	.	1	.	.	.	1
Rosalina vilardeboana d'Orbigny	2	6	1	5	3	*X*	3	1	5	*X*	.	*X*	8	2	.	.	.	2	.	.	.	.	.	*X*	*X*	*X*	.	.	.	.	.	.
Pateoris australis (Parr)	2	3	2	3	3	.	2	1	1	*X*	1	.	2	*X*	.	.	.	.	.	.	*X*	*X*	.	.	*X*	*X*	.	.	.	.	.	.
Large Diagnostic Species																																
Amphistegina madagascariensis d'Orbigny	2	.	1	*X*	*X*	1	1	9	13	6	.	58	**22**	1	**91**	95	**54**	**56**	16	.	8	4	80	**44**	38	5	43	61	.	1	.	.
Cymbaloporetta bradyi (Cushman)	3	*X*	2	2	5	2	2	2	2	2	3	.	1	3	.	.	.	.	**6**	**5**	3	19	.	**X**	**3**	**3**	.	.	.	11	.	2
Fijiella simplex (Cushman)	5	3	7	4	4	14	6	8	6	11	8	*X*	**4**	6	*X*	.	.	**2**	3	3	2	7	.	3	3	2	.	1	.	5	7	2
Marginopora vertebralis Blainville	5	.	8	.	3	7	4	7	2	9	4	9	**10**	2	*X*	5	32	2	**19**	3	29	10	14	13	10	22	5	20	.	.	7	1
Peneroplis pertusus (Forskål)	*X*	.	1	1	1	1	1	1	.	1	*X*	*X*	.	1	.	.	.	*X*	3	*X*	3	4	*X*	1	1	.	5	.	.	.	.	.
Quinqueloculina curta Cushman	11	14	15	4	9	20	9	10	7	18	21	6	9	19	2	.	.	8	9	13	2	13	*X*	7	8	10	13	4	.	36	22	8
Quinqueloculina parkeri (Brady)	1	.	2	1	1	2	1	2	1	4	5	*X*	9	1	*X*	.	.	.	5	5	11	6	*X*	2	1	3	5	.	.	1	7	1
Spirolina aretina (Batsch)	6	4	5	3	3	7	5	10	3	16	4	1	6	4	1	.	11	**4**	9	8	11	11	2	3	4	4	5	.	.	3	.	1
Other Species																																
Anomalina glabrata Cushman	*X*	.	*X*	*X*	*X*	.	*X*	*X*	2	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	*X*	.	.	.	.	.	.	.
Bolivina limbata Brady	2	2	1	3	1	*X*	2	2	1	1	*X*	.	1	1	.	.	.	*X*	*X*	*X*	2	*X*	.	.	*X*	1	.	.	.	.	.	1
Bolivinella folia (Parker & Jones)	*X*	.	.	.	*X*	.	.	.	.	.	*X*	.	.	*X*	.	.	.	.	.	.	.	.	.	.	.	*X*	.	.	.	.	.	.
Clavulina pacifica Cushman	1	.	.	.	*X*	1	*X*	.	.	.	*X*	.	2	1	.	.	.	.	*X*	.	.	.	.	.	*X*	.	.	.	.	.	.	.
Elphidium advenum (Cushman)	*X*	*X*	*X*	1	1	*X*	.	.	1	*X*	.	.	.	*X*	.	.	.	*X*	.	*X*	1	.		.	.	.	.	.	.	.	.	.
Elphidium simplex Cushman	*X*	*X*	.	*X*	1	.	.	.	.	.	1	.	.	.	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.	.	.	*X*
Fissurina marginata (Montagu)	.	.	.	.	.	.	*X*	.	.	.	.	.	.	.	.	.	.	*X*	.	.	.	.	.	*X*	*X*	.	.	.	.	.	.	.
Globigerinoides trilobus (Reuss)	.	*X*	1	.	*X*	*X*	*X*	.	1	*X*	.	.	.	*X*	.	.	.	.	*X*	*X*	.	.	.	.	.	.	2	.	.	.	.	*X*
Hauerina ornatissima (Karrer)	1	3	.	.	*X*	1	*X*	*X*	2	1	2	.	1	1	.	.	.	.	*X*	3	.	1	.	.	*X*	1	.	.	.	.	.	.
Hauerina pacifica Cushman	12	15	17	19	24	12	14	8	1	3	6	.	4	16	*X*	.	.	**7**	9	22	7	9	.	8	10	17	5	4	.	11	22	33
Heterostegina suborbicularis d'Orbigny	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	*X*	*X*	.	.	.	.	.	.	.	.	.	.	.	.

