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Sand Deposits Offshore Oahu, Hawaii[1]

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ABSTRACT: The value of sand as aggregate for concrete for the construction industry and as sediment for artificial beach replenishment at tourist destinations on Oahu has increased following a legislative moratorium on the mining of beach sand. Concern for future shortfalls of sand supply prompted prospecting for offshore deposits. Sand channels extend offshore from major valleys and coastal embayments on Oahu. Most of these accumulations join sinuous deposits of sediment ponded on ancient terraces that parallel the coastline. Sand cores were collected from these mapped deposits. Statistical analysis of particle size distributions of 279 samples from these cores reveals local areas that are promising for future exploitation. In some areas, variations of grain size can be related to water depth and distance from shore, but in most areas, grain sizes are not simply related to the geographic distribution of sampled sand. Along the leeward Oahu coast, size distributions are related to depth in core: 5 ft of fine sand covers medium and coarse sand. Comparisons between samples from different locales reveals relationships primarily to submarine geomorphology and secondarily to coastal wave climate.

Our investigation focuses on the relationships of grain size distributions of offshore sand deposits to water depth, distance from shore, wave climate, and proximity to submarine canyons or terraces, with the goal of identifying deposits with the potential for commercial exploitation. Sand is a valuable resource for the State of Hawaii. In addition to its use in the construction industry, it is in demand for numerous beach-stabilization and shoreline-enhancement projects (Gerritsen 1978). The need is particularly acute along the strip of hotels at Waikiki, now an artificial strand nourished by sand imported from other areas around Oahu. With a legislative moratorium on the mining of beach sand within the state, the dune and offshore deposits have acquired an increased value (Dollar 1979). The extent of the dune deposits and grain size distributions of their sand are well known through mapping from aerial photographs and through size analysis of deposits now actively mined—for example, at Waimanalo (Figure 1). In contrast, knowledge of the offshore deposits is scanty. Prospecting for offshore reserves has been the focus of several University of Hawaii Sea Grant studies and projects (Campbell et al. 1970, 1971, Coulbourn 1971, Coulbourn et al. 1974, Moberly and Campbell 1969, Moberly et al. 1975), which have delineated the general outlines of the larger deposits between the shoreline and 100-m water depth (Figure 2).

Sand channels are incised into the reef flat fringing Oahu, their courses originally established by subaerial erosion during Pleistocene low stands of sea level (Moberly 1968). Quaternary sea level fluctuations have left shorelines and reefs exposed and submerged at various elevations around Oahu, and these stands have been the subject of numerous investigations (see Coulbourn et al. 1974, Stearns 1978 and references therein). Of importance to the current study is the relationship between submarine terrace formation and sand accumulation. Typically, these accumulations are derived from biogenic grains

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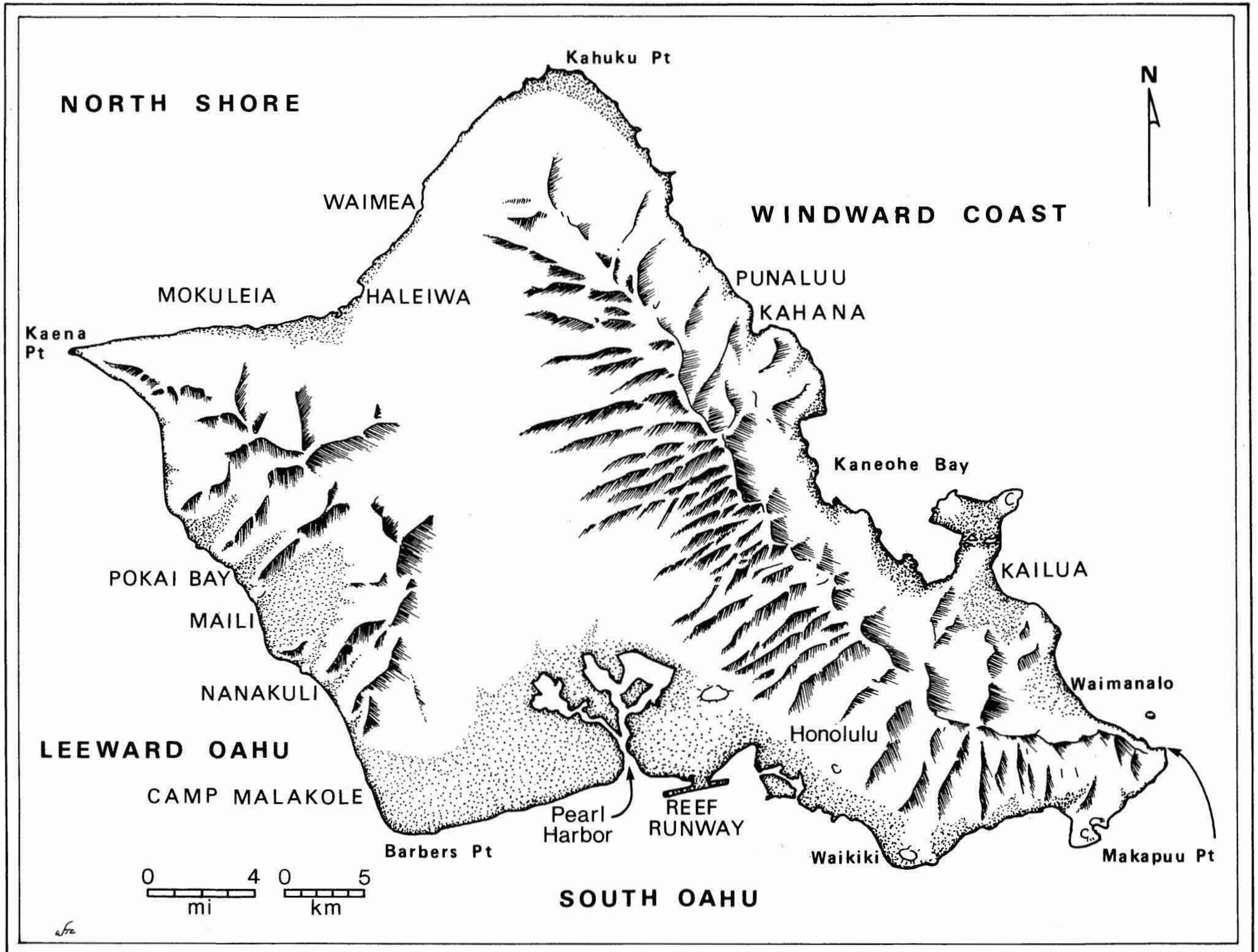

FIGURE 1. Location of place names, Oahu, Hawaii. Dot pattern outlines alluviated coastal plains and line pattern locates general topography of the Koolau (right) and Waianae (left) mountains.

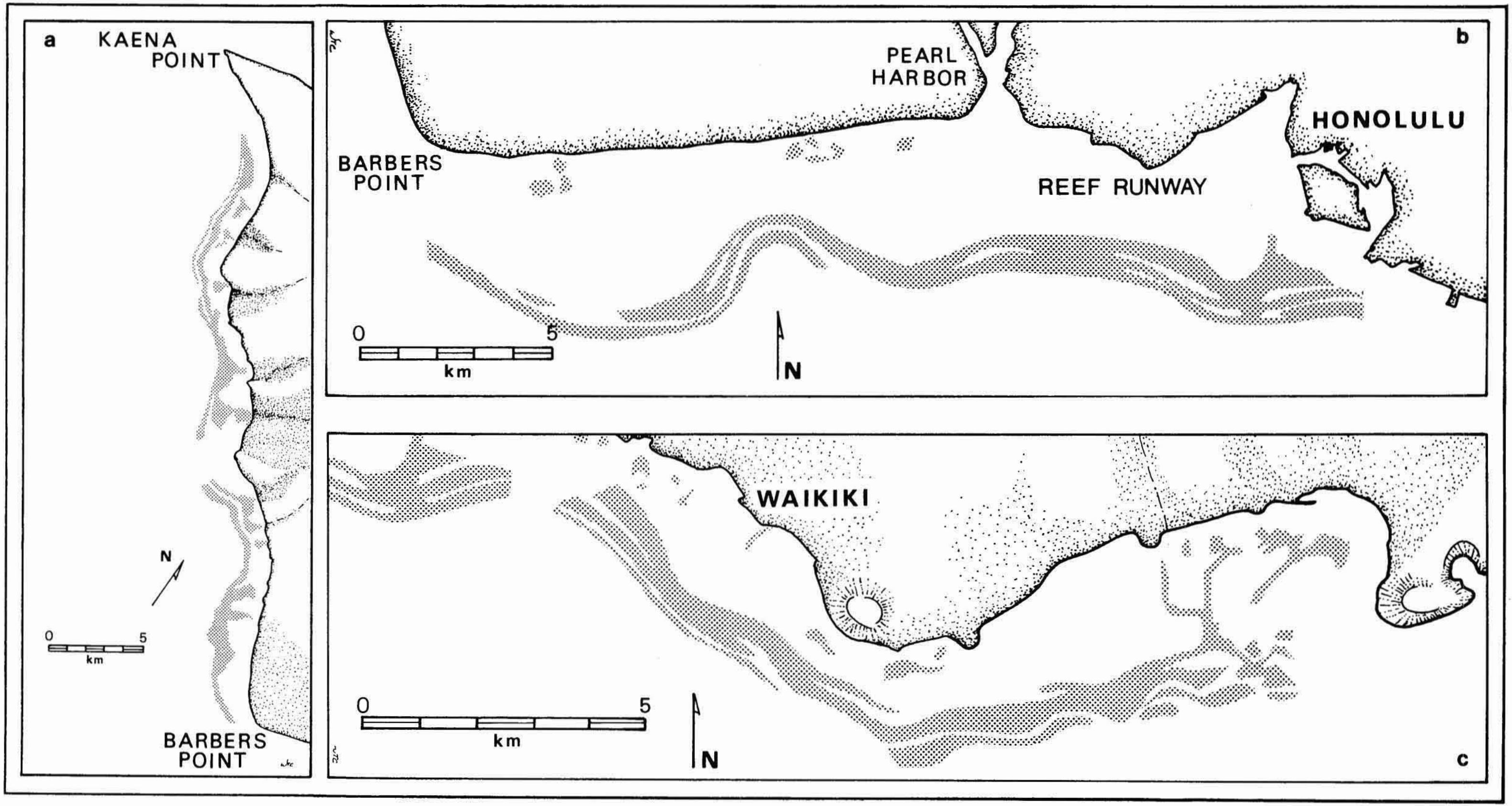

FIGURE 2. Distribution of sand offshore (gray dotted pattern areas): (*a*) leeward Oahu, (*b*) Pearl Harbor, and (*c*) Waikiki (after Coulbourn et al. 1974). Major streams are shown as dashed lines.

that were driven across the reef flat, onto and then along the beach face, before transport seaward by rip currents flowing through channels (Inman et al. 1963, Moberly 1968). These rip currents are particularly strong during high surf conditions, when they carry plumes of sediment seaward within channels as adjacent beach faces rapidly retreat. Seasonal heavy rains flush detrital grains seaward from estuaries, mixing them with the calcareous component accumulating offshore. Most of the deposits sampled are in sand channels or are lens-shaped in cross section and bury benches cut into the island slope or constructed as the surface of ancient fringing reefs. Particle-size distribution data for all 279 samples collected are available from the senior author.

Seismic surveys of Oahu coasts (Campbell et al. 1970) served as a guide for later research (Ocean Innovators 1977, 1979), and samples from cores taken during those various projects were analyzed for their grain size distributions (Campbell 1979). The data issuing from these projects are the basis for this report.

Changes in grain size and microconstituents may arise from the range of variability of the environment of production and of deposition in any one area, but also may indicate changes in the environment such as migration of deposystems. Because beach sands are related to coastal exposure (Moberly et al. 1965), we expect the offshore sands to reflect differences along each coast. Synthesis of our findings should add a measure of predictability to future searches for sand resources off the shores of the Hawaiian Islands.

ENVIRONMENT

The coastal geology of Oahu is varied in response to the microclimates created by the island topography, stream discharge, reef growth, wave climate, catastrophic events, tidal currents, and fluctuations in sea level (Figure 1; Macdonald and Abbott 1970).

Rainfall is mostly orographic. Because the island is located in the belt of northeast tradewinds, most of the precipitation falls on the windward, northeast coast where large drainage systems and submarine canyons are best developed, especially at Kahana and Punaluu (Coulbourn et al. 1974). The leeward, or southwest-facing, coast represents the opposite extreme. The tradewinds are depleted of moisture after crossing first the Koolau and then the Waianae mountain ranges; runoff is minimal, and terrigenous sediment is carried to the sea only during large local storms. Other coastal segments, such as those at Pearl Harbor and Waimea–Haleiwa–Mokuleia, represent conditions between these two extremes. Stream discharge is related to rainfall and inhibits or prevents reef growth altogether.

Wave climate also affects reef growth and sand transport. Wave frequency and surf amplitude vary seasonally (Inman et al. 1963, Moberly and Chamberlain 1964). Tradewind-driven waves predominate most of the year, primarily affecting the coast from Makapuu Pt. to Kahuku Pt. During the winter months, storms with southwesterly winds pass over the island chain, producing brief periods of wind-driven waves from Kaena Pt. to Barbers Pt. and eastward to Makapuu Pt. Also in winter, North Pacific storms drive larger, long-period swells toward the islands. These swells generate high surf along the entire coast between Kahuku Pt. and Kaena Pt. and at promontories between Kaena Pt. and Barbers Pt. In contrast, the long-period swell that is produced in the southern hemisphere by Antarctic winter storms reaches the south shore of Oahu in the summer months and generates surf along the coast from Makapuu Pt. to Barbers Pt., and also on the Waianae coast. Seasonally, Hawaiian waves probably rework sands to depths of several hundred feet. For example, waves 16.5 ft high with a period of 15 sec can set medium-grained quartz sand in motion at depths of 385 ft (Komar 1976). The lower density of organically formed calcite grains dominant in Hawaiian sands would deepen this threshold, as would longer-period waves of greater height.

Catastrophic events also shape the coast and transport sand. Hurricanes are infrequent (Armstrong 1983), but their impact is locally severe [e.g., Hurricane Iwa; see Tsutsui et al. (1987)]. Direct evidence in the form of transported moored current meters demonstrates the association between high surf and substrate movement (Noda 1983). Tsunamis occur from time to time: 1946 from Alaska, 1952 from Kamchatka, 1957 from the Aleutian Islands, 1960 from Chile, and 1964 from Alaska (Armstrong 1983). Highest runups are generally 20–30 ft; but locally, runups as high as 55 ft for the 1946 and 1960 events were recorded for the windward and north shores of the Hawaiian Islands (Armstrong 1983, Gerritsen 1978, Shepard 1963, Wiegel 1964). Although probably of major importance in shaping the distribution of offshore sediment around the islands of Hawaii, the influence of tsunamis on sediment accumulation patterns has not been systematically studied.