TABLE 1 (*cont.*)

	IV FINE CHANNEL SANDS LOW TERRIGENOUS CONTENT											Va DEEP CHANNEL			Vb REEF FLAT SANDS														VI FOSSIL BEACH SANDS			
SAMPLE NUMBER	106	108	114	119	203	300	301	302	306	308	700	600	401	402	404	800	1002	1100	1101	1102	1200	1201	1300	1301	1302	1304	1305	1306	13	16	18	19
Planorbulina mediterranensis d'Orbigny	1	.	1	*X*	.	.	2	.	1	1	*X*	.	.	1	.	.	.	.	.	.	.	1	*X*	*X*	*X*	2	5	.	.	.	.	.
Quinqueloculina distorqueata Cushman	3	5	1	3	1	2	5	1	2	1	*X*	*X*	1	3	.	.	.	1	3	5	2	1	*X*	*X*	*X*	3	3	2	.	.	.	4
Quinqueloculina granulocostata Germeraad	2	3	3	.	2	2	2	2	1	2	1	*X*	3	*X*	.	.	.	1	2	5	*X*	*X*	*X*	.	*X*	*X*	.	4	.	5	.	1
Quinqueloculina kerimbatica (Heron-Allen & Earland)	.	.	.	.	1	1	.	*X*	*X*	1	*X*	.	.	2	.	.	.	.	*X*	.	.	*X*	.	.	*X*	.	.	.	.	.	.	.
Quinqueloculina laevigata d'Orbigny	2	3	4	8	2	5	2	6	7	3	6	17	3	3	*X*	.	.	*X*	*X*	*X*	.	1	1	7	*X*	3	2	.	.	3	.	4
Quinqueloculina poeyana d'Orbigny	1	.	*X*	3	1	*X*	*X*	1	1	1	*X*	.	1	.	.	.	.	1	.	.	*X*	.	.	*X*	.	.	.	.	.	.	.	1
Siphogenerina costata Schlumberger	*X*	*X*	.	*X*	.	*X*	1	1	.	*X*	*X*	.	.	1	.	.	.	*X*	.	.	*X*	.	.	.	*X*	*X*	.	.	.	.	.	*X*
Siphonina tubulosa Cushman	.	.	.	.	.	.	.	.	.	.	.	.	.	.	*X*	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	*X*
Siphoninoides echinata (Brady)	1	1	1	2	.	6	*X*	2	4	3	3	*X*	.	2	.	.	.	*X*	5	*X*	4	5	.	*X*	2	1	.	.	.	8	14	*X*
Spirillina inaequalis Brady	.	.	1	.	.	.	1	1	*X*	1	.	.	.	.	.	.	.	**X**	.	.	.	.	.	*X*	*X*	.	.	.	.	.	.	.
Spiroloculina communis Cushman & Todd	*X*	*X*	.	.	1	.	*X*	*X*	.	*X*	*X*	.	.	*X*	.	.	.	.	*X*	*X*	1	.	.	*X*	*X*	1	.	.	.	.	.	.
Spiroloculina corrugata Cushman & Todd	4	*X*	3	3	1	2	3	2	1	1	.	*X*	.	1	*X*	.	.	2	2	4	.	*X*	.	.	*X*	*X*	.	.	.	.	.	.
Spiroloculina elegantissima Said	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	*X*	.	.	.	.	.	.	.	.	.	.	.	.
Textularia agglutinans d'Orbigny	2	.	*X*	1	.	1	2	3	13	3	9	1	2	1	2	.	.	.	.	.	.	.	*X*	*X*	*X*	1	.	.	.	.	.	*X*
Trifarina bradyi Cushman	10	4	4	6	10	4	8	5	1	2	4	.	2	9	.	.	.	4	2	7	4	3	.	2	5	5	.	2	.	3	7	9
Triloculina irregularis (d'Orbigny)	1	.	*X*	.	*X*	1	.	*X*	.	.	*X*	*X*	1	.	.	.	3	.	*X*	.	.	.	.	*X*	*X*	.	.	.	.	8	.	.
Triloculina linneiana d'Orbigny	2	*X*	1	2	.	2	1	.	1	1	1	*X*	.	*X*	.	.	.	.	.	.	.	*X*	*X*	*X*	*X*	2	.	.	.	.	.	.
Triloculina oblonga (Montagu)	4	.	2	2	*X*	2	2	1	2	1	3	*X*	2	*X*	.	.	.	3	*X*	.	.	.	.	.	.	.	.	.	100	4	.	4
Triloculina trigonula (Lamarck)	1	2	2	1	*X*	.	2	1	4	1	2	.	1	*X*	.	.	.	*X*	.	.	*X*	.	.	.	.	.	.	.	.	.	.	.
Others (7 spp.)	3	*X*	6	2	3	2	3	2	8	1	6	*X*	.	3	.	.	.	1	2	3	2	*X*	*X*	*X*	1	5	5	.	.	.	.	*X*
Number of specimens/g sediment	392	86	169	141	96	97	281	128	119	142	30	5	3	259	7	3	5	4	19	11	6	59	14	28	40	22	1	1	*X*	2	*X*	92

NOTE: values in bold-faced type indicate living specimens present. *X* = < 1 %.

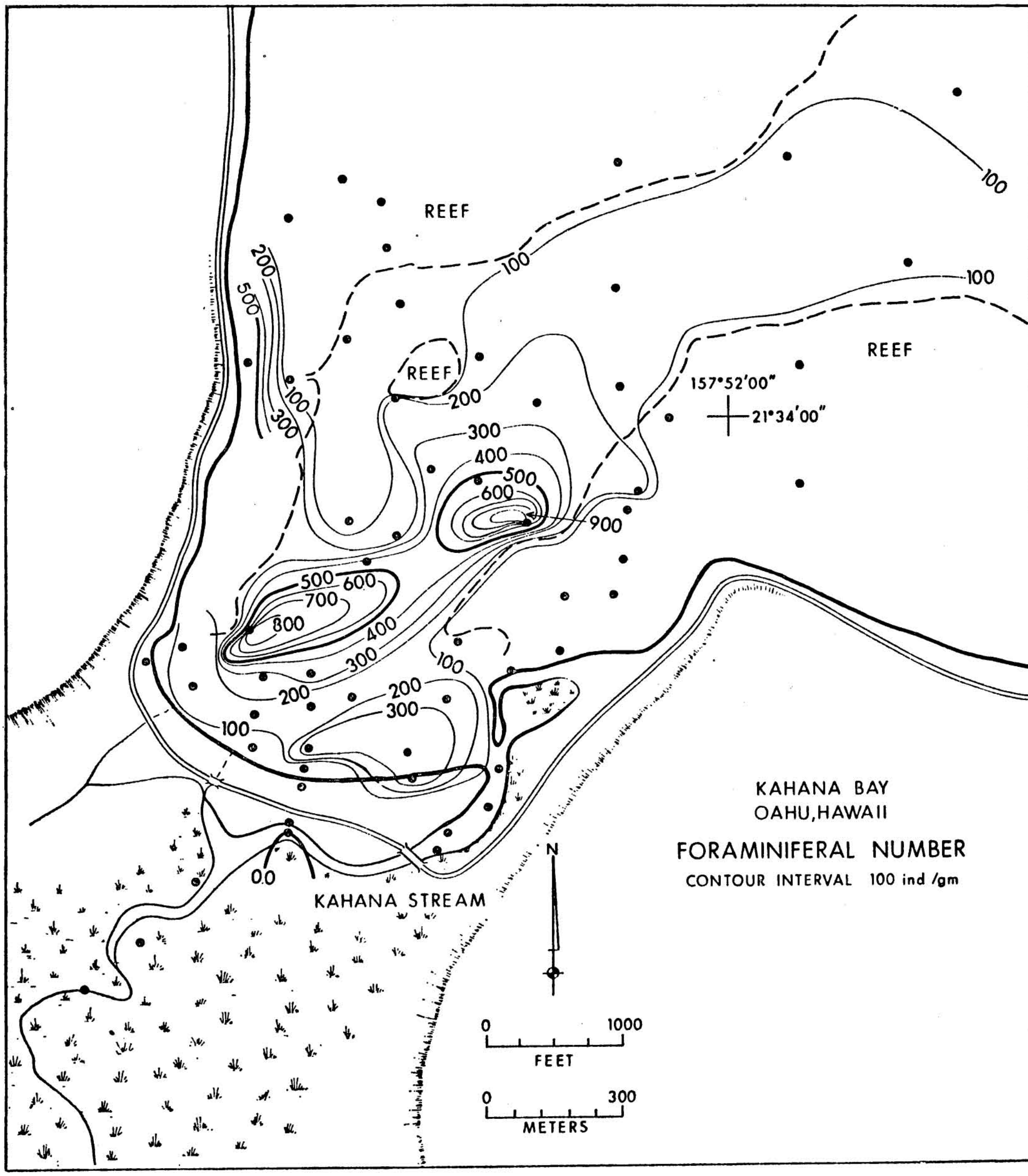

FIGURE 4. Population density: foraminifera.

small tests. For example, even though each of the species occurs along the beach in small quantity, the decrease in their percentages as wave energy increases from east to west suggests that surf agitation effectively winnows out the tests.

Large Species

The distribution of the large species *Cymbaloporetta bradyi* (Cushman), *Fijiella simplex* (Cushman), *Peneroplis pertusus* (Forskål), *Quinqueloculina curta* Cushman, *Q. parkeri* (Brady),