Currents around Oahu follow complex patterns that vary with the season and with the ebb and flood of the tide (Armstrong 1983, Laevastu et al. 1964). Little is known about current velocities at depth, and at this time the sample coverage is too sparse to predict current velocity from particle size distribution.

DATA COLLECTION AND ANALYSIS

Samples were obtained with a sand-core device that is jetted ahead as sand is pumped upward for collection (Ocean Innovators 1977, 1979). Some mixing of sediment from various subbottom depths is inevitable, and all primary structures are lost in the process. Most of our samples were taken at intervals of 5 ft downcore, a scale coarse enough to record longer-term sediment contrasts and to smooth fluctuations produced by sediment mixing during the coring process. The corer is restricted to operation at depths less than 300 ft but is capable of penetrating to about 60 ft subbottom. Boreholes were completed at 32 stations in 76 locations around Oahu. Sampling was not random. Published maps (Figure 2) were used to locate large deposits, which scuba divers visually inspected. If no hard substrate was showing, the deposit was test probed with a water jet. Deposits were cored where thickness warranted.

The samples were analyzed for size with nested sieves at $\frac{1}{2}$-ϕ increments. The laboratory procedure followed is standard. Grains passing the 4-ϕ sieve are not included in our analyses, sharply truncating some of the distributions.

The sample notation refers to: core location–sublocation–core number–subbottom depth within that core. For example, core 56-2-1-10 is offshore of Kailua, Oahu (locality 56), from sublocality 2, and was sampled from the first core at 10 ft below the sea floor. The last number listed indicates depth below the sea floor, irrespective of core number.

Statistical procedures were used to evaluate spatial and depth trends within these particle size distributions and between the distributions and the environment. Initially, the statistics of mode, mean, standard deviation, and skewness were computed for each of the size–frequency distributions (after Griffiths 1967). (A list of moments, communalities, and varimax factor loadings is available from the senior author.) These values indicate a high degree of variability both within and between locations. Because this variability persists even when only core-top samples are considered, we partitioned the data into subsets. These subdivisions are geographic and assume that each contains samples exposed to similar oceanographic conditions, particularly with respect to wave exposure. This partition allows identification and removal of sample outliers, information that obscures broad patterns in analytic syntheses.

Cluster analysis is applied herein as an exploratory procedure to examine and to attempt to map major groupings, and to identify aberrant samples within each data subset. A weighted pair-group average linkage of euclidean distances[3] was used to gene-

[3] Euclidean distance as used here is the geometric mean of the sum of the differences between percentages:

$$d_{ij} = \left| \frac{\sum_{k=1}^{m} (x_{ik} - x_{jk})^2}{m} \right|^{1/2}$$

where d_{ij} = distance between sample i and sample j, m = number of size fractions, x_{ik} = proportion of the kth size fraction in sample i, and x_{jk} = proportion of the kth size fraction in sample j.

rate *Q*-mode dendrograms for sand samples taken from offshore of Kailua, Kahana, Punaluu, Waimea, Haleiwa, Mokuleia, Pokai Bay, Maili, Nanakuli, Camp Malakole, and the reef runway (Figure 1). The analytic procedure is described in Davis (1973). Identification of clusters is arbitrary but is supported by the statistics computed for the distributions within each locality. The cluster analysis method is particularly well suited for our investigation because our goal is not merely to find clean, coarse-to-medium sand, but also to develop a predictive capability. Ideally, the cluster patterns will outline areas of fine sands (areas to be avoided in future investigation) while highlighting areas containing the more valued coarse sands—deposits that should be mapped in detail for consideration for future exploitation.

Where the depth distribution of samples permitted, the relationship of the particle size distributions to geographic setting is examined with a multiple linear regression analysis, and the strength of the equation is assessed by the goodness-of-fit, the statistic *R*-square. We used the BMD 2R stepwise multiple linear regression routine (Dixon and Jennrich 1985).

After examination of the individual locales along each coast, cluster and factor analysis were used to analyze the combined and edited (outliers removed) data for each of the four distinct coastlines. Because one of our goals is to lay the groundwork for future prospecting, a standard sample was included in each analysis (referred to as ASTM-STD). The ASTM standard curve shown in Figure 3 is drawn within an envelope of particle size distributions considered ideal for fine aggregate for highway construction (ASTM Commit-

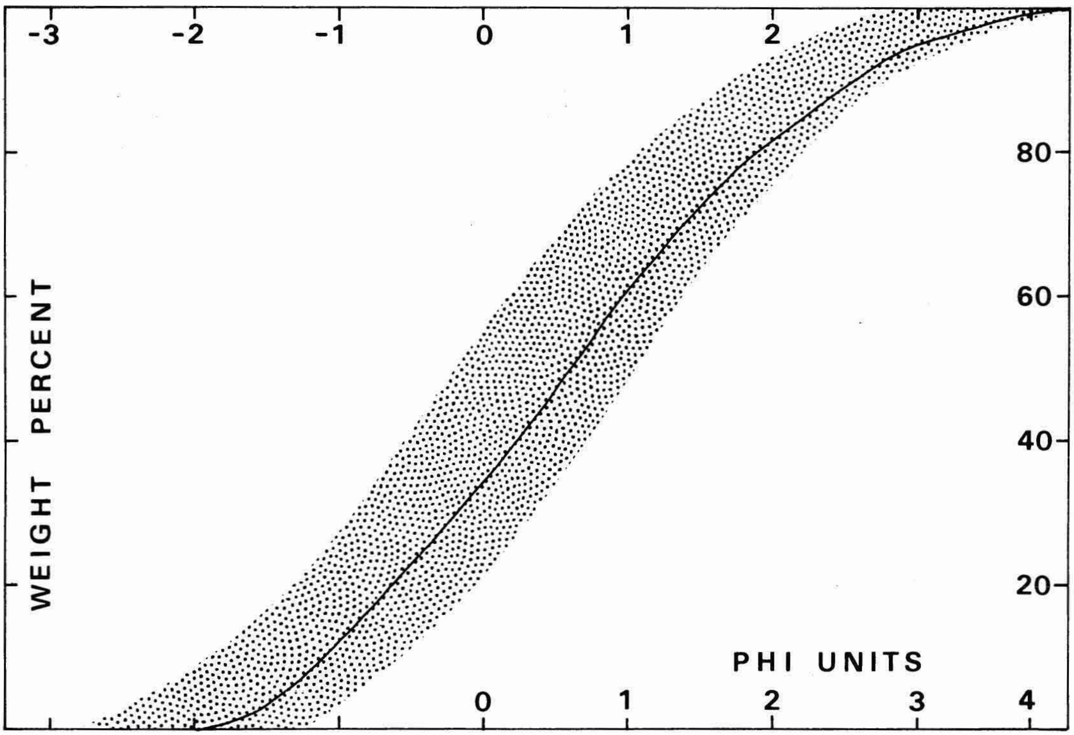

FIGURE 3. ASTM particle size distribution for fine aggregate suitable for highway construction (ASTM Committees C-9 and D-4 1952). Solid line represents cumulative curve of distribution used in multivariate statistical analyses (designated as ASTM-STD in text).

tees C-9 and D-4 1952:1). Samples with distributions resembling the ASTM standard are also coarse and well sorted enough to serve as suitable material for beach replenishment. A *Q*-mode factor analysis was applied to check the robustness of the pattern indicated in the cluster analysis. The analysis uses the statistical routine of Klovan and Kipp (1975), which produces a table of factor loadings and scores [see Joreskog et al. (1976) for details of method application]. The structure in the table of factor loadings is expected to correspond to that produced by the cluster analysis where the particle size distributions come from distinct populations, despite different similarity coefficients and analytic treatment. Where size distributions form a continuum or distinctions are smeared by mixed samples, the classifications produced by the two methods may differ. In the analysis of data from each coastline, factors represented by eigenvalues greater than 1 were retained. Because each analysis produced a three-factor model, a typical outcome in the analysis of size–frequency data (Syvitski 1984), the resulting factor components (row-normalized loadings) were plotted on ternary diagrams. The displays provide visual estimates of the similarity of all samples to each other and to the ASTM standard.

The distinctness of sample clusters along each coast was examined with a stepwise discriminant analysis (Jennrich and Sampson 1985, Pirkle et al. 1984). Each sample is coded according to its group assignment, as determined in the cluster analysis. Centroids, or averages, are computed for each group (Table 1). The distinctness of each group is assessed in the stepwise selection of a weighted linear combination of phi intervals that best predicts group assignment. The result is plotted as the distribution of sample points and centroids on a plane determined by two axes, or canonical variables (CV). This plane is oriented so that the separation of group centroids is maximized in the display. The variables (grain size intervals) selected and the weightings assigned to each can be used to attempt to assign a sedimentological interpretation to each axis.

WINDWARD OAHU

The northeast coast of Oahu stretches from Makapuu Pt. to Kahuku Pt. (Figure 1). Long expanses of beach are protected by broad fringing reefs at Waimanalo and Kailua. The only barrier reef in the Hawaiian Islands forms a lagoon at Kaneohe Bay. The area seaward of this reef remains unexplored for sand, but the volume of deposits inside the reef was the subject of investigation by Moberly and Campbell (1969). Northwest of Kaneohe Bay, submarine canyons head at steep-sided river valleys and cut seaward across fringing reefs.

Kailua

The 36 samples from Kailua Bay were cored from a sand channel that trends seaward with a low gradient (Figure 4*a*). The shallowest samples were taken from about 18 ft and the deepest from a little more than 60 ft. Northwest-flowing currents seaward of the reef flat (Laevastu et al. 1964) may affect the sand sampled at station 56. Except for location 55-1, most sands at stations 55 and 56 are fine-grained, like the sand on Kailua Beach (Moberly and Chamberlain 1964); the means generally exceed 2.5 ϕ and most are negatively skewed.

Cluster analysis identifies four major groups (Figure 4*b*) and one outlier, sample 56-2-2-15, which has two modes separated by a dearth of grains in the 1.5-ϕ interval. The samples are neatly clustered according to grain size: coarse sands (mean 0.11–1.14 ϕ) in cluster 4, medium and fine sands (mean 1.53–3.27 ϕ) in cluster 1, fine sands (mean 2.27–3.09 ϕ) in cluster 2, and very fine sands (mean > 3.10 ϕ) in cluster 3. Surface sands tend to be coarser and for the most part are grouped in clusters 1 and 4; finer sands generally occur below 10 ft subbottom (clusters 2 and 3). A lack of spatial trends in the surface sands may arise from reworking of sediment within this relatively shallow and narrow channel during tsunamis. Blocks of coral transported to shallow depths on this reef flat and high-water marks near the ceilings of the beach-front

TABLE 1

CENTROIDS FOR SAMPLE CLUSTERS

	WINDWARD OAHU					NORTH SHORE				
	CLUSTER					CLUSTER				
ϕ	1	2	3	4	ALL	1	2	3	4	ALL
−2.0	1.8	3.6	2.4	3.4	2.7	1.7	1.1	0.5	0.2	1.1
−1.5	1.7	2.9	1.8	2.7	2.3	1.1	0.5	0.3	0.3	0.7
−1.0	3.0	2.9	1.9	5.9	3.2	2.1	0.9	0.4	0.2	1.2
−0.5	4.7	2.7	1.5	12.1	4.6	3.1	1.4	1.3	0.3	2.0
0.0	8.2	3.6	1.0	27.4	8.4	5.4	2.0	1.7	1.4	3.2
0.5	16.6	6.6	1.2	25.4	11.8	11.6	3.9	2.8	8.1	6.8
1.0	21.8	9.1	1.2	13.6	12.2	18.8	7.1	4.4	28.0	12.0
1.5	22.0	12.3	1.5	5.3	12.0	24.1	17.7	7.4	46.5	18.8
2.0	10.2	7.7	2.4	2.5	6.6	18.3	27.7	11.4	11.5	18.8
2.5	4.4	10.6	5.9	0.6	6.1	9.3	23.7	21.0	2.2	16.3
3.0	3.5	19.7	24.6	0.5	12.5	3.2	11.6	33.0	0.7	13.5
3.5	1.3	12.9	37.5	0.3	12.0	0.9	1.9	13.6	0.3	4.6
4.0	0.4	4.4	14.6	0.1	4.5	0.2	0.4	1.2	0.2	0.5

	LEEWARD OAHU					SOUTH OAHU			
	CLUSTER					CLUSTER			
ϕ	1	2	3	4	ALL	1	2	3	ALL
−2.0	4.3	0.6	1.6	0.4	1.5	2.5	0.8	5.4	2.4
−1.5	4.6	0.3	1.3	0.0	1.3	2.8	1.0	5.6	2.6
−1.0	7.4	0.6	2.1	0.0	2.1	5.2	2.1	12.1	5.2
−0.5	9.7	0.7	3.0	0.7	2.9	7.7	2.9	16.1	7.3
0.0	13.2	1.2	4.9	1.0	4.3	10.5	4.7	19.3	9.8
0.5	16.0	2.3	7.4	1.5	6.2	14.5	6.7	18.3	12.2
1.0	15.1	3.7	11.6	1.8	8.5	13.7	8.7	9.5	11.1
1.5	11.1	7.8	17.7	3.5	12.3	14.1	10.7	5.4	11.3
2.0	7.8	14.2	19.0	4.0	15.2	11.4	12.7	3.3	10.5
2.5	5.4	23.9	15.9	6.7	17.9	8.3	16.0	2.6	10.2
3.0	3.1	29.1	9.6	22.5	17.4	5.4	19.0	1.7	9.9
3.5	1.5	11.4	4.1	28.6	7.2	2.5	10.3	0.6	5.1
4.0	0.6	3.8	1.6	19.7	2.6	1.2	3.7	0.0	1.9

homes attest to tsunami power, but the effect of tsunamis on the distribution of sand remains unassessed.

Kahana and Punaluu Sand Channels

Kahana and Punaluu beaches front coastal embayments that are the subaerial expression of relatively broad and deeply incised channels. Beach sands are poorly sorted and medium- to coarse-grained at Punaluu, and also poorly sorted but medium- to fine-grained at Kahana, where dilution of the calcareous component by fine, terrigenous input is considerable (Coulbourn 1971, Moberly and Chamberlain 1964). Both beaches are prograding (Campbell 1972), and sand extends seaward, completely flooring and partially filling the channels, each of which could hold accumulations of sand several tens of feet thick (Figure 5*a*). Microfossil indicators demonstrate that the sand in Kahana channel is derived from adjacent reef flats and the adjacent estuary, but the rate of seaward transport is unknown (Coulbourn 1971).