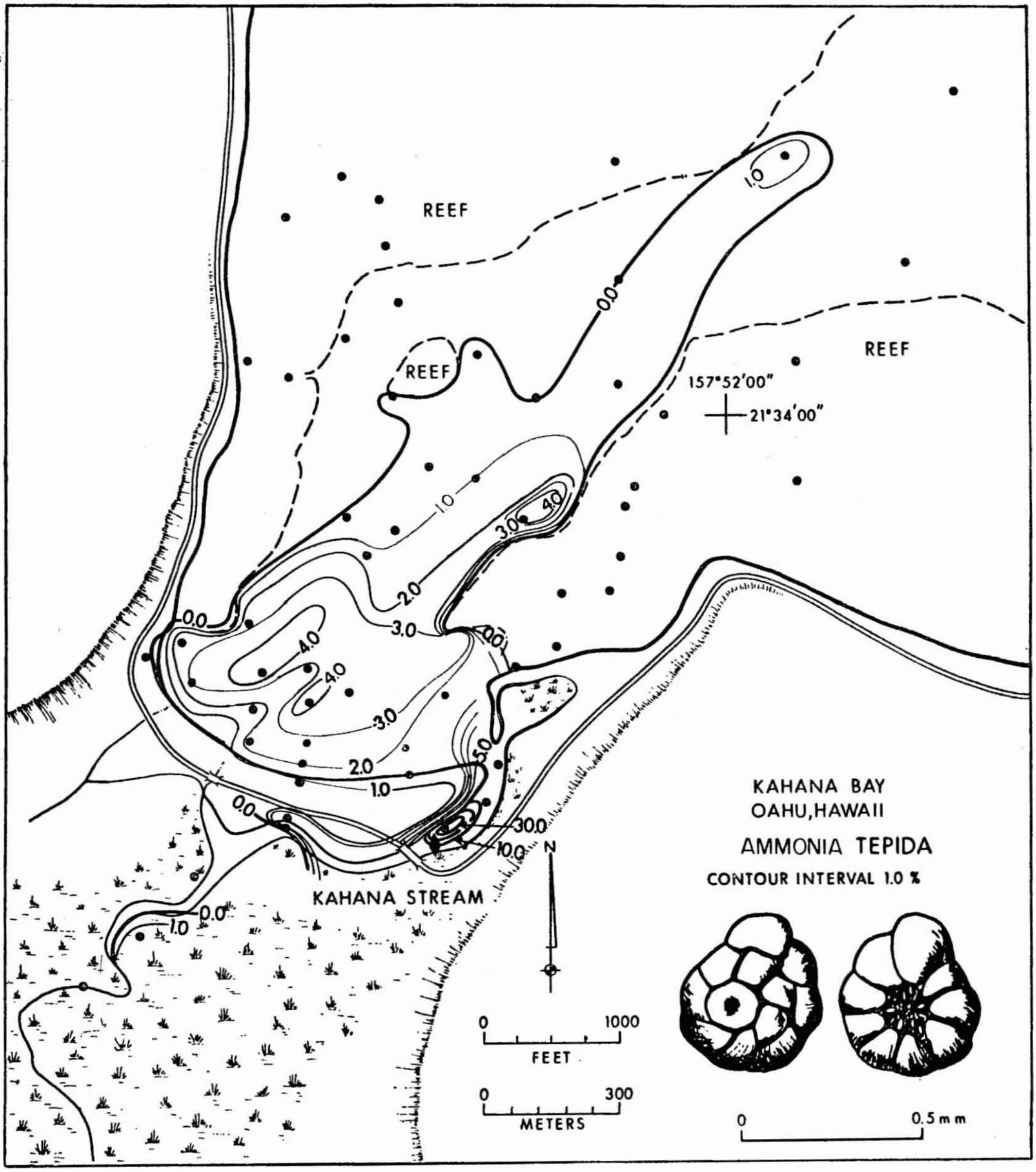

FIGURE 5.

and *Spirolina arietina* (Batsch) that are generally either angular or disc-shaped follows that of *Marginopora vertebralis* Blainville (Fig. 7). All of these forms are concentrated on the reef flat, and distributed downdrift to the adjacent channel sands, the beach, and the nearshore high-energy environments. Spotty distributions over the reef flat occur because most samples from this area have small foraminiferal numbers, so that the chance recovery of minor constituents must be small. Minimal values occur in the central sand channel areas associated with fine sediment. This pattern is the opposite of that previously described for the

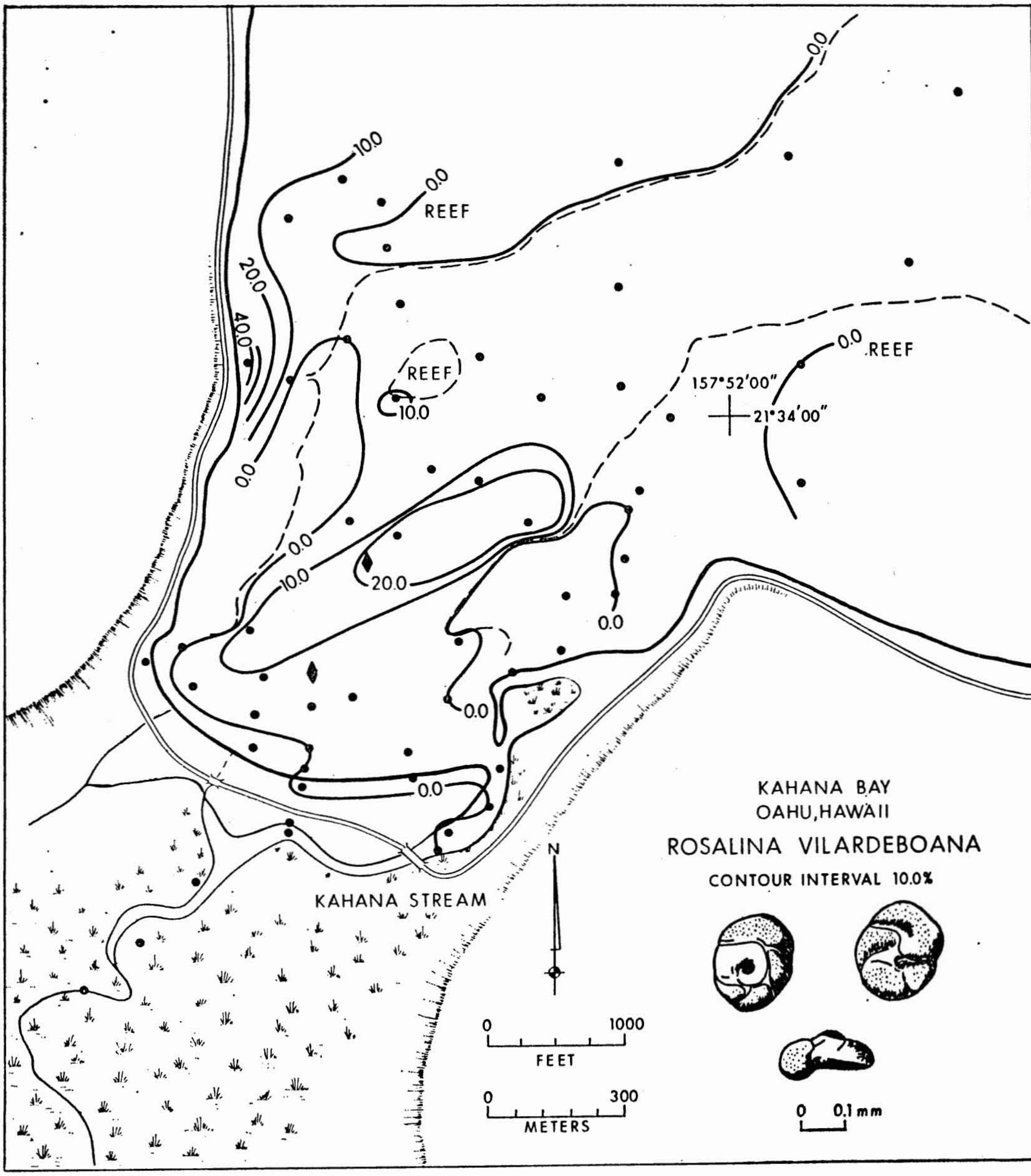

FIGURE 6.

small species. The contours suggest that the eastern reef flat is probably the source of these tests. The high gradients of the percentage contours of *Marginopora vertebralis* along the eastern reef edge and a paucity of all the large species along most of the eastern sand channel, indicate that little transport occurs across that boundary. Distributions of the large species around the patch reef are particularly interesting; low percentages found on the southern side of the reef, as well as the southeasterly drift of tracer sand at grids 1 and 2 (Figure 3), indicate that the tests are swept around the sides of the reef and moved into the bay. All species have relatively high percentage values on the western reef, but generally have lower values