Samples from the two localities in Kahana

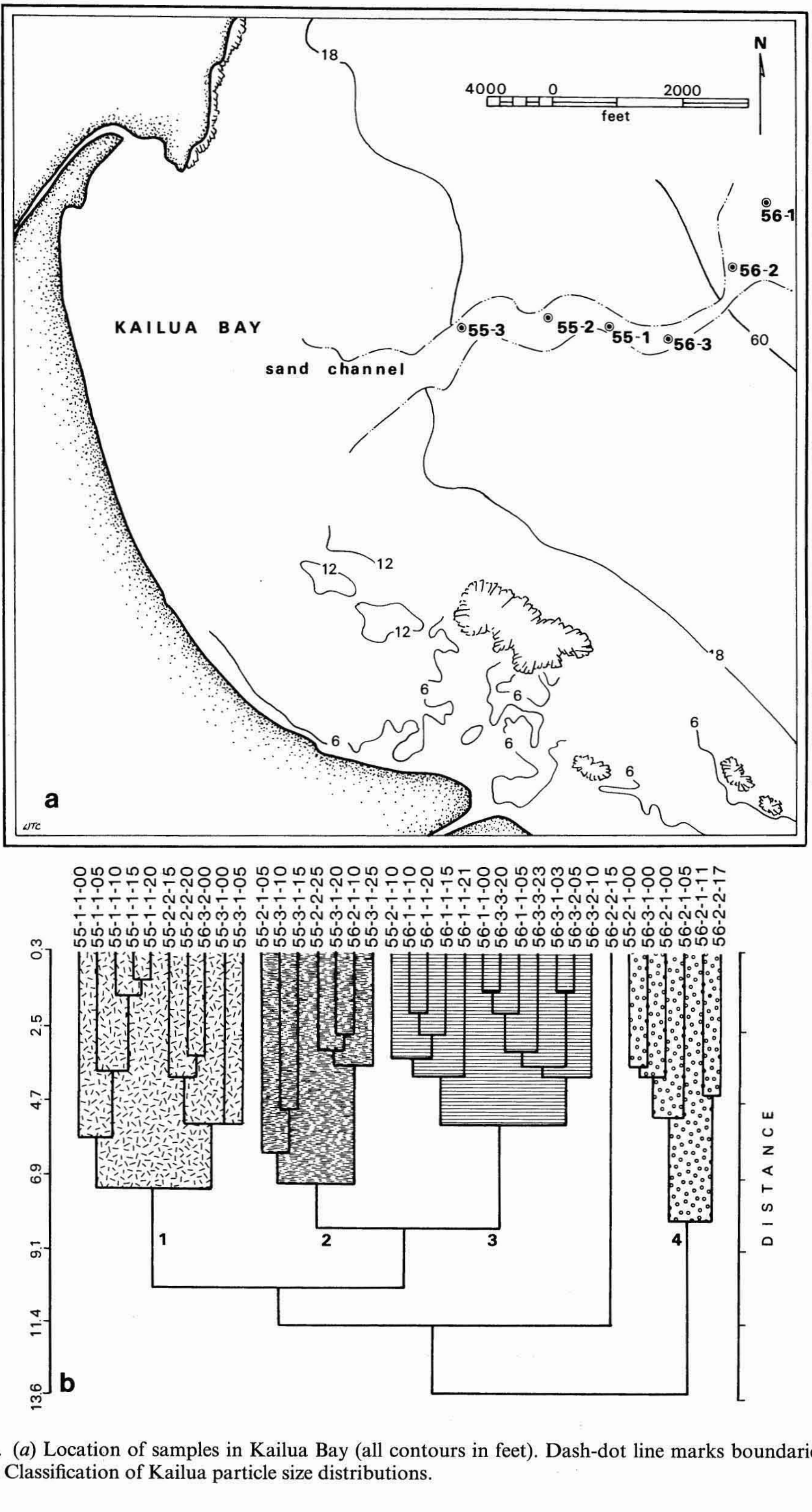

FIGURE 4. (*a*) Location of samples in Kailua Bay (all contours in feet). Dash-dot line marks boundaries of sand channel. (*b*) Classification of Kailua particle size distributions.

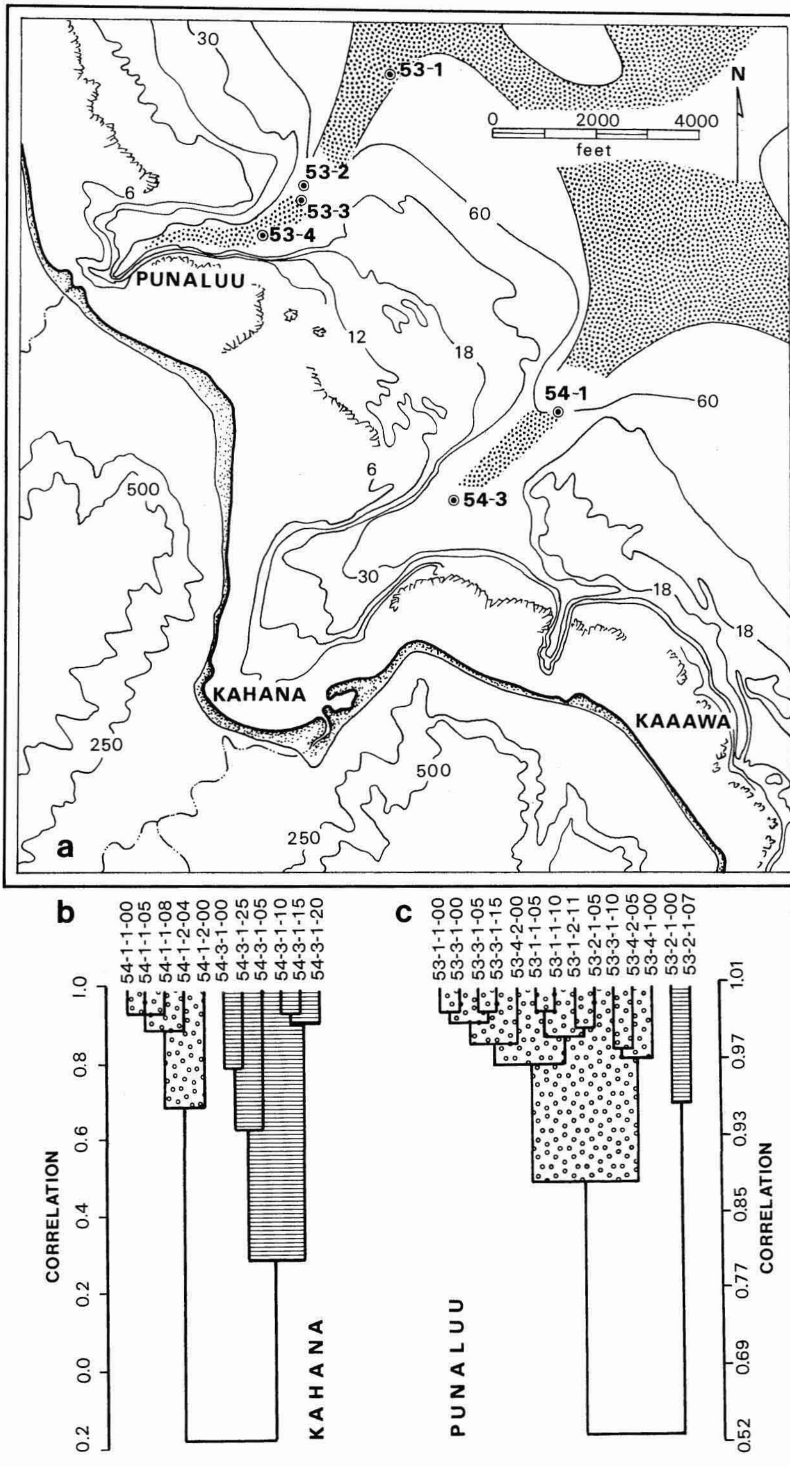

FIGURE 5. (*a*) Location of samples in Kahana and Punaluu sand channels (all contours in feet). Dot pattern outlines thick accumulations of sand in stream channels and farther offshore (after Coulbourn et al. 1974). (*b*) Classification of Kahana particle size distributions. (*c*) Classification of Punaluu particle size distributions.

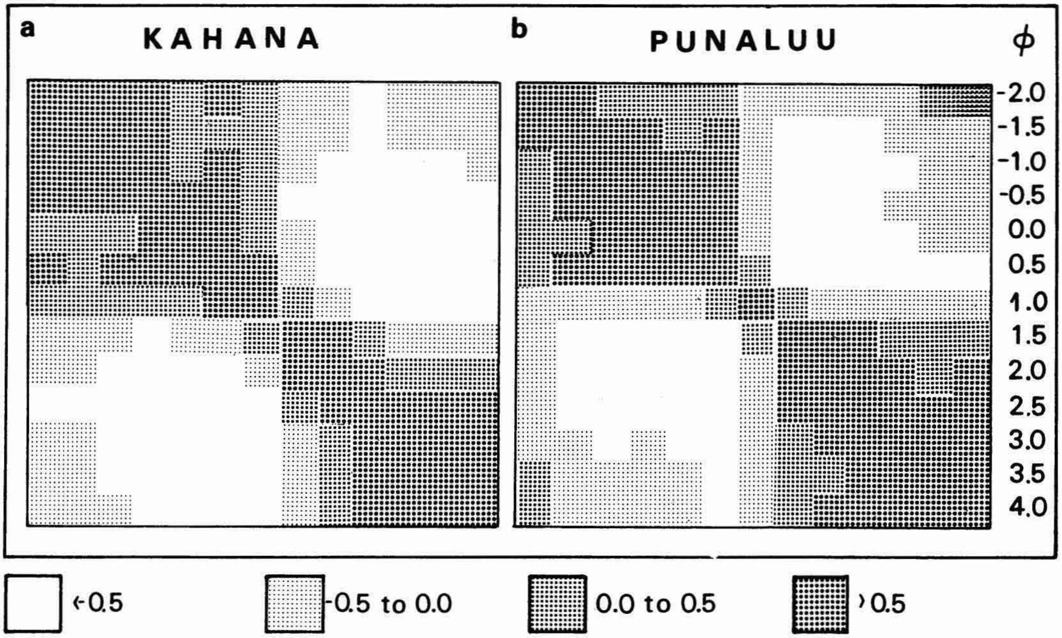

FIGURE 6. Patterned similarity matrices for Kahana and Punaluu samples. Shading density represents values of the correlation coefficient (r), where r varies between -1 and $+1$ as an indication of a perfect negative or positive correlation, respectively. Values near 0 reflect the absence of a correlation. (*a*) Variable-to-variable correlations (phi intervals), Kahana Bay. (*b*) Variable-to-variable correlations (phi intervals), Punaluu channel.

channel are grouped in two distinct clusters (Figure 5*b*). As expected, the mean grain size of samples within each group differs, but unexpectedly, the nearshore samples from location 54-3 are finer than those from location 54-1, farther offshore. This pattern is related to the relatively high flux of fine, terrigenous grains from Kahana Stream, deposited with relatively coarse grains derived from the adjacent reef flat. The fine fractions are deposited faster than they are resuspended by waves, a pattern common to Hawaiian deltas (Moberly et al. 1965).

In contrast to the Kahana channel jet cores, all samples from Punaluu are correlated at a level of 0.5 or higher (compare scale bars in Figures 5*b* and 5*c*). Although two samples from location 53-2 branch apart from the others from this channel because of their coarser mean grain size, sediment size generally fines with increasing water depth [water depth $= Y = 97.0 + 16.7(\% - 1.0\ \phi) - 7.6(\%\ 0.5\ \phi) + 4.7(\%\ 1.0\ \phi) - 9.0\ (\%\ 2.0\ \phi) + 9.2(\%\ 2.5\ \phi)$, R-square $= 0.92$].

Instead of euclidean distance, we used the correlation coefficient[4] in the analysis of Kahana and Punaluu samples, because the patterned similarity matrices offer a sharp picture of the contrasts within each sample set (Figure 6). As measured by r, the relationship of weight percent between each phi unit displays a contrast between the fine- and coarse-grain fractions. The 1.0-ϕ interval is pivotal in both instances.

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[4] The correlation coefficient is computed as

$$r_{ij} = \frac{1}{m-1} |\textstyle\sum_{k=1}^{m} z_{ik} \cdot z_{jk}|$$

where r_{ij} = correlation between sample i and sample j, m = number of phi intervals, and z = the z-score for each data entry [if x is a raw data entry (% here), $\bar{x}$ is the column mean and s is the column standard deviation, then $z = (x - \bar{x})/s$].

Windward Oahu Synthesis

Despite sharing the same wind and wave exposure, sand samples from the windward Oahu coast represent a wide variety of particle size distributions. This variability is demonstrated in the four groupings formed in a *Q*-mode cluster analysis of these samples (Figure 7*a*). As expected, because of the contrasts within each geographic area, the Kailua, Kahana, and Punaluu samples are again split into subgroups but are linked in this result with corresponding samples from the other windward Oahu locations. Of particular interest are the samples clustered with the ASTM standard distribution (cluster 1, Figure 7*a*). Cores from Punaluu channel dominate this group, but only cores from locations 54-1 (outer Kahana channel), 55-1 (mid-Kailua channel), and 56-1 (outer Kailua channel) contain no samples classed with the ASTM standard. The sand is too fine at location 56-1 and too coarse at locations 54-1 and 55-1 to be of commercial use.

The sample groupings constructed in the cluster analysis are distinct (Figure 7*b*). Examination of the centroids (Table 1) reveals a general trend toward coarser distributions from cluster 3, to 2, to 1, with the coarsest samples belonging to cluster 4. Of the 13 phi intervals, 6 are selected in this discriminant analysis. The weightings for the *x* axis (CV1 in Figure 7*b*) contrast coarse with fine grain size in an equation of the form

$$x = 0.44 - (0.21)(\%\ 0.0\ \phi) - (0.57)(\%\ 0.5\ \phi) + (0.31)(\%\ 1.0\ \phi) - (0.38)(\%\ 2.0\ \phi) + (0.30)(\%\ 2.5\ \phi) + (0.35)(\%\ 3.5\ \phi),$$

where, for example, % 3.5 ϕ denotes weight percent sand retained in the 3.5-ϕ sieve. In this result, for any given sample, the higher the weight percentages recorded in the coarse fraction, the more negative is the score for that sample on the first canonical variable (*x* axis, Figure 7*b*). The weightings for the *y* axis primarily contrast the weight percent found in the 0.5- and 1.0-ϕ size intervals (CV2 in Figure 7*b*). The position of each sample on the second canonical variable is computed by forming an equation of the same form as that for the *x* axis, where the weightings listed for the second canonical variable replace the coefficients listed above.