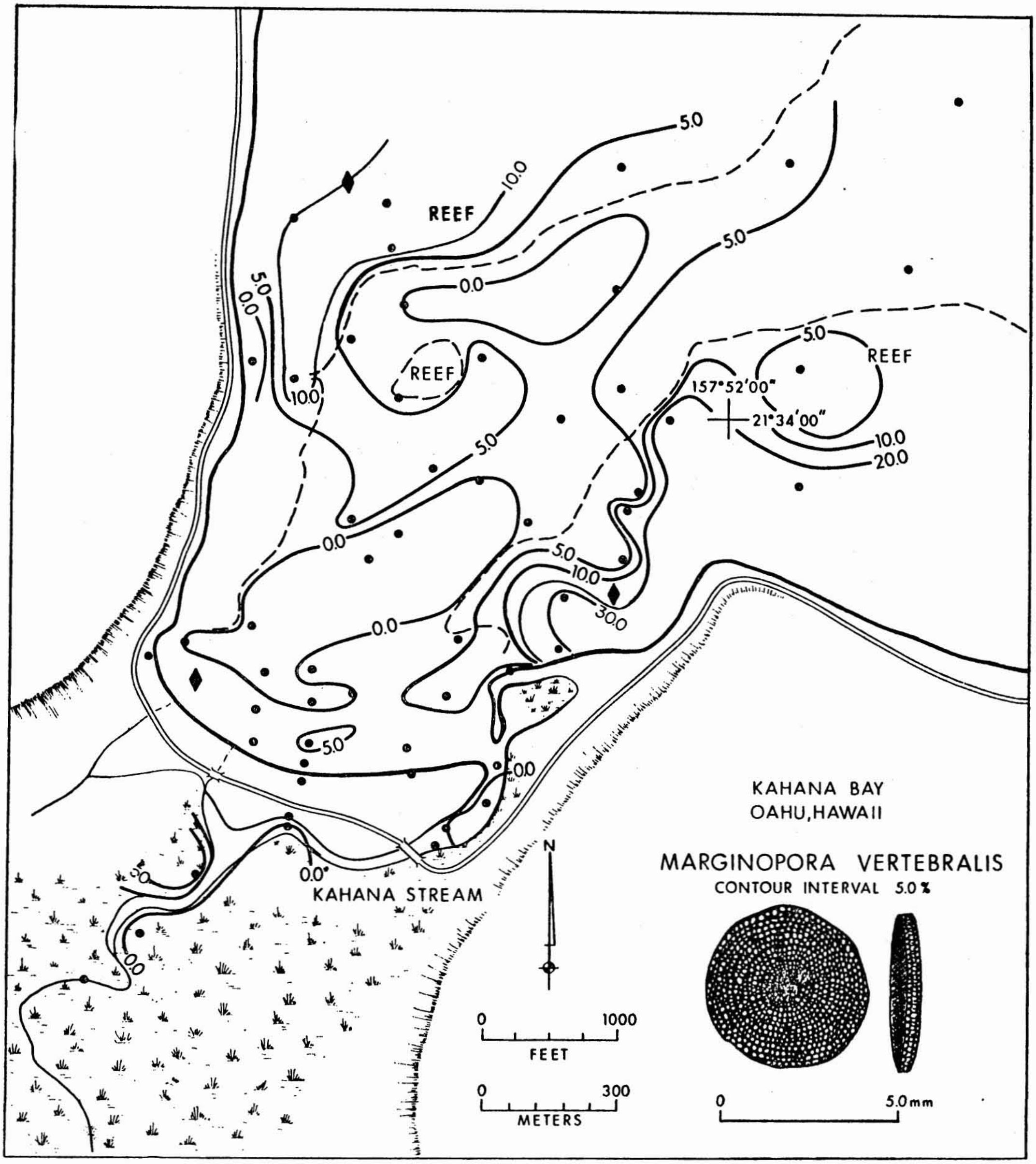

FIGURE 7.

in the very high-energy zone of the northern reef flat. These species are either absent (e.g., *Marginopora*) or rare along the northern side of the channel. It seems that the dominant transport of microfauna living on the reef flat may be first toward the west shore, then south, and finally eastward into the bay (at points such as the site of station 1201-F, Figure 3) along the western reef margin. This pattern of movement (summarized in Figure 9) corresponds to the pattern of water flow and sand movement across reef flats as proposed by Inman, Gayman, and Cox (1963). In a similar environment on Kauai, those workers found reef-dissecting

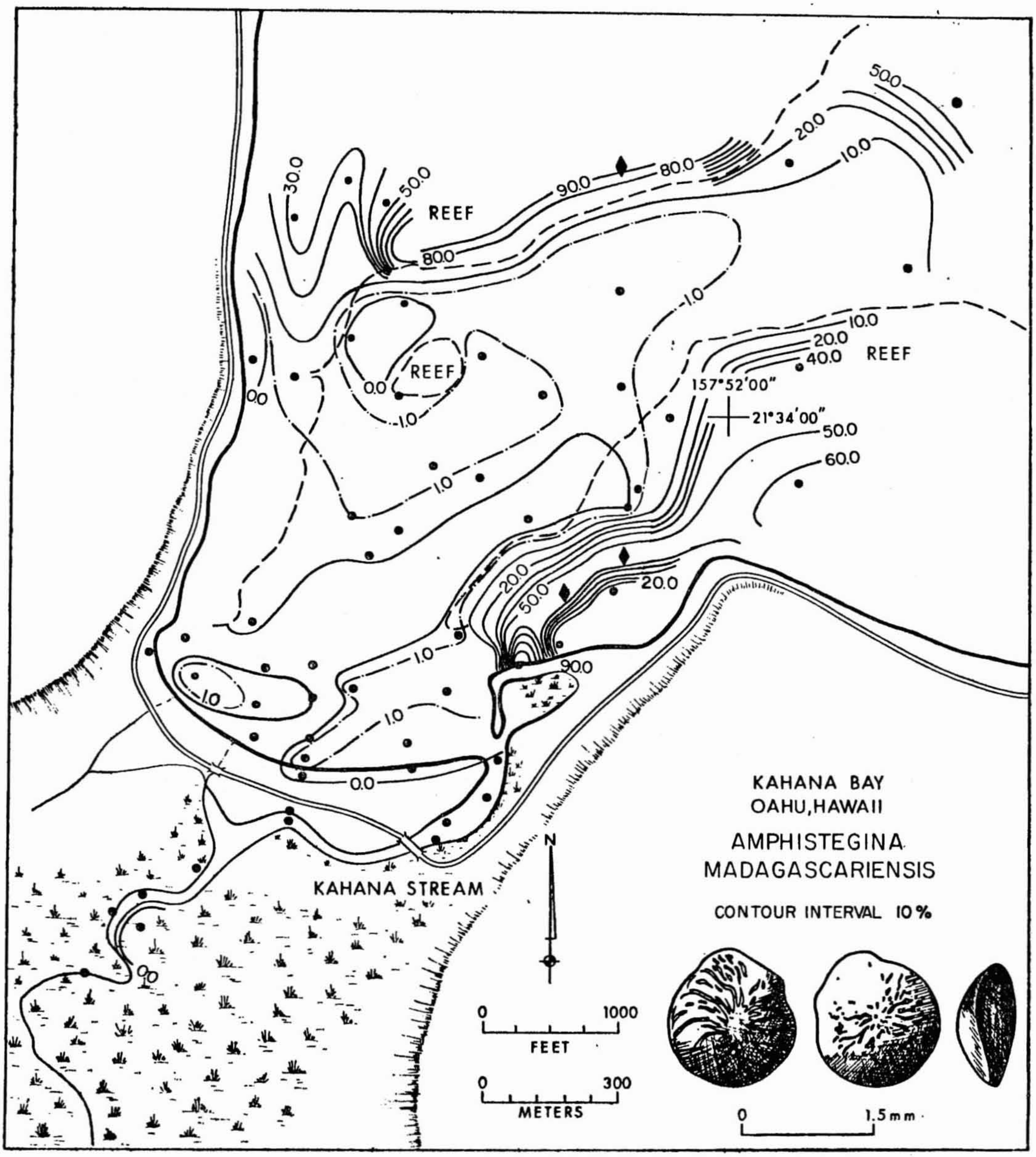

FIGURE 8.

sand channels with ripple marks aligned parallel to the shore, from which they deduced the dominant component of sand movement to be shoreward.