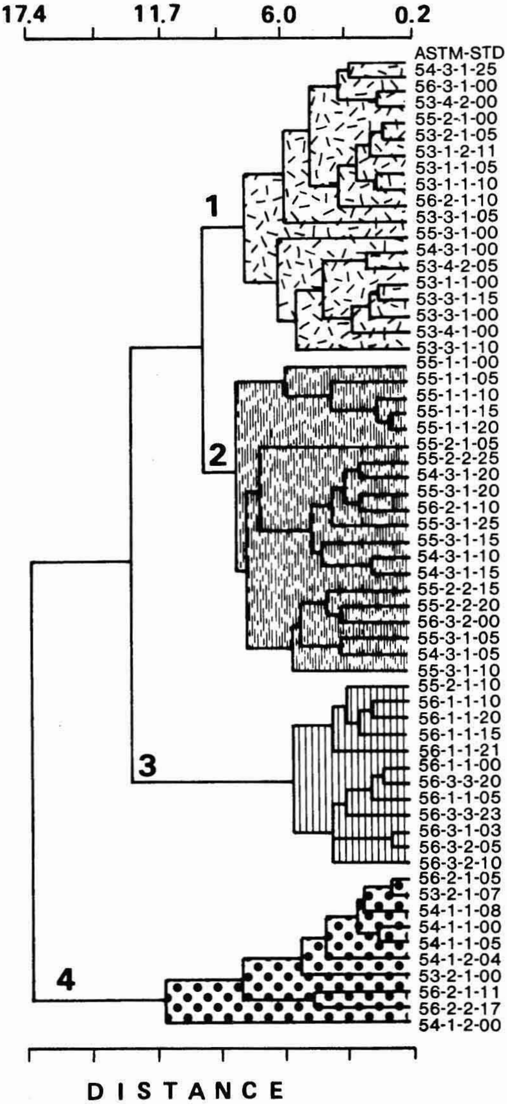

FIGURE 7*a*. Classification of windward Oahu sand samples and ASTM standard distribution for sand for aggregate.

A ternary plot of factor loadings after normalization displays the association of Kailua samples with factor 2 and their lack of association with factor 3 (Figure 7*c*). Examination of the factor scores (Table 2), the raw

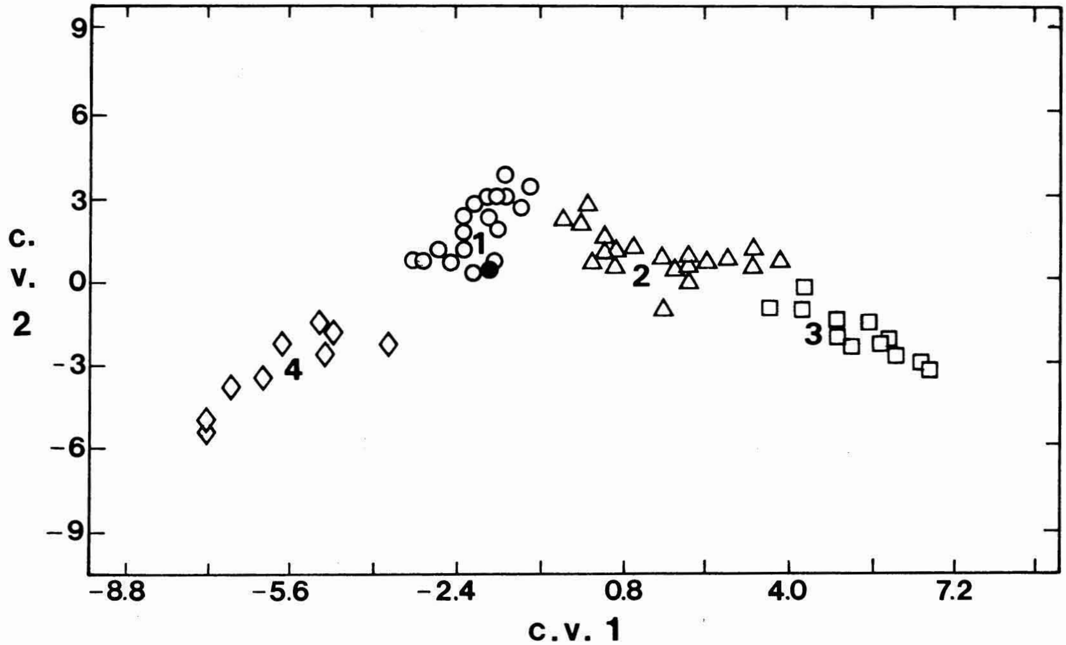

FIGURE 7*b*. Projection of windward Oahu samples onto a plane determined by the first two canonical variables. Sample code assigned according to classification shown in Fig. 7*a*. Filled circle represents ASTM-STD. Group centroids for each cluster are plotted as integers 1–4. Coefficients for the canonical variables (CV):

Variable	CV1	CV2
0.0 ϕ	−0.209	−0.115
0.5 ϕ	−0.574	−0.457
1.0 ϕ	0.308	0.503
2.0 ϕ	−0.382	−0.095
2.5 ϕ	0.295	0.202
3.5 ϕ	0.352	−0.184
Constant	0.440	0.868

data, or moments indicates that these samples have high percentages of fine sand and, as expected, are represented by high factor scores for the 3.0- and 3.5-ϕ size intervals (boldface type in Table 2). Medium-grained Kailua samples load highly on factor 1 (location 55-1, Table 2). Punaluu samples are generally coarser and plot along the border of the diagram—a range that reflects the concentration of grains in the 0.5- to 2.0-ϕ size intervals. Samples from Punaluu location 53-1 plot closest to, and therefore most closely resemble, the ASTM-STD, a result that parallels the outcome of the cluster analysis (Figure 7*a*). Samples from Kahana channel cover a wide range of size distributions and plot over the entire field of the ternary diagram (Figure 7*c*). The overall distribution of points from these windward Oahu localities forms a horseshoe-shaped pattern; points plot around two borders of the diagram and away from the center and base-line field. The pattern is an artifact of the method (Syvitski 1984), but this does not diminish the usefulness of it to our search for sample associations.

THE NORTH SHORE

The north shore of Oahu as designated here stretches from Kahuku Pt. to Kaena Pt.

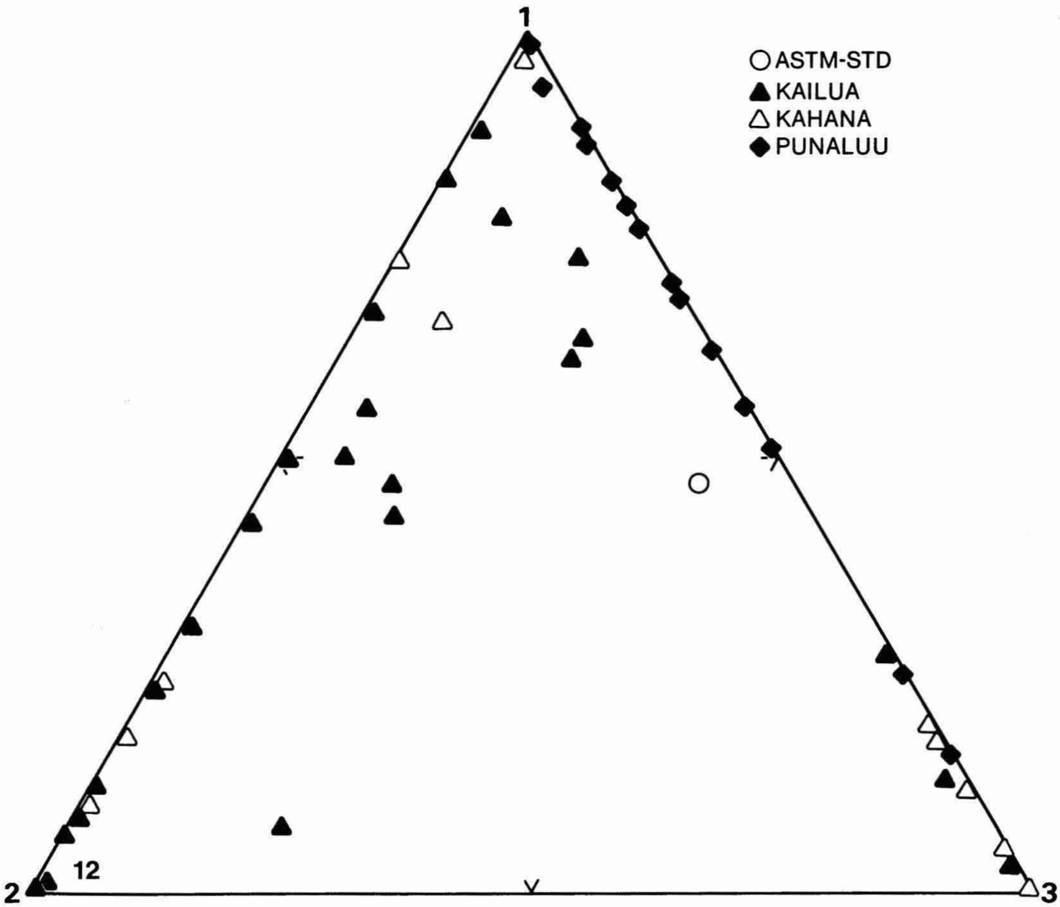

FIGURE 7c. Ternary plot of normalized factor loadings for windward Oahu sand samples.

(Figure 1). Rivers cut across a relatively narrow coastal plain at Waimea and at Haleiwa. Numerous gulches are incised into the ancient wave-cut cliff, forming the landward border of the coastal plain. Long, unbroken, and relatively wide stretches of beach border sections of this coast north of Waimea, but at places like Waimea, beach sands are impounded in coastal embayments or, as along much of the coast at Mokuleia, form narrow strands protected behind wide reef flats or behind exposures of beach rock. This coast is particularly vulnerable to episodic events; shoreline retreat was marked and immediate following the 1946 tsunami and again 23 years later when exceptionally large swells from an early winter storm reached Oahu (Hwang 1981).

Waimea

Waimea Bay is renowned for large winter surf (30-ft breakers), but is less well known for the placid conditions that prevail there during most of the year. Rocky promontories isolate the coarse sand of Waimea beach from neighboring littoral cells (Figure 8*a*). Waimea Beach has gradually retreated over the last 100 years, receding 215 ft in the period between 1928 and 1962, leading to the suspension of the mining of sand from that beach in 1962 (Campbell and Hwang, 1982; Hwang 1981).

TABLE 2

VARIMAX FACTOR SCORES FOR OAHU SAND SAMPLES

PHI INTERVAL	WINDWARD OAHU, FACTOR 1	WINDWARD OAHU, FACTOR 2	WINDWARD OAHU, FACTOR 3	NORTH SHORE, FACTOR 1	NORTH SHORE, FACTOR 2	NORTH SHORE, FACTOR 3
−2.0	0.114	0.258	0.247	0.099	0.009	0.096
−1.5	0.151	0.171	0.200	0.124	0.019	−0.007
−1.0	0.062	0.172	0.572	0.230	0.044	−0.047
−0.5	−0.071	0.129	**1.149**	0.330	0.118	−0.075
0.0	−0.256	0.074	**2.294**	0.556	0.131	−0.096
0.5	0.680	−0.036	**2.080**	**1.387**	0.215	−0.403
1.0	**1.763**	−0.124	0.852	**2.380**	0.251	−0.605
1.5	**2.529**	−0.032	−0.351	**2.137**	−0.040	0.994
2.0	**1.365**	0.226	−0.518	0.311	0.069	**2.689**
2.5	0.792	0.731	−0.493	−0.477	**1.327**	**1.889**
3.0	0.367	**2.290**	−0.391	−0.142	**3.031**	−0.495
3.5	−0.512	**2.486**	0.359	0.078	**1.376**	−0.645
4.0	−0.186	0.907	0.148	−0.001	0.115	−0.029

PHI INTERVAL	LEEWARD OAHU, FACTOR 1	LEEWARD OAHU, FACTOR 2	LEEWARD OAHU, FACTOR 3	SOUTH OAHU, FACTOR 1	SOUTH OAHU, FACTOR 2	SOUTH OAHU, FACTOR 3
−2.0	0.024	0.566	−0.142	0.545	−0.003	−0.136
−1.5	−0.002	0.591	−0.163	0.607	0.020	−0.181
−1.0	−0.001	0.947	−0.261	**1.266**	0.051	−0.476
−0.5	−0.003	**1.244**	−0.330	**1.720**	0.047	−0.554
0.0	−0.046	**1.664**	−0.303	**1.991**	0.083	−0.327
0.5	−0.107	**1.871**	−0.038	**1.760**	0.002	0.726
1.0	−0.232	**1.609**	0.697	0.742	0.205	**1.607**
1.5	−0.223	0.719	**2.008**	0.222	0.603	**1.877**
2.0	0.466	0.002	**2.221**	−0.139	0.937	**1.661**
2.5	**1.636**	−0.373	**1.472**	−0.270	**1.540**	0.859
3.0	**2.805**	0.208	−0.571	−0.101	**2.412**	−0.808
3.5	**1.362**	0.510	−0.782	0.085	**1.767**	−1.165
4.0	0.513	0.259	−0.355	0.043	0.625	−0.407

NOTE: Boldface type highlights scores greater than 1.000.

Jet-core locations are aligned on the axis of the submerged portion of the Waimea River canyon (Coulbourn et al. 1974). The ten samples from locations 52-1 and 52-2 have identical modes (3.25 ϕ) and are well-sorted, negatively skewed, fine- and very fine-grained sands. In the cluster analysis (Figure 8*b*), these sands are distinguished from the coarser and more poorly sorted, surficial sands that have accumulated nearshore at location 52-3. Sands below 15 ft subbottom are also fine at location 52-3. High percentages in the coarse size fractions isolate sample 52-3-1-20 (Figure 8*b*). Stepwise multiple regression selected the 3.0-ϕ and 4.0-ϕ size intervals as the best predictors of water depth [$Y = 13.7 - 0.9(\%\ 3.0\ \phi) + 3.6(\%\ 4.0\ \phi)$, R-square = 0.83].