Amphistegina madagascariensis d'Orbigny

Muller (1972), in a recent study of the population dynamics of *Amphistegina madagascariensis* from Oahu, found that species living on algae attached to a rocky substrate, and producing an estimated 2×10^8 tests m^{-2} yr^{-1}, or 5×10^2 g $CaCO_3$ m^{-2} yr^{-1}. *Amphistegina* constitutes 0 to 95 percent of the foraminifera on the reefs of Kahana Bay (Figure 8), where numerous living specimens were recovered, even though the sampling was of reef sands. Its thick, lenticular

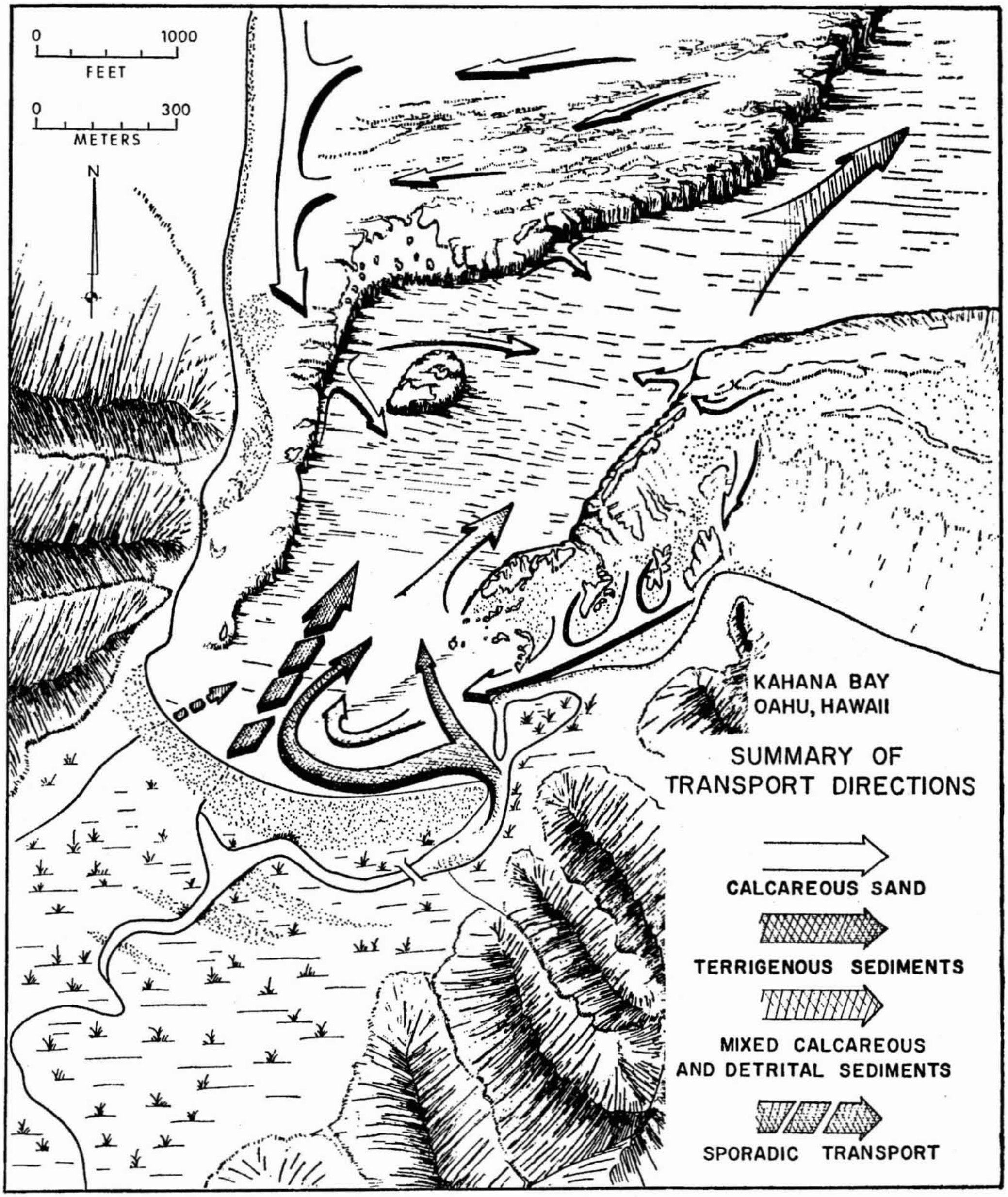

FIGURE 9.

test can withstand breakage in the high-energy reef environment; and individuals evidently can live for some time in sand pockets, even though their normal habitat is on the algae.