Haleiwa

Anahula River reaches the coast at Haleiwa, an embayment with a beach park on the east side and a small-boat harbor on the west (Figure 9*a*). Nearshore currents are directed seaward, but currents farther offshore parallel

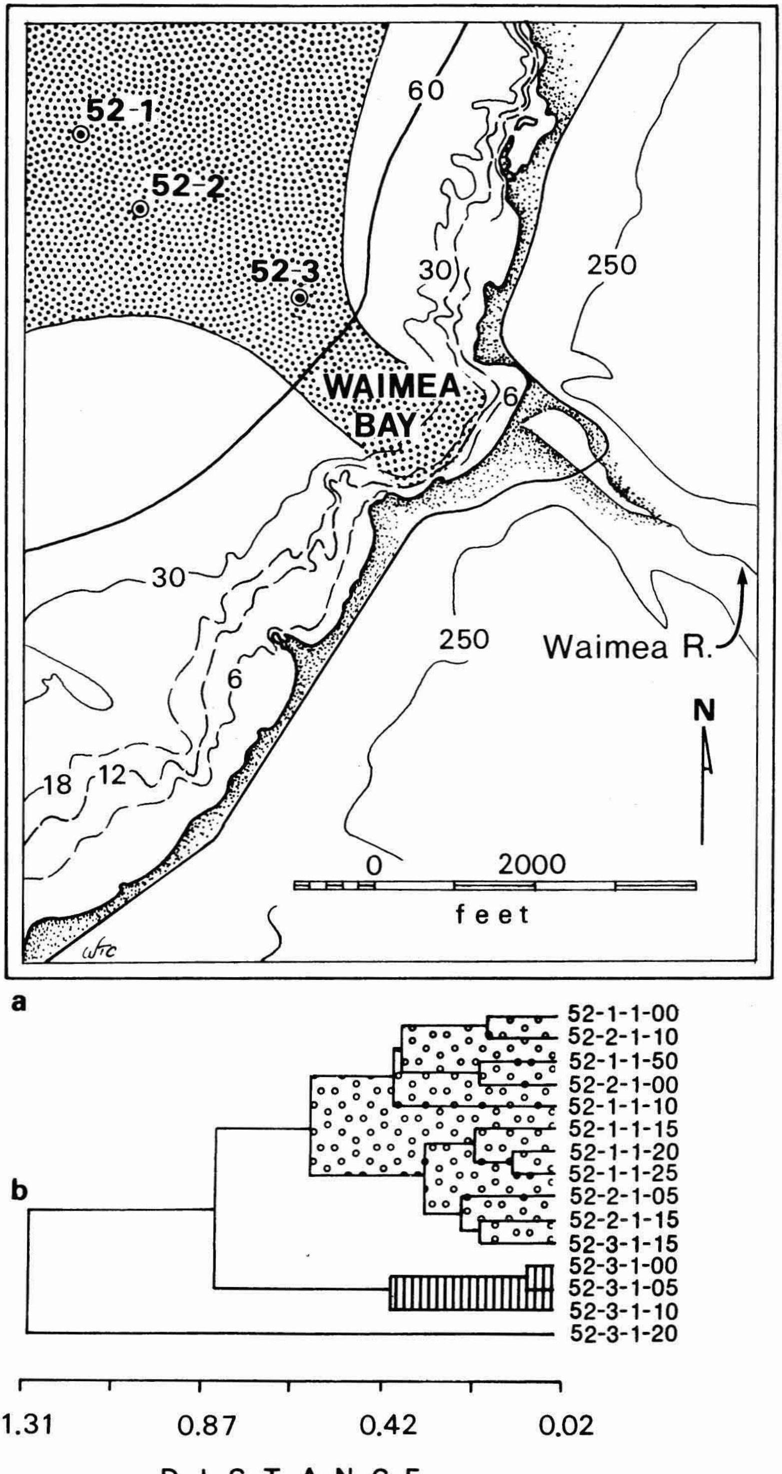

FIGURE 8. (*a*) Location of samples offshore of Waimea Bay (all contours in feet). (*b*) Classification of Waimea particle size distributions.

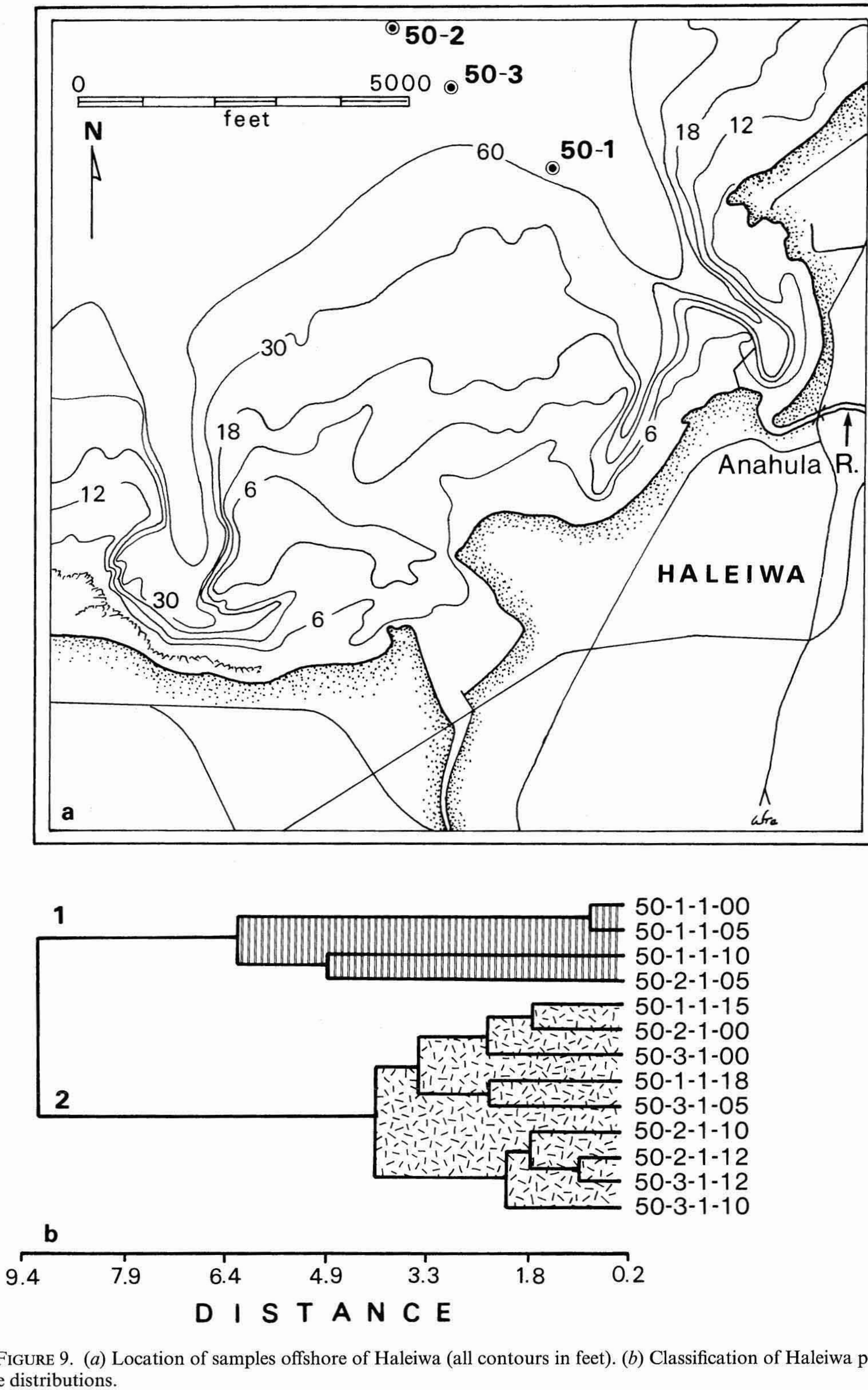

FIGURE 9. (*a*) Location of samples offshore of Haleiwa (all contours in feet). (*b*) Classification of Haleiwa particle size distributions.

the coast (Laevastu et al. 1964). Infrequently, wave setup is sufficient to transport large quantities of sand landward onto the beach park (Gerritsen 1978). Jet cores were taken within the offshore portion of this channel, and the particle size distributions are assigned to two groups (Figure 9*b*). Samples from cluster 1 are medium-grained, well-sorted sands with modal peaks at 1.75 ϕ; all but one are from nearshore location 50-1. Cluster 2 grouped samples of fine (mode = 2.25 ϕ, mean > 2.0 ϕ), relatively poorly sorted, positively skewed sands from locations 50-3 and 50-2, which are farther offshore.

Mokuleia

Jet cores were collected between 60- and 132-ft depths seaward of a gulch incised in the cliff east of Dillingham Airfield at Mokuleia (Figure 10*a*). The seaward extension of this drainage system is completely buried beneath sand but is revealed in seismic reflection profiles (Coulbourn et al. 1974). Of the 14 samples collected, 8 are the medium sands grouped in cluster 1 and 5 are the fine sands in cluster 2 (Figure 10*b*). Fine sands are interbedded with, and deposited adjacent to, coarse sands; as expected, coarser sands were pumped from near the channel axis. The coarsest sands may not have been sampled, because sample locations straddle the channel axis. One outlier, sample 51-3-2-05, is coarser than others in cluster 1. Grain sizes at Mokuleia are related to water depth [$Y = 157.2 - 2.5(\%\ 1.0\ \phi) + 2.3(\%\ 2.0\ \phi) - 12.7\ (\%\ 2.5\ \phi) + 10.5(\%\ 3.0\ \phi) + 30.5(\%\ 3.5\ \phi) + 26.3(\%\ 4.0\ \phi)$, R-square = 0.82].

North Shore Oahu Synthesis

The four sample groups identified in a cluster analysis of the north shore samples (Figure 11*a*) plot as distinct groupings on the plane determined by the first two canonical variables (Figure 11*b*). Examination of the coefficients for each of the three phi sizes selected by the analysis reveals that the x axis is a measure of grain size (weight percent in the 1.5-ϕ class is contrasted with weight percent in the 2.0- and 3.0-ϕ size intervals)—the coarser the particle size distribution, the more positive the sample score on the first canonical variable (x axis, CV1 in Figure 11*b*). The y axis is a crude measure of sorting (the 2.0-ϕ size interval is contrasted with weight percent in the 1.5- and 3.0-ϕ size intervals). Factor analysis of these samples produces another three-factor solution with a horseshoe-shaped distribution of points (compare Figures 7*c* and 11*c*). The sample associations indicated by the factor loading pattern resemble those outlined in the cluster analysis, except that the samples from clusters 1 and 4 are combined in a group represented by factor 1. The factor score pattern indicates that coarse and medium sands are associated with factor 1, and fine and very fine sands are associated with factors 2 and 3 (boldface entries, Table 2). Offshore sands from Waimea are the finest sediments cored on the north shore. Sands from Haleiwa and Mokuleia are the coarsest and most closely resemble the ASTM standard.

LEEWARD OAHU—THE WAIANAE COAST

Broad, relatively continuous beaches and fringing reefs cut by sand channels characterize the semiarid southwest coast of Oahu. Sand channels trend offshore from Keaau, Makaha, Pokai Bay, Maili, and Nanakuli, most connecting with sinuous accumulations of sand ponded on wave-cut terraces paralleling the coastline (Figure 2).

Makua Valley to Waianae Valley

The section of coast between Makua and Waianae valleys was sampled at only four locations (Figure 12). Because the sample coverage is sparse and distances between each sample site are relatively great, no clustering algorithms were applied to these data. Notable among these samples are those from Makua; all four have fine, well-sorted, and negatively skewed distributions.

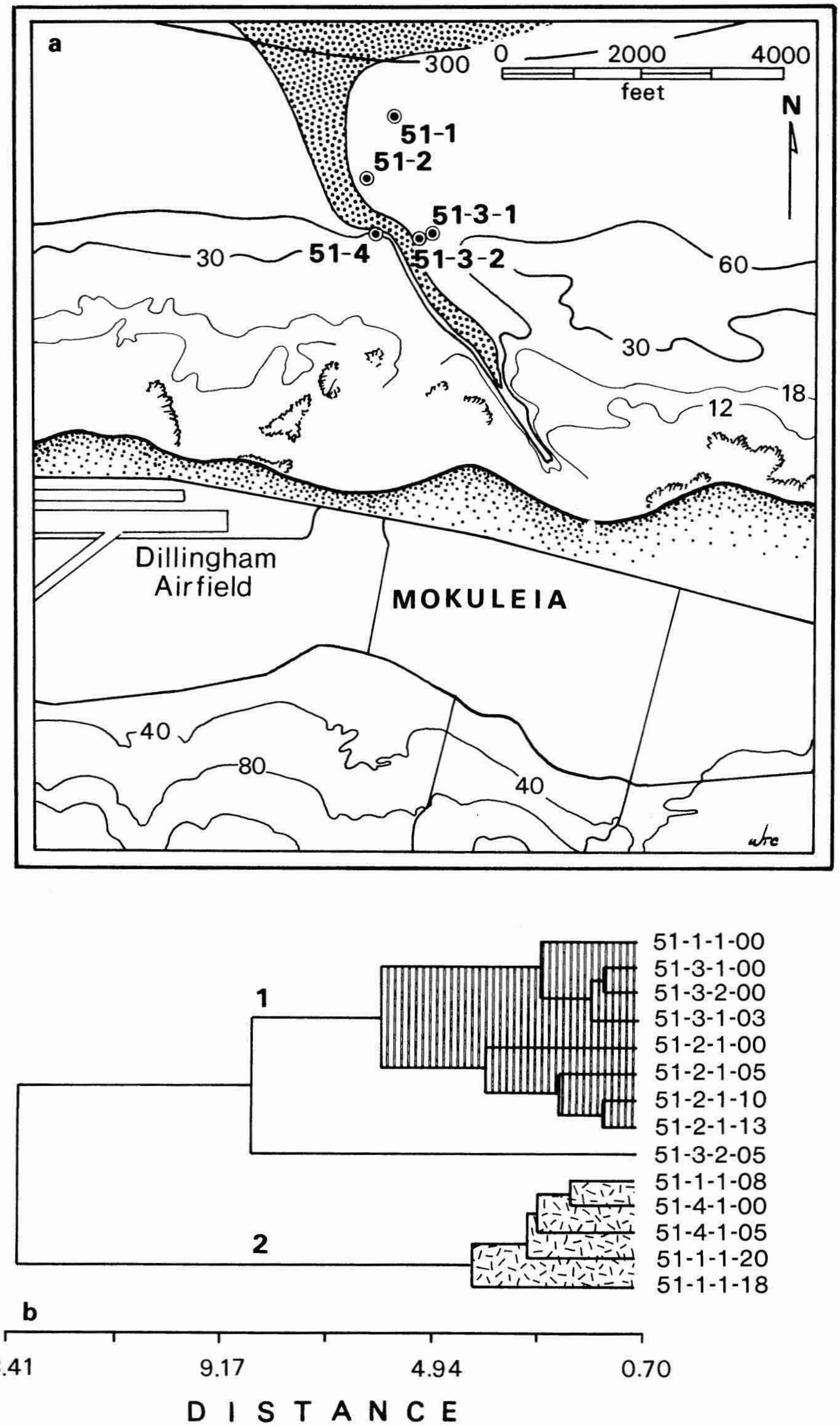

FIGURE 10. (*a*) Location of samples offshore of Dillingham Airfield, Mokuleia, Oahu (all contours in feet). Dot pattern outlines channel axis and thick accumulations of sand offshore (after Coulbourn et al. 1974). (*b*) Classification of Mokuleia particle size distributions.

Pokai Bay

Medium-grained, moderately well-sorted calcareous sand accumulates on Pokai Bay beach, an arcuate pocket beach partly protected within the Pokai small-boat harbor (Moberly and Chamberlain 1964). Leading seaward from the central part of this beach, a sand channel with terraced edges contains at least 18 ft of sand (Moberly 1968). Our jet-core samples are from a broad wedge of sediment ponded on a terrace directly seaward of this channel (Figure 13*a*). The two major clusters of Pokai Bay samples are related to grain size; fine and very fine sands (2.35–3.55 ϕ) of cluster 2 contrast with coarse and medium sands (0.06–1.87 ϕ) of cluster 1 (Figure 13*b*). Sample modes contrast sharply between these two clusters—those with modes exceeding 3.0 ϕ are classed in cluster 2 and those with modes less than 1.75 ϕ in cluster 1. The sample clusters are only weakly related to distance from shore, water depth, and bottom contour. For example, sample 4-1-2-15 from a water depth of 60 ft on a gradual slope and sample 13-3-1-08 from a depth of 180 ft on a steep slope have the greatest similarity of any two samples (Figure 13*b*). In contrast, sample clusters are strongly related to subbottom depth; all samples in cluster 2 are from the uppermost 5 ft of sediment. Coarse sands are near the surface only at locations 4-1 and 5-3. Elsewhere, 5 ft of fine sand covers at least 10 ft of coarse-to-medium sand.

Maili

Medium-grained, well-sorted carbonate sand composes the wide, straight, and seasonally variable beach at Maili (Moberly and Chamberlain 1964). This strand lacks a shallow, protective reef flat offshore, and high winter surf has caused retreat of the north and south ends of the beach. The four localities cored offshore Maili span depths ranging from 30 to 200 ft. With exceptions, the two major groups constructed in the cluster analysis correspond to the spatial distribution of samples; localities 1 and 2 are separated from those farther offshore, localities 12 and 14 (Figure 13*c*). The basis for this separation is revealed in the moments. Grain size can be used to predict water depth [$Y = 52.0 + 35.3(\% -1.5\ \phi) - 10.0(\% -0.5\ \phi) + 5.9(\%\ 3.5\ \phi)$, R-square = 0.88]; sands are finer and better sorted farther offshore. Depth in core influences higher-level clustering; for example, no sample in cluster 1b is from less than 10-ft subbottom, and most samples from cluster 2a are from greater subbottom depths than those from the remainder of cluster 2 (Figure 13*c*). As offshore of Pokai Bay, the deeper sands are generally coarser, indicating a temporal variation in depositional environment.

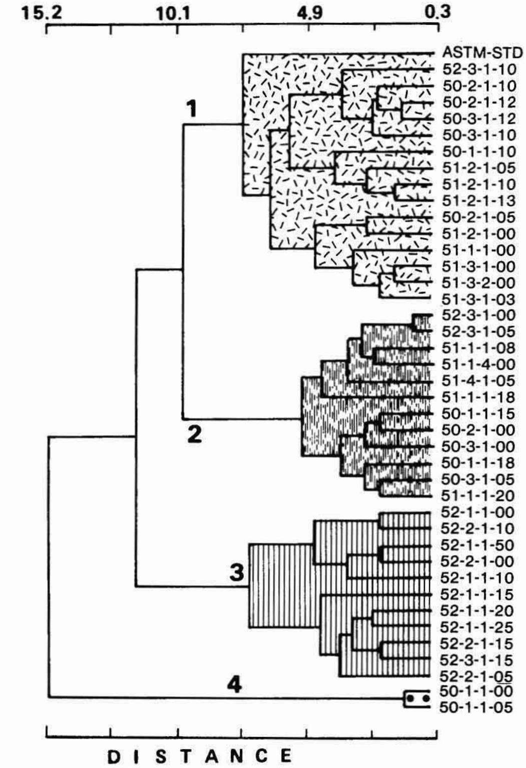

FIGURE 11*a*. Classification of north shore Oahu sand samples and ASTM standard distribution for sand for aggregate.

Nanakuli

Forty-eight samples were taken from 14 jet-core locations in a lens of sand paralleling Nanaikapono Beach at Nanakuli (Figure 14*a*).

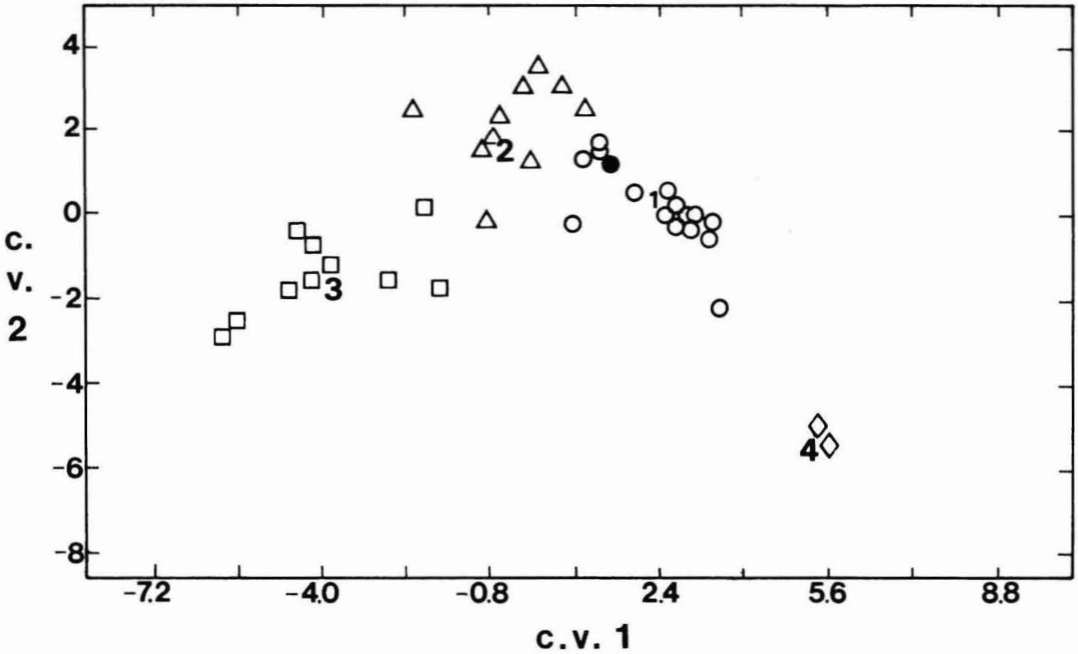

FIGURE 11*b*. Projection of north shore Oahu samples onto a plane determined by the first two canonical variables. Sample code assigned according to classification shown in Fig. 11*a*. Filled circle represents ASTM-STD. Group centroids for each cluster are plotted as integers 1–4. Coefficients for the canonical variables (CV):

Variable	CV1	CV2
1.5 ϕ	0.114	−0.139
2.0 ϕ	−0.097	0.101
3.0 ϕ	−0.210	−0.186
Constant	2.111	2.876

Grain size distributions for these samples are classified into four clusters, with one coarse sand, sample 23-4-1-15, as an outlier (Figure 14*b*). The basis for clustering is explainable in terms of mean grain size: medium sand ($\bar{x}$ = 1.63–1.87 ϕ) in cluster 4, medium and fine sands ($\bar{x}$ = 1.89–2.38 ϕ) in cluster 2, fine sands ($\bar{x}$ = 2.14–2.63 ϕ) in cluster 3, and fine to very fine sands ($\bar{x} > 2.42$ ϕ) in cluster 1. A spatial basis for clustering or geographic coherence of sample groups is less clear. Cluster 1 includes samples from all localities except 23-1, 23-2, and 40-5. Clusters 2 and 3 link samples with no spatially or stratigraphically coherent pattern. Samples from cluster 4 are from at least 10 ft beneath the sea floor at locations 18 and 23. Again, as at other leeward Oahu locations, coarse sands tend to lie beneath a covering of fine sands.

Camp Malakole

Seven samples were taken from only two localities near Barbers Pt., the southwest tip of Oahu (Figure 15*a*). Four of these samples, medium and fine sands, resemble each other in terms of their grain size distributions (shaded branches, Figure 15*b*). The remaining medium and coarse sands are considered outliers; samples 15-2-1-03 and 15-2-1-25 are among the coarsest sands garnered in this collection.

Leeward Oahu Synthesis

Samples from leeward Oahu form three distinct clusters that are related to grain size but not to geography (Figure 16*a*). Cluster 1 contains the ASTM standard and samples most

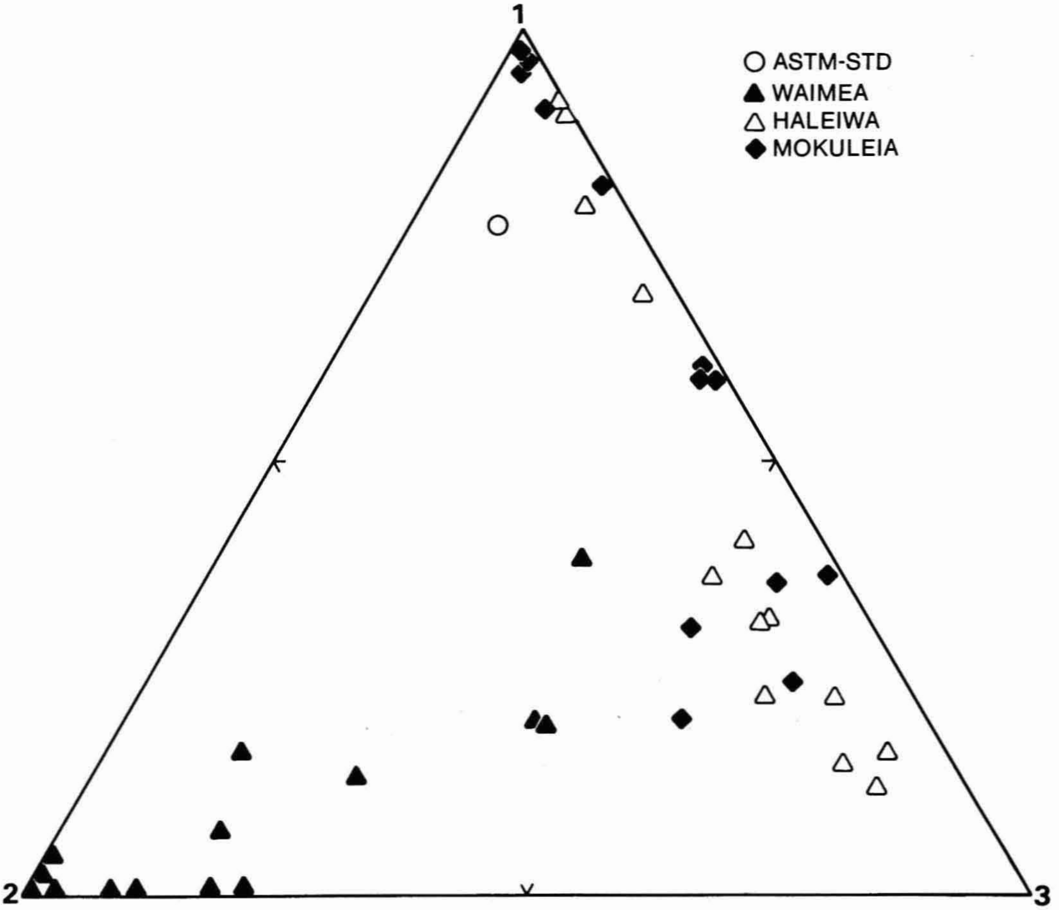

FIGURE 11*c*. Ternary plot of factor components for north shore Oahu sand samples.

suited for beach replenishment—coarse- and medium-grained sands with a preponderance of grains in the 0.0–1.5-ϕ size range (Table 1). Fine and very fine sands are grouped in cluster 2, and medium sands in cluster 3. Sample 5-4-1-00 is an outlier (Figure 16*a*) because of its very fine grain size ($\bar{x} = 3.54\ \phi$). Discrimination between members of these three groups is based on grain size percentages in fractions finer than 1.5 ϕ and reveals little overlap of sample points from different clusters (Figure 16*b*). The lack of spatial coherence in sediment type is vividly illustrated in the mix of symbols over the entire field of a ternary plot of factor components (Figure 16*c*). Factors 1, 2, and 3 represent fine, coarse, and medium sands, respectively. Although the result is of little use in separating samples into groups, it does display the resemblance between the ASTM standard and the coarsest sands, most of which are from offshore of Pokai Bay (Figure 13*a*) and Lahilahi Pt. (Figure 12).

SOUTH OAHU ANALYSIS AND SYNTHESIS

Urban Honolulu dominates the south coast of Oahu. The broad reef fringing this coast has been repeatedly dredged; one recent, large-scale project is the construction of a reef runway for Honolulu International Airport

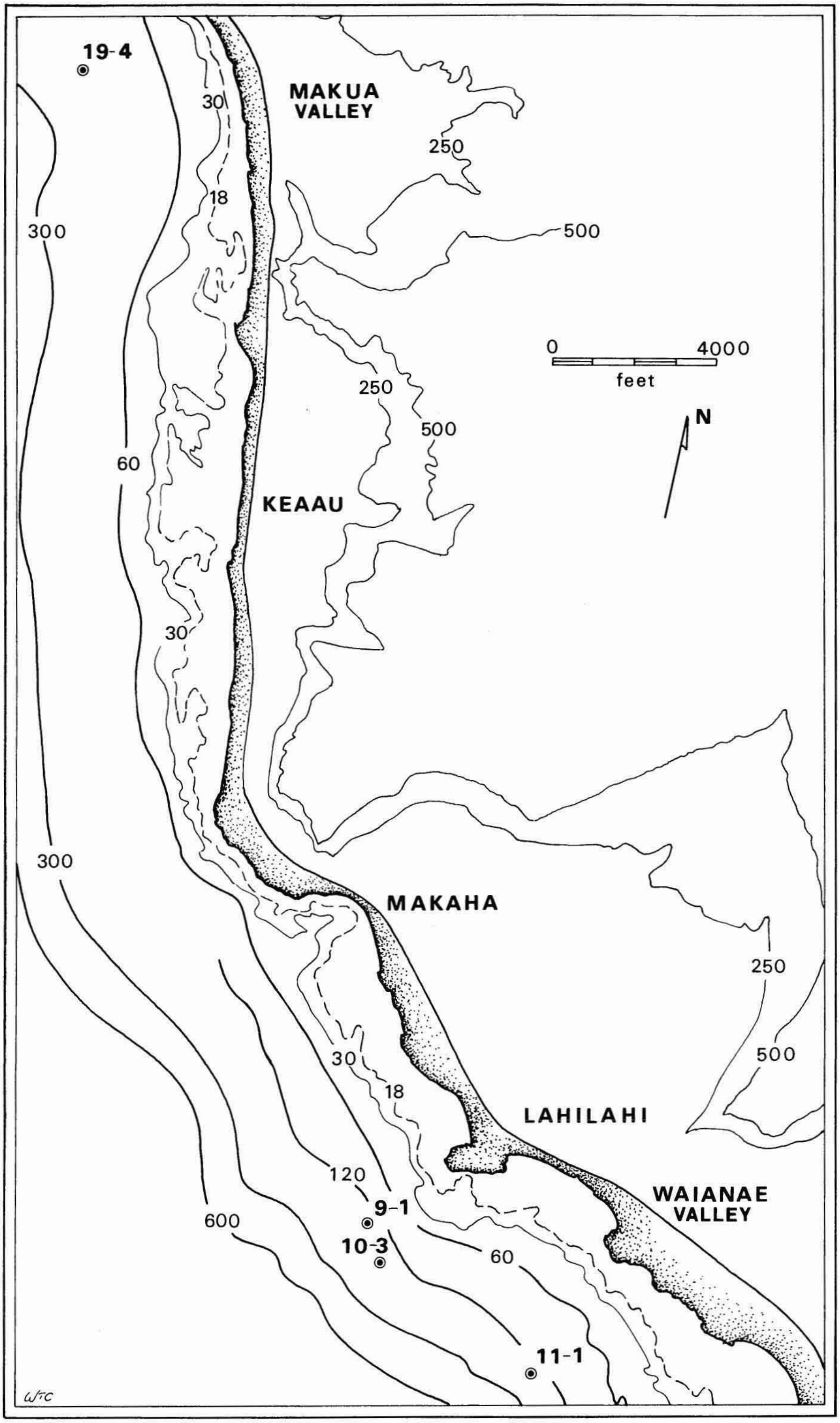

FIGURE 12. Location of samples taken between Makua and Waianae valleys, leeward Oahu.