The demarkation presented by sharp percentage contour gradients along the reef margins is exaggerated due to the generally low foraminiferal numbers and low species diversity in the reef sands as compared with those in the channel sediments. Nevertheless, the distribution pattern indicates that the tests of *Amphistegina* are washed from the eastern reef across the stream mouth bar to the western corner of the bay. Currents apparently are not strong enough to transport the large tests of this species to the central bay area and portions of the beach. Absence of *Amphistegina* as well as *Heterostegina* and *Marginopora* from the beach is unusual since those genera are the dominant components of most Hawaiian beaches (Moberly and Chamberlain 1964).

There is a significant increase in percentages of *Amphistegina* in deeper water samples. Because concentrations of this species in the shallower channel sands are low, it would appear that the higher concentrations in deeper water must be derived from another source; e.g., the tests are probably washed directly off the outer reef flats by high wave-energy.

Relationship of Selected Species to Total Assemblages

Table 1 shows that only about one-third of the total species in the foraminiferal assemblages of the bay has been selected for discussion. The remaining species are of interest as being characteristic of this particular shallow water environment; however, they are unsuitable as sediment transport indicators because their distributions are ubiquitous (*Hauerina pacifica*), their representation too sparse (*Siphonina tubulosa*), or their percentage plots simply inconclusive.

SUMMARY

Relative concentrations of 16 species of foraminifera and live-dead distribution of three of these define paths of sediment transport in Kahana Bay (Figure 9).

Ammonia tepida and *Protelphidium tisburyense* were noted to be living only in the estuary of Kahana Stream, but their tests occurred westward in the inner bay and seaward on the eastern side of the channel. The components of transport are clearly delineated by the distribution of these brackish water species, and the accumulation of their small tests points out the low-energy regions of the bay.

Amphistegina madagascariensis, living on the reef, accumulates in reef pocket sands after death, and is transported offshore from the seaward reef margins, where wave action is strongest. Due to low wave-energy in the bay, tests are not moved toward the shoreline, to be incorporated in beach sands, as they are on most other Hawaiian beaches.

Other species showing distinctive distributional patterns make up less than one-third of the total species noted in the bay sediments. They may be grouped into small and large species, and their distribution appears to be principally a function of sorting as related to transport energy. Few specimens of these species were recovered alive.

The conclusions drawn from the distribution of the select species are borne out by data derived from physical measurements in the bay.

ACKNOWLEDGMENTS

Financial support for the study of sediment transport was provided by National Science Foundation under the National Sea Grant Program (grant no. GH 93). The study of the shallow water foraminiferal populations was partially supported by the National Science Foundation (grant no. GA 10421). J. O'Brien and F. Casciano of Look Laboratory generously supplied equipment and assistance for dyeing of the tracer sand. The writers are indebted to many colleagues for their opinions, freely given, on various aspects of the hydrology, oceanography, and sedimentation of the bay, among them: R. Moberly, J. F. Campbell, D. Gordon, L. Lepley, F. Peterson, and G. Shepherd.

LITERATURE CITED

Campbell, J. F., W. T. Coulbourn, R. Moberly, Jr., and B. R. Rosendahl. 1970. Reconnaissance sand inventory: off leeward Oahu. HIG 70-16. Hawaii Institute of Geophysics, University of Hawaii, Honolulu. 14 pp.

Coulbourn, W. T. 1971. Sedimentology of Kahana Bay, Oahu, Hawaii. HIG 71-14. Hawaii Institute of Geophysics, University of Hawaii, Honolulu. 141 pp.

Cox, D. C., and L. C. Gordon, Jr. 1970. Estuarine pollution in the State of Hawaii. Vol. 1. Statewide study. Water Resources Research Center, University of Hawaii, Honolulu. 151 pp.

FOLK, R. L. 1968. Petrology of sedimentary rocks. Hemphills, Austin, Texas. 170 pp.
GRABERT, B. 1971. Zur Eignung von Foraminiferen als Indikatoren für Sandwanderung. Dtsch. hydrogr. Z. 24: 1–14.
INMAN, D. L., W. R. GAYMAN, and D. C. COX. 1963. Littoral sedimentary processes on Kauai, a subtropical high island. Pacif. Sci. 17: 106–130.
MINK, J. F., K. H. LEE, and L. J. WATSON. 1963. Oahu water plan. Board of Water Supply, City and County of Honolulu. 68 pp.
MOBERLY, RALPH, JR. 1968. Loss of Hawaiian littoral sand. J. sediment. Petrol. 38: 17–34.
MOBERLY, R., JR., and T. CHAMBERLAIN. 1964. Hawaiian beach system. HIG 64-2. Hawaii Institute of Geophysics, University of Hawaii, Honolulu. 95 pp.
MULLER, P. H. 1972. Sediment production and population biology of *Amphistegina madagascariensis* (foraminifer), Oahu, Hawaii. M.S. Thesis. University of Hawaii, Honolulu.
OBDYKE, J. B. 1966. Fluorescent tracer manufacture. Paper from University of Florida Department of Coastal and Ocean Engineering.