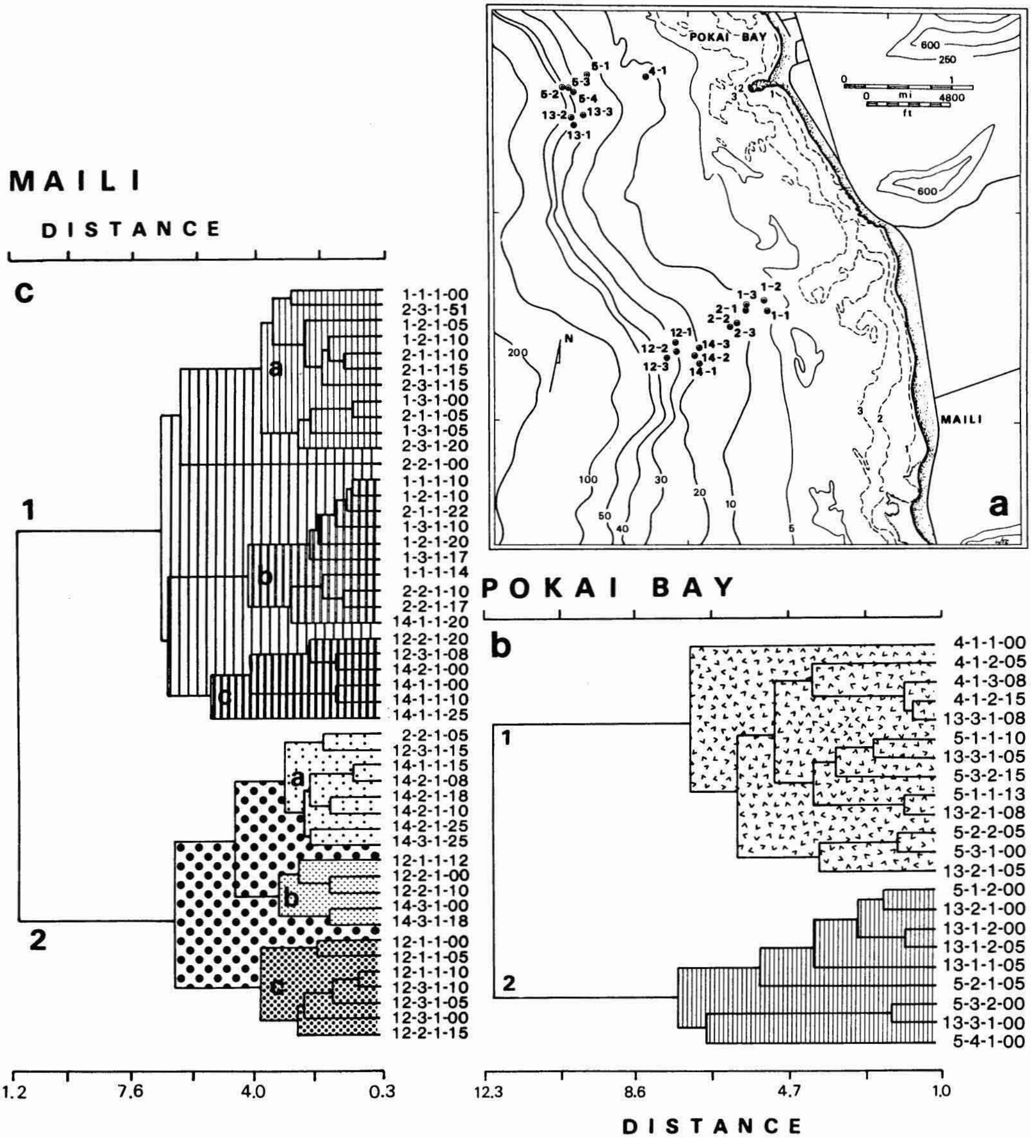

FIGURE 13. (*a*) Location of samples offshore of Pokai Bay and Maili (submarine contours in fathoms, subaerial contours in feet). (*b*) Classification of Pokai Bay particle size distributions. (*c*) Classification of Maili particle size distributions.

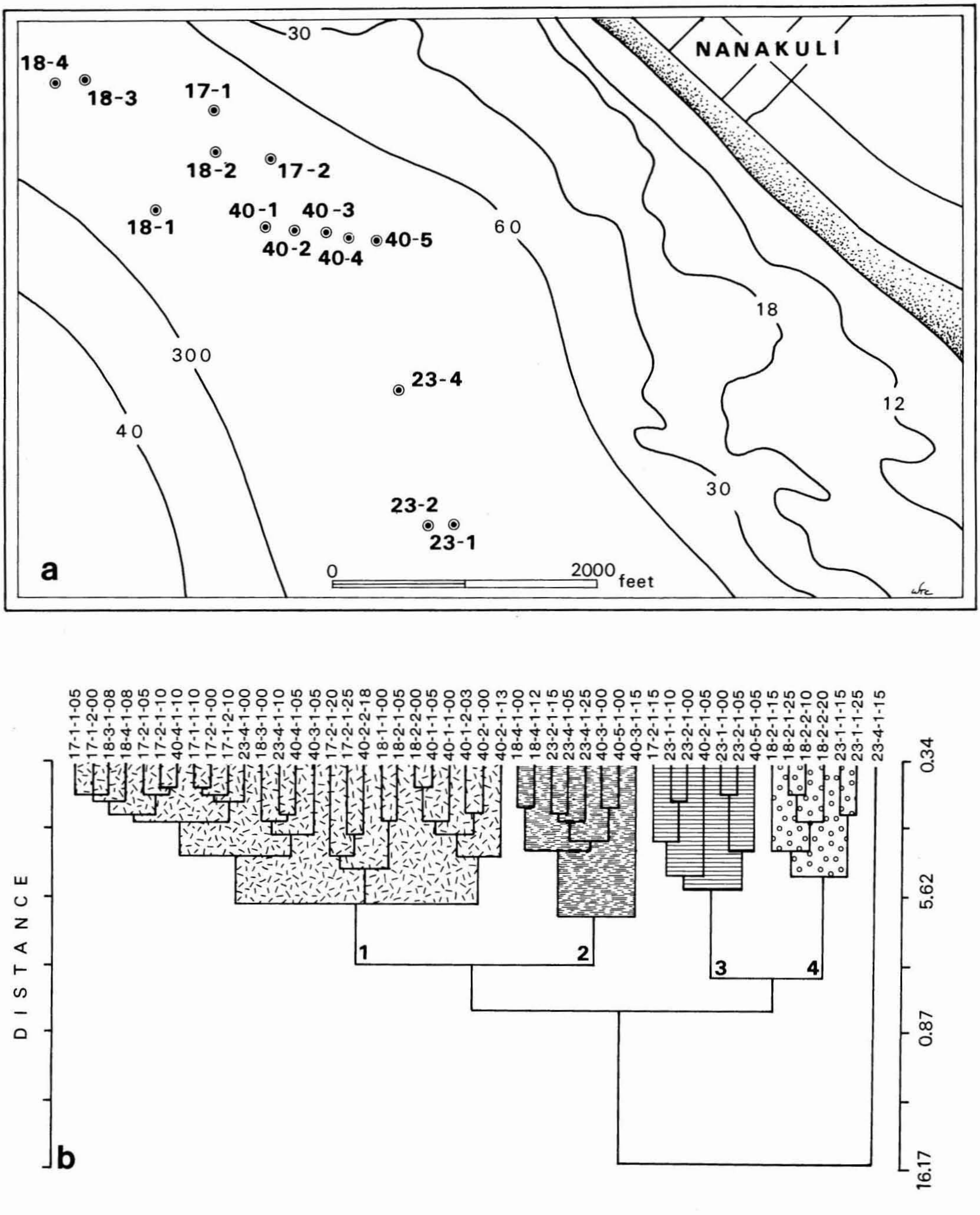

FIGURE 14. (*a*) Location of samples offshore of Nanaikapono Beach, Nanakuli (all contours in feet). (*b*) Classification of Nanakuli particle size distributions.

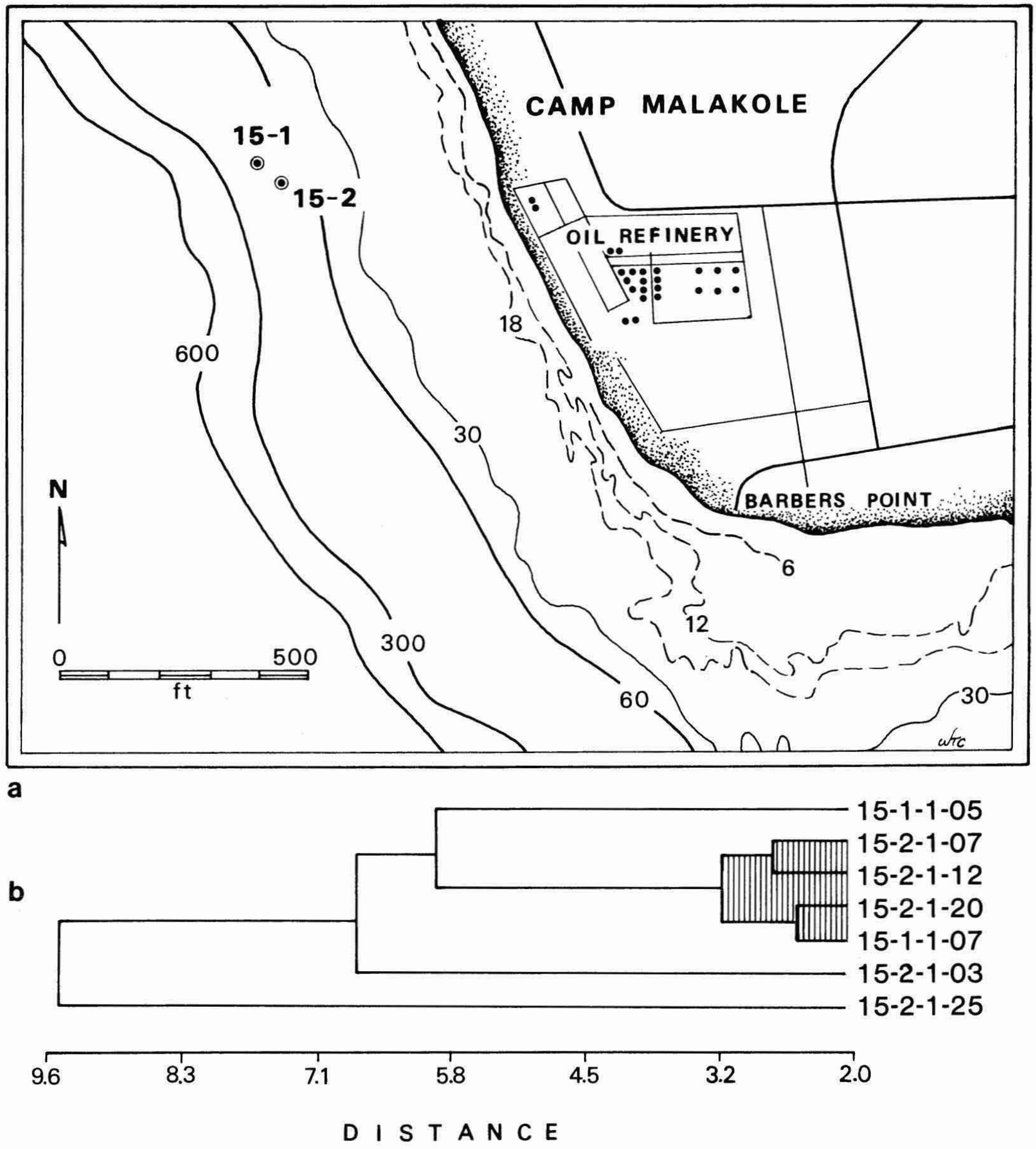

FIGURE 15. (*a*) Location of samples offshore of Barbers Pt. (all contours in feet). (*b*) Classification of Barbers Pt. particle size distributions.

(Figure 17*a*). Subaerial drainage systems, the drowned estuaries of Waikele, Waiawa, Waimalu, Kalauao, Aiea, and Halawa streams (Stearns 1966), reach the sea just to the west of the reef runway at Pearl Harbor (Figure 1). The lochs, or coastal embayments, of Pearl Harbor trap terrigenous grains. Reef runway samples were collected from a sand wedge (Figure 2) at five locations between Pearl Harbor and the Keehi lagoon seaplane runways (Figure 17*a*). These samples are amalgamated in three clusters, with one outlier remaining (Figure 17*b*). The 15 samples in cluster 2 are fine sands, but the remaining 24 samples in clusters 1 and 3 are medium and coarse sands, respectively (Table 2). This area excels as a source of sand for beach replenishment; 17 samples cluster with the ASTM standard. More desirable is the proximity of this potential source to market—the eroding stretches of beach at Waikiki are located only 6 mi to the east.

DISCUSSION AND RECOMMENDATIONS

These results show that recovery of offshore sand for any purpose will be hindered by a complicated and varied distribution of grain sizes, unless the purpose has a wide tolerance for sands of a variety of distributions. In the embayment at Kahana, the fine sands are nearshore, medium and coarse sands offshore. In contrast, this spatial trend is reversed at Punaluu, Waimea, Haleiwa, and Maili, and is lacking at Kailua, Mokuleia, Pokai Bay, and Nanakuli. In a temporal context, the most systematic distributions are along the leeward Oahu coast, where coarse and medium sands are buried under a 5-ft-thick cover of fine sand.

Good sources for beach replenishment are at Punaluu, in the subbottom sands offshore of Pokai Bay, and in the few samples cored from Camp Malakole. The best source for offshore beach sand for beach replenishment is the wedge of sand paralleling the reef runway on the south shore of Oahu. Nearly half the samples analyzed from this area closely resemble the ASTM standard and many others are coarser, probably a result of the entrapment of fine detritus in the coastal embayments of Pearl Harbor and of reworking of offshore sands by long-period waves and passing hurricanes. This deposit is also close to the area of need at Waikiki, but not as close as sands immediately offshore of the hotels. The wedge of sand directly paralleling the coast of Waikiki should be surveyed and cored at several locations before the potential sources identified in this report are resurveyed as serious targets for mining.

CONCLUSIONS

As expected, throughout the sequence of analyses the basis for clustering is clearly related to the statistic for the mean. More unexpected and unfortunate for prospecting efforts is the complicated spatial pattern for distribution of sand grain sizes. Although the patterns within most littoral cells are mappable in terms of water or subbottom depth, sands of all size ranges occur on each coast. This diversity of distribution is an indication of the variability of microenvironment at each location and of variability of proportions of diverse biogenic components; it is probably not merely a result of smearing of patterns by the coring method. Nor does a lack of a general islandwide pattern stem from temporal changes, despite the temporal patterns recorded for samples from the leeward coast where fine sand blankets coarse sand. Exploratory attempts to cluster all surface samples in a single analysis failed to reveal structure within the data.

Our application of statistical techniques has greatly eased the task of identifying desirable versus undesirable resources. The sequence of analyses on subsets of the data allowed us to decipher relationships that were not obvious by inspection of the size distributions or simple univariate statistics. Our approach, however, has not succeeded in relating grain size to specific environments along each island coast. The shortcoming lies in neither the choice nor the efficacy of the methods, but in the data available for our analyses. We have expressed the complex interaction of wave, wind, and current regime; the exposure to

FIGURE 16*a*. Classification of leeward Oahu sand samples and ASTM standard distribution for sand for aggregate.

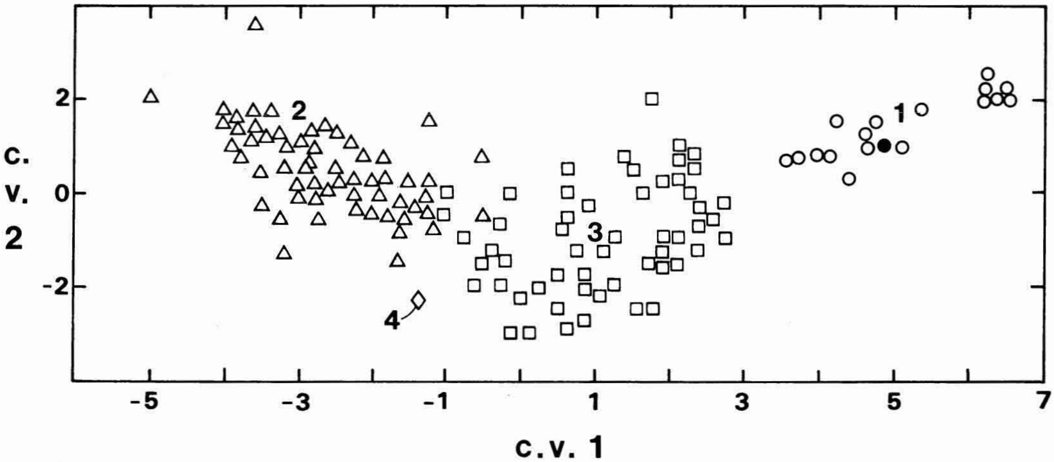

FIGURE 16*b*. Projection of leeward Oahu samples onto a plane determined by the first two canonical variables. Sample code assigned according to classification shown in Fig. 16*a*. Filled circle represents ASTM-STD. Group centroids for each cluster are plotted as integers 1–4. Coefficients for the canonical variables (CV):

Variable	CV1	CV2
$-1.5\ \phi$	-0.243	-0.020
$1.0\ \phi$	-0.018	-0.301
$1.5\ \phi$	-0.234	0.091
$3.0\ \phi$	-0.300	0.002
$4.0\ \phi$	-0.334	-0.302
Constant	8.406	3.311

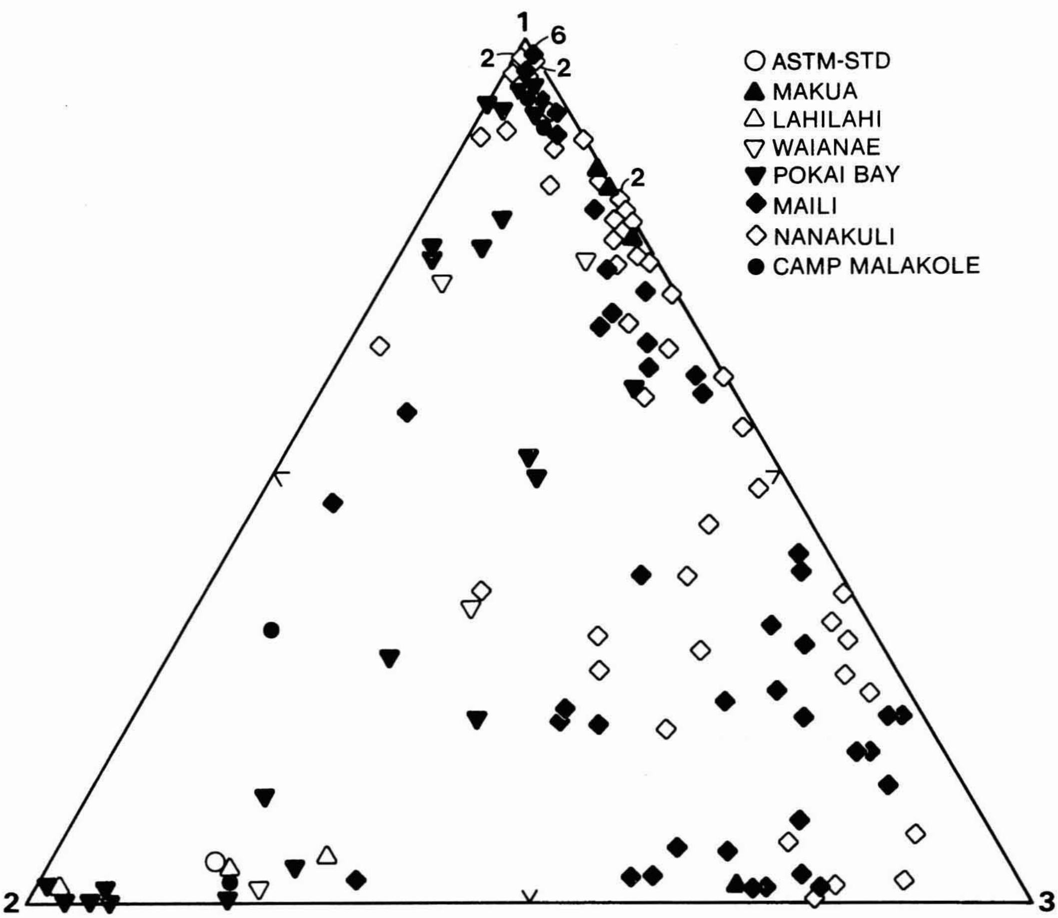

FIGURE 16*c*. Ternary plot of factor components for leeward Oahu sand samples.

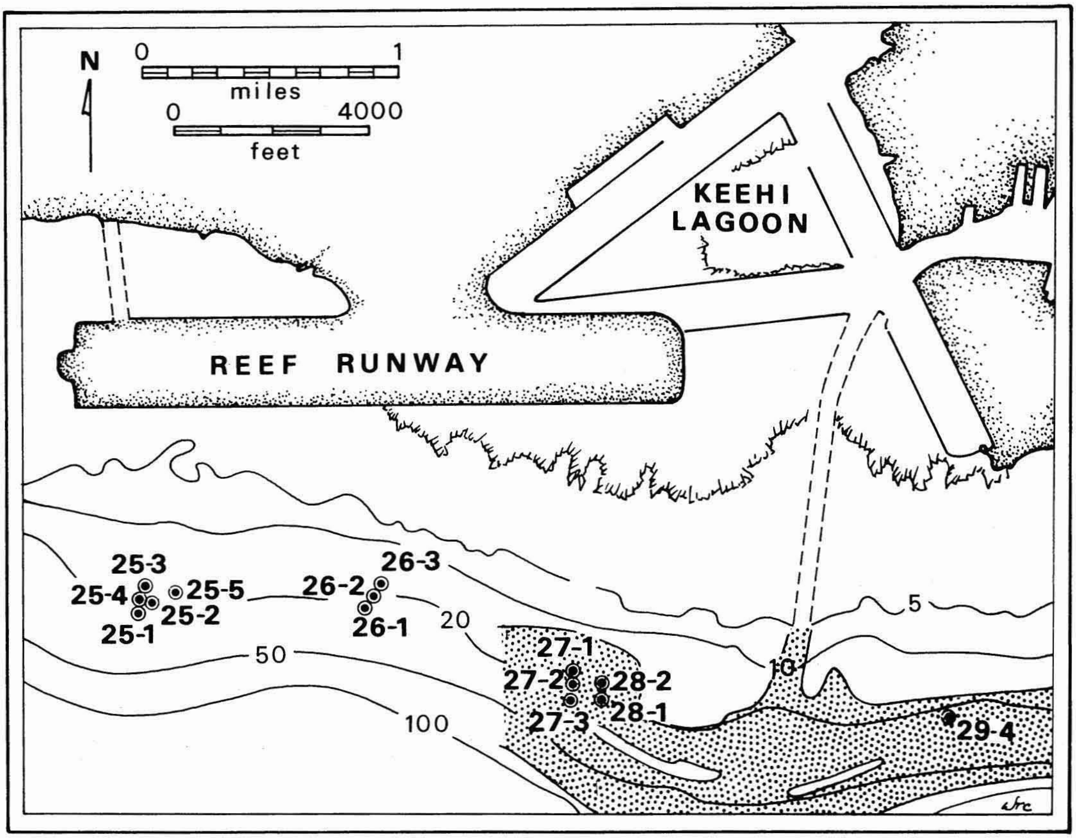

FIGURE 17*a*. Location of samples offshore of Pearl Harbor and the reef runway, south coast Oahu (all contours in feet). Dot pattern outlines accumulations of offshore sand (after Coulbourn et al. 1974).

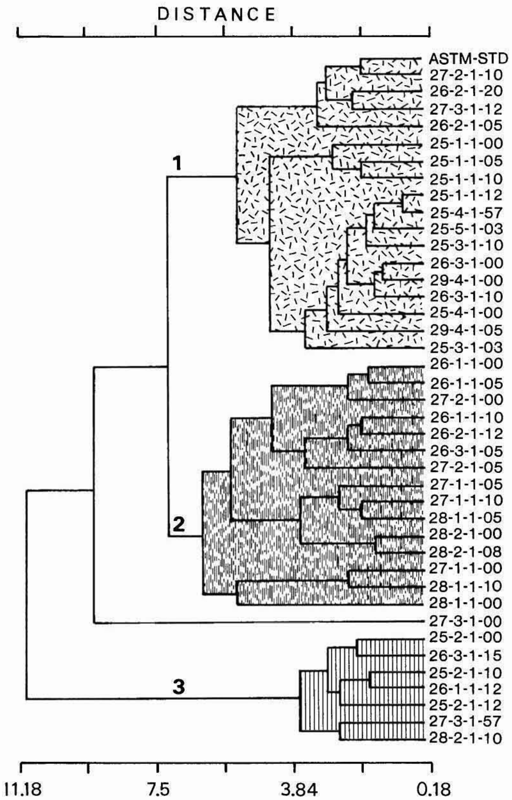

FIGURE 17*b*. Classification of south coast Oahu particle size distributions.

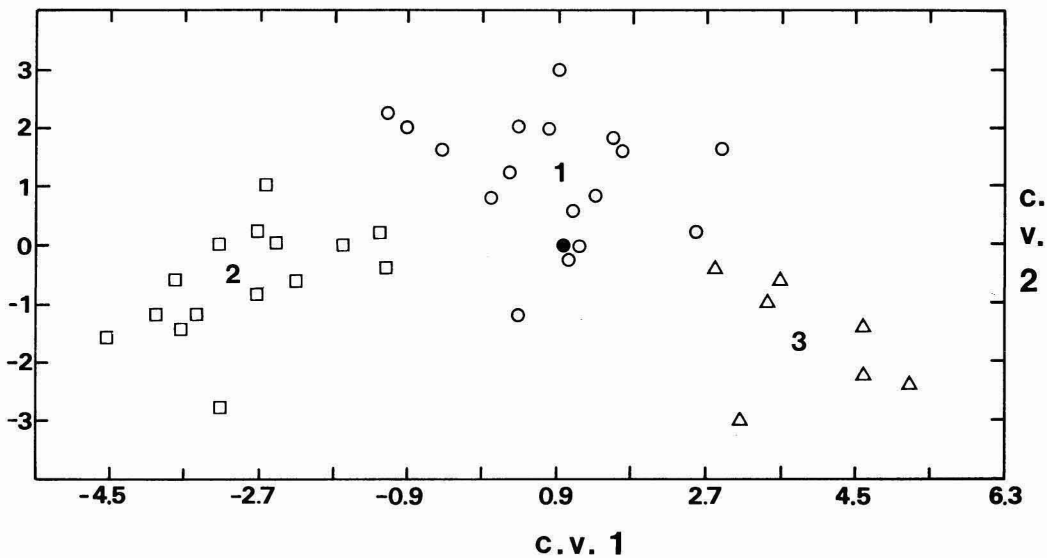

FIGURE 17*c*. Projection of south coast Oahu samples onto a plane determined by the first two canonical variables. Sample code assigned according to classification shown in Fig. 17*b*. Filled circle represents ASTM-STD. Group centroids for each cluster are plotted as integers 1–3. Coefficients for the canonical variables (CV):

Variable	CV1	CV2
0.00 ϕ	0.623	0.082
1.50 ϕ	0.209	0.419
Constant	−7.184	−5.011

catastrophic events; and proximity to subaerial drainage systems in terms of variables such as water depth and sample location. This short-cut has allowed us to identify patterns within most subsets of the data, but does not permit specific statements relating environment to grain size, much less an assignment of cause and effect.

ACKNOWLEDGMENTS

